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PERFORMANCE SIMULATION OF AN IDEAL MIXER-EJECTOR TURBOFAN ENGINE FOR A SUPERSONIC BUSINESS JET

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Abstract

In the European ITP HISAC the feasibility of an environmentally friendly and economically viable small size supersonic transport aircraft (S4TA) is investigated. Main environmental issues are fuel consumption, noise, emissions and sonic boom. Three design teams exercise a Multiple Disciplines Optimization resulting in three variants of a S4TA. This work includes engine performance simulations for various types of engines covering the whole business jet flight envelope. The NLR Gas Turbine Simulation Program GSP is one of the engine performance modeling vehicles used for the so-called mixer-ejector engine variant, which is applied to reduce noise at take-off. It appeared that the engine core flow mixing with the entrainment flow through the exhaust ejector doors is supersonic. GSP can handle as standard component the mixer-ejector with subsonic in- and outflows and has been adapted to include the supersonic core flow. This paper gives the method and results from the GSP modification to include a mixer with supersonic core flow. It appears that GSP is well suited to predict the performance of the mixer-ejector engine. The engine performance simulation results however came too late to feed the HISAC MDO studies.

1 Introduction

In the European ITP HISAC (Environmentally Friendly High Speed Aircraft) the feasibility of an environmentally friendly and economically viable small size supersonic transport aircraft (S4TA or also denoted as SSBJ (Supersonic Business Jet)) is investigated by three MDO-exercises [1]. The cruise flight Mach number of the supersonic business jet is 1.6/1.8 and the payload is 1000 kg (8 passengers). Main environmental issues for a S4TA are fuel consumption, noise, emissions and sonic boom. Engine performance simulations are a vital element in this chain and performed within this consortium by Dassault (Gasturb of Kurzke [2]), SNECMA (Proprietary Software), CIAM (ECTASE) and NLR (GSP). Three engine configurations are studied: (i) a conventional low-bypass ratio turbofan, (ii) a variable cycle turbofan and (iii) a so-called mixer-ejector engine. The low-by-pass ratio turbofan suffers at S4TA take-off of a relatively high jet velocity and therefore high jet noise. The latter two engines tackle this S4TA jet noise problem at take-off by increasing the actual by-pass ratio and lowering the jet velocity. Depending on the type of jet noise source, the total radiated acoustic energy at equal thrust scales to V_{jet}^4 (as main contributor a dipole type of noise source for hot jets) or to V_{jet}^6 (as main contributor a quadrupole type of noise source for cold jets).

The exhaust of the mixer-ejector engine consists of a variable geometry at both cruise and take-off (Fig. 1). At cruise conditions the variable condi-nozzle guarantees a perfectly expanded jet. At take-off and initial climb conditions the ejector doors are opened and entrained ambient air is mixed with the high-speed core flow by a forced mixer, which leads to a significant reduction of jet exhaust velocity. The effect on net thrust with ejector doors open is very dependent on the geometry applied and the flight conditions and can be either advantageous or lead to additional drag. The turbofan engine performance with forced mixer-ejector for the S4TA had to be simulated by GSP.

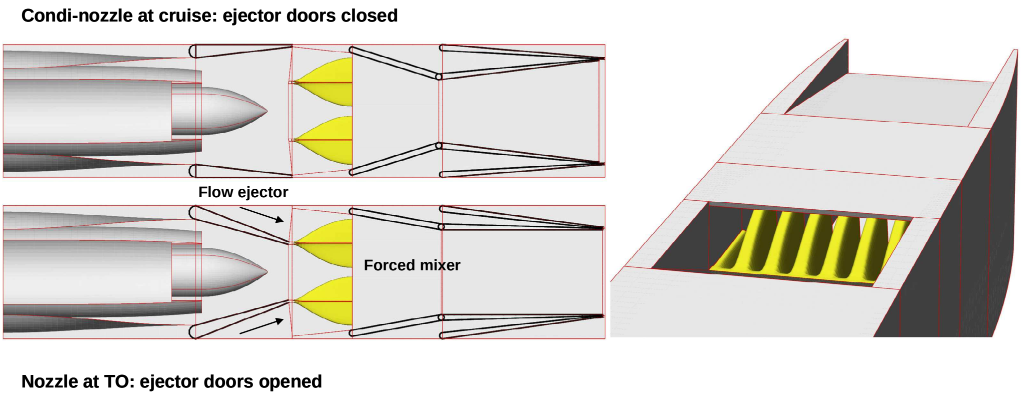

Fig. 1 The exhaust condi-nozzle of the mixer-ejector engine with ejector doors

2.1 NLR Gas Turbine Performance Simulation Program GSP

Gas turbine performance simulations and predictions have a wide range of applications. It is used among others in design (cycle optimization), mission analysis, optimization of system performance and control logics, diagnostics and prognostics, failure analysis, structural and thermal load prediction, life prediction, flight simulators and prediction of engine emissions. Engine performance simulation can be done at various levels from 0-D component stacking to fully 3-D CFD. Because of the many different gas turbines configurations and the wide variety of system performance analysis problems encountered in practice, the gas turbine performance prediction model should have a high degree of flexibility.

The Gas turbine Simulation Program GSP, a 0-D component based modeling environment is NLR's primary tool for gas turbine engine performance analysis [3]. GSP's flexible object-oriented architecture allows steady state and transient simulation of any gas turbine configuration using a user-friendly drag & drop interface with on-line help running under Windows. The thermodynamics include real gas effects as dissociation and the combustor can be extended to a 1-D Multi-Reactor component for more accurate calculations of engine emissions. Note that a light version of GSP is freely downloadable from internet [4].

2.2 Mixer-ejector configuration for a S4TA

The mixer-ejector engine consists of a low-bypass ratio mixed flow turbofan coupled to an exhaust mixer ejector configuration (ejector doors and forced mixer) followed by a condi-nozzle (Fig. 1). NLR's Flight Physics Department (AVFP, Laban) did exploratory CFD design calculations with an Euler code to capture the main flow physics of the mixer-ejector. Points of attention were the maximum core and "bypass" flow Mach number distributions and the amount of mixing, which determines the reduction in exhaust jet velocity necessary to lower the radiated jet noise. Main disadvantage of the mixer-ejector is the additional weight and drag during cruise. Main result for engine performance simulations with GSP is that with engaged doors the engine core flow Mach number is supersonic (Fig. 2).

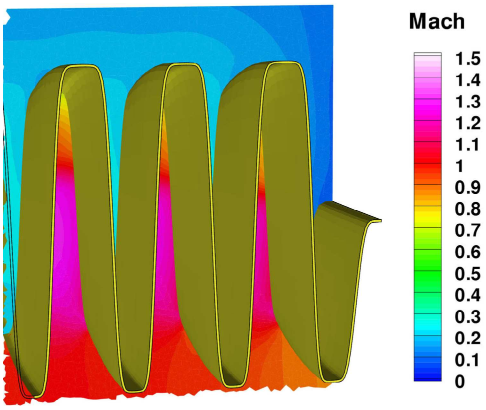

Fig. 2 Mach number distribution in the forced mixer calculated with the NLR Euler code (Laban)

2.3 GSP mixer for supersonic core flow

GSP as other 0-D engine performance simulation programs distinguish design and off-design calculations. Prior to the off-design calculations, the engine model is scaled at the design point calculation and the engine component characteristics or maps are scaled accordingly. A GSP off-design engine model consists of a system of non-linear thermodynamic equations with the so-called state variables characterizing the engine components as compressor, turbine and others. This system is solved with an iterative Newton-Raphson procedure, which minimizes the so-called error vector to a required accuracy.

An ideal mixer is a GSP standard component with subsonic core, by-pass and exhaust flows. The flow and thermodynamic solution for design and off-design conditions is found by solving the mass, momentum and energy conservation equations. For a design point calculation two input parameters from a list are chosen and depending on the selected parameters an additional error equation may be minimized. If for example the core and by-pass duct area’s are specified, the (subsonic) inflows are separately solved giving the static pressure ratio at the merging inflow trailing edge and the mixed exhaust flow. If for example the total area and pressure ratio is chosen, an iterative procedure will minimise an error in the static pressure ratio (specified minus actual) as function of the area-ratio. The mixer component for off-design engine performance calculations has no model state variable, but an error equation is added related to the static pressure ratio at the intersecting point where both inflows merge. For the HISAC engine performance studies the design-option with the total area and static pressure ratio was chosen, since the total frontal area is important engine design parameter for supersonic aircraft. The static pressure ratio between the merging core and ejector flows was set to 1 without loss of generality.

A mixer with one or both of supersonic inflow-branches is much more complex. This is caused by the ambiguity related to 1-D compressible flow. At fixed total temperature, pressure and area larger than the critical area, there are two flow solutions: a subsonic and a supersonic one. For a mixer with two inflows and one outflow there are in fact 7 possibilities (in-in-out: sub-sub-sub and variants). The variant sub-sub-super is not allowed since this leads to a decrease of mass averaged entropy and violates therefore the second law of thermodynamics [5]. Another problem with the transonic mixer is the convergence, since at equal entropy the derivative of the Mach number to the area $\frac{dM}{dA}$ at critical (or near critical) condition is infinite (or very large).

The GSP mixer component was modified to enable supersonic flow in the entry ducts. For design and off-design calculations, two different approaches were taken. To circumvent the ambiguity in the 1-D compressible flow calculations at design point, instead of the area ratio the static pressure was taken as variable and the error equation was expressed in terms of the area ratio, so the roles of both variables were switched (original: pressure ratio used for the error equation; modified: total area used for the area equation). The second problem at design calculation the poor convergence was solved by including an analytical estimator for the inflow static pressure when minimizing the error in the total area leading to following equations: (1=core, 2=duct, i=1,2)

The error equation (1) reads:

$$\left|1-\frac{(A_1+A_2)}{A_{total}}\right| \le \varepsilon \qquad (1)$$

with area $A_i(P_s)$ and ε the error (A_{total}=fixed specified total mixer exhaust area).

For the static pressure estimator in the iterative procedure denoted by i (1=core,2=duct) and iterative time step j the following equations are used (equations 2 and 3):

$$f_i = \frac{P_{s,i}}{A_i\left[\frac{P_{t,i}}{P_{s,i}}\left(\frac{1}{M_i}+\frac{(\gamma-1)M_i}{2(1+\frac{(\gamma-1)}{2}M_i^2}\right)\left(\frac{1}{\gamma M_i(1+\frac{(\gamma-1)}{2}M_i^2)^{\frac{1}{(\gamma-1)}}}\right)-1\right]} \quad (2)$$

$$P_{s,j+1} = P_{s,j} + \frac{(A_{total}-(A_1+A_2))\,f_1\,f_2 H_{P_s}}{((f_1+H_{P_s}\,f_2)} \quad (3)$$

with

A = Area

P_s = Static pressure

P_t = Total pressure

H = Specified static pressure ratio

M = Mach number

γ = ratio of specific heats

For off-design calculations a different approach was taken, since the initial design condition would be the starting point for the off-design calculations. Static pressure equality (both for subsonic and supersonic flows) is taken as boundary condition at the trailing edge of the splitter plate (starting of the mixing zone). The outer flow static pressure was taken as reference (i=1) and it was checked whether the static pressure was lower or higher than the static pressure of the core flow at sonic conditions. Depending on the outcome a subsonic or supersonic static flow parameters routine is called. The above described methods are implemented and a selection of GSP results for the mixer-ejector turbofan for a S4TA or SSBJ is shown hereafter.

3.1 Results design point calculation

Dassault and SNECMA issued the design parameters of the so-called conventional reference engine at take-off condition (ISA + 15 K) among other points not relevant for the supersonic mixer (emergency TO, climb out, cruise and landing). It is noted that many aspects not covered by this article (cycle optimization, specific fuel consumption, installation effects, weight, engine component constrains, noise certification, lifing, maintenance and operational costs) play a vital role in the optimization an engine for a supersonic business jet. This reference engine, a conventional turbofan with variable geometry condi-nozzle (without ejector) has a by-pass ratio of 3.65 at a total inlet mass flow of 165 kg/s, an overall pressure ratio of 27 and a static thrust of 58 kN at a maximum jet velocity of 350 m/s. Note that the by-pass ratio for the conventional (not variable cycle or mixer-ejector) reference turbofan is unnecessarily large to keep the jet velocity low for noise certification at TO. A selection of the engine parameters for the mixer-ejector engine at TO design point is given in table 1.

Table 1: Selection of engine TO-design parameters for the mixer-ejector engine

Intake mass flow	134.5 kg/s	Mass flow ejector doors	30.5 kg/s
Fan by-pass ratio	2.15	By-pass ratio mixer/ejector	0.22
Overall pressure ratio	30	Static pressure ratio trailing edge mixer/ejector	1
Engine thrust	58 kN	Jet velocity	350 m/s

The GSP engine model is shown in figure 3. It consists up to the mixer-ejector (red box) of a low-bypass ratio mixed turbofan. The mixer-ejector is simulated by a duct for the core flow, an inlet representing the ambient air through the open ejector doors and a forced mixer. The exhaust is a variable condi-nozzle to ensure perfectly expanded jet conditions during end of climb and cruise conditions. Note that the mixer-ejector configuration is only used during the first phase of take-off. A short period after rotation the ejector doors are closed and the engine reacts as a conventional turbofan with a variable geometry condi-nozzle.

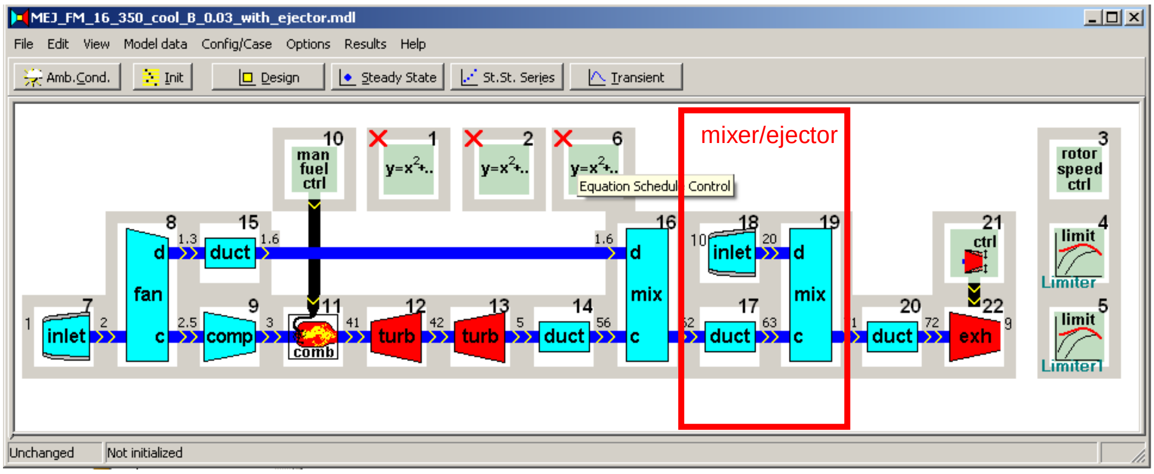

Fig. 3 GSP low by-pass ratio mixed flow turbofan engine model with mixer-ejector configuration (red box)

The design point calculations converge and the results show that the core flow in the mixer-ejector is supersonic (see table 2). Core flow Mach number is 1.12. Flow Mach number through the engaged ejector doors is 0.41. Static pressure ratio at the inflow trailing edge is 1. Exit flow Mach number of the mixer-ejector component is 0.72. Engine thrust is 58 kN and exit jet velocity is also 350 m/s for the engine with a much lower by-pass ratio than the conventional turbofan, which is advantageous at cruise condition. (2.15 for the mixer-ejector engine and 3.65 for the reference conventional turbofan). Note that in the core region upstream of the mixer-ejector a sonic venturi is present, which for the real engine is caused by the engaged or employed ejector doors, which reduce the core through flow area.

Table 2: GSP results supersonic mixer/ejector at design point TO (ISA + 15 K)

Core flow (gas station # 63)		Flow through ejector doors (# 20)		Combined exit flows (# 71)	
W_{core}	134.5	$W_{ejector}$	30.5 kg/s	$W_{exit\ mixer}$	165 kg/s
M_{core}	1.12	$M_{ejector}$	0.41	$M_{exit\ mixer}$	0.72
A_{core}	0.415 m^2	$A_{ejector}$	0.195 m^2	$A_{exit\ mixer}$	0.61 m^2

The preceding section shows that the gas turbine performance simulation program GSP successfully can incorporate a mixer-ejector exhaust system with a supersonic core flow at design condition. The following step is to prove this functionality for off-design calculations, where the non-linear thermodynamic equations of the gas turbine (all components) are solved iteratively.

3.2 Results off-design point calculations

The off-design calculation for design point conditions immediately returns the same results as those obtained from the calculations of the design point. This leads to the cautious conclusion that a supersonic mixer can be successfully implemented in GSP for off-design calculations.

The engine performance simulations for the MDO exercise at TO with open doors were specified for various engine settings (reduced or corrected engine fan speeds $N_{c\ fan}$) and environmental or aircraft operating conditions (altitude Z_p and flight Mach number M_a). A selection of GSP results of off-design calculations for the mixer-ejector component and engine is given in table 3. Number 0 represents the results of the off-design calculation at design conditions, which return the same results as the design exercise. The core flow Mach number varies between 1.113 and 1.242 and the flow through the ejector doors varies between 29.9 and 35 kg/s. Note that the varying core-flow Mach number in the simulations implies a (very) small adjustment of the sonic throat area.

Table 3: GSP off-design performance simulation results for the mixer-ejector turbofan

Number	Z_p	M_a	$N_{c\ fan}$	W_{ejctor}	W_{core}	$M_{ejector}$	M_{core}	$M_{exit\ mixer}$	V_{jet}	FN
	[m]	[-]	[%]	[kg/s]	[kg/s]	[-]	[-]	[-]	[m/s]	[kN]
Design point (DP)	0	0	100	30.5	134.5	0.430	1.113	0.723	350.3	57.8
0	0	0	100	30.5	134.4	0.430	1.113	0.723	350.3	57.8
1	0	0	105.2	34.3	139.5	0.503	1.228	0.748	384.1	66.8
2	0	0.2	100	32.6	137.4	0.454	1.126	0.735	361.3	49.6
3	0	0.2	105.2	36.2	142.4	0.525	1.242	0.755	395.2	58.2
4	305	0.2	100	31.5	133.0	0.454	1.126	0.734	359.7	47.8
5	305	0.2	105.2	35.0	137.9	0.524	1.241	0.755	393.6	56.0
6	762	0.2	100	29.9	126.6	0.453	1.125	0.734	357.5	45.2
7	762	0.2	105.2	33.3	131.2	0.525	1.242	0.755	391.1	53.0

The exhaust jet velocities vary between 350 and 395 m/s for the mixer-ejector turbofan with a fan by-pass ratio of 2.15. For the same turbofan without mixer-ejector at the same thrust the jet exhaust velocities will vary between 426 and 470 m/s (Table 4). The application of the mixer-ejector at equal thrust can possibly lead to a noise reduction estimation based on simple scaling laws (from the introduction) of 3.8 to 5.2 dB depending on the dominant noise source mechanism (see also table 4 for a comparison between the reductions in jet velocities and maximum radiated acoustic power between the mixer-ejector turbofan and a conventional with a by-pass ratio of 2.15 at equal thrust). This is at the expense of additional weight and drag at the business jet supersonic cruise condition. Note that the simulated mixer in GSP is ideal. In practice the mixing of the flow through the ejector doors and core will be not perfect depending on the details of the mixer-ejector geometry. Note furthermore that no assumptions have been made about the deceleration of the supersonic core flow (for instance by shocks, which might be present in the real mixer/ejector), since only the balance equations (mass, momentum and energy) are solved. Additional losses related to shocks can be accounted for in GSP by adding a duct component with (prescribed) pressure losses.

GSP functionality for the ideal supersonic mixer-ejector has been demonstrated. In combination with its open nature (availability to third partners), flexibility (any gas turbine configuration can be defined) and graphical user interface it can be an useful and powerful engine performance simulation tool for supersonic transport studies on various types of engines.

Table 4: Comparison of the reductions in jet velocities and radiated acoustic power (AP) between the mixer-ejector (ME) turbofan and a conventional (CT) mixed-flow turbofan with BPR of 2.15 at equal ambient and thrust conditions (see table 3)

Parameter \ Number	DP	0	1	2	3	4	5	6	7
FN [kN]	57.8	57.8	66.8	49.6	58.2	47.8	56	45.2	53
ME V_{jet} [m/s]	350.3	350.3	384.1	361.3	395.2	359.7	393.6	357.5	391.1
CT V_{jet} [m/s]	426.2	428.0	466.1	432.6	469.9	419.7	456.0	416.7	453.5
ΔVj_{et} [%]	21.7	22.2	21.4	19.7	18.9	16.7	15.8	16.6	16.0
ΔAP_{max} [dB]	5.1	5.2	5.0	4.7	4.5	4.0	3.8	4.0	3.9

4 Conclusions

In the European ITP HISAC the feasibility of an environmentally friendly and economically viable small size supersonic transport aircraft (S4TA) is investigated. Three design teams exercise a Multiple Disciplines Optimization resulting in three variants of a S4TA. This work includes engine performance simulations for various types of engines covering the whole business jet flight envelope. The NLR Gas Turbine Simulation Program GSP is used as engine performance modeling tool for the so-called mixer-ejector engine variant, which is applied to reduce noise at take-off. It appeared that the engine core flow mixing with the entrainment flow through the exhaust ejector doors is supersonic. The GSP ideal mixer component has been modified to allow supersonic core flow. These modifications were tailored to either the design-point calculation or the off-design point calculations. The findings are:

1. GSP design point calculations for the supersonic mixer lead to conversion by changing the state and error variables and the inclusion of an analytical estimator in the iteration process.
2. For GSP off-design calculations the ambiguity in the 1-D compressible flow equation (at fixed area larger than the critical area both a subsonic and supersonic solution exist) has been circumvented by checking whether the static pressure at the trailing edge of one branch (core or by-pass/ejector duct) is higher or lower than the critical static pressure. Depending on the outcome the appropriate subroutine is called to calculate the static gas path properties.
3. It is shown that both methods work well and allow supersonic core flow in the mixer-ejector engine.
4. The application of this mixer-ejector can lead to a reduction of about 20% of the exhaust jet velocity. The corresponding reduction in emitted noise based on elementary scaling laws may vary between 3.5 and 5.2 dB dependent on dominant jet noise source mechanism.
5. The NLR Gas Turbine Simulation Programme GSP can be customized to various types of engines relevant to supersonic transport.

These GSP results came to be too late to be included in the HISAC MDO-process for the supersonic business jet. The performance simulation results for a mixer-ejector engine were alternatively provided by CIAM using their engine performance program ECTASE.

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