CRUISE NOx EMISSION REDUCTION BY THE RATIONAL CHOICE OF SUPERSONIC BUSINESS JET ENGINE DESIGN VARIABLES

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Abstract

The reduction of cruise pollutant emission is a key environmental problem for the commercial supersonic aircraft development. The solution of the problem for supersonic business jet (SSBJ), taking into account the necessity of meeting requirements to range, field length, noise, sonic boom etc., may be facilitated by rational choice of SSBJ design variables (DV).

The reduction of cruise NOx emission and change in near surface temperature, characterizing impact of cruise pollutant emission on the ozone concentration and climate change, are considered in the study.

The main engine cycle parameters (such as bypass ratio, overall pressure ratio, takeoff turbine rotor temperature), takeoff thrust throttle ratio, cruise flight speed and takeoff wing loading were taken as DV to be rationally selected at the conceptual design.

The results indicated that rational selection of DV provides reduction of cruise NOx emission by 30-35%.

1 Introduction

The feasibility of commercial supersonic transport is defined by the possibility to meet requirements to basic mission, environmental and operational performances (such as these to range, noise, emission, sonic boom, life time etc.). Meeting the requirements may be facilitated by the rational selection of DV such as aircraft wing and engine thrust loading, bypass ratio, temperature throttle, overall pressure ratio, the engine size etc.

Recent SSBJ studies were focused on the problem of optimal selection of the main SSBJ DV at conceptual design [1-4].

The main objectives of the study are:

- addition of SSBJ emission parameters in the list of SSBJ efficiency criteria;
- selection and adjustment of mathematical models for emission assessment;
- analysis of influence of DV on the SSBJ performances, including emission;
- multiobjective optimization of SSBJ DV under the set of criteria, including emission criteria.

Cruise NOx emission is one of the most important emission parameters of SSBJ impact on ozone concentration. Hence it was included in the list of criteria. The criterion is defined by combustion efficiency, air parameters in the combustor inlet, and total cruise fuel consumption.

Change in near surface temperature induced by cruise emission of water vapor H_2O, carbon dioxide CO_2 and nitrogen oxides NOx is another important emission parameter characterizing the SSBJ impact on the climate change. The parameter was considered as the second emission criteria.

The emission parameters, which should be limited to provide considerable reduction of aircraft impact on the climate, have been widely discussed in ICAO for the last years. Restrictions on altitude emissions have not yet been established. In contrary, actual standards on emission in the vicinity of airport become constantly stronger.

2 Problem statement

SSBJ with passenger capacity of 10 and takeoff weight of 56t was considered in the study. SSBJ is equipped with propulsion system based in the two mixed turbofan, variable supersonic nozzle, and conventional combustor operated under diffusion mode. General view of SSBJ is illustrated in Fig.1.

Fig. 1. General view of SSBJ.

Engine size (and takeoff thrust loading correspondingly) at the given aircraft takeoff weight was defined by the given required balanced field length *BFL* of 1983m (6500ft).

Takeoff bypass ratio *BPR*, takeoff turbine rotor temperature *T41TO*, takeoff overall pressure ratio *OPR*, takeoff thrust throttle ratio TR_{TO}, cruise flight Mach number M_{cr} and takeoff wing loading *W/S* were included in the vector of DV optimized (1):

$$Vector\ of\ DV = \begin{bmatrix} BPR \\ T41TO \\ OPR \\ TR_{TO} \\ M_{cr} \\ W/S \end{bmatrix} \qquad (1)$$

TR_{TO} (characterises engine takeoff power and defines the engine takeoff oversizing at given *BFL*), M_{cr} and *W/S*, were included in the list of DV in order to study the additional possibilities of noise and emission reduction.

Since the level of the maximal turbine rotor temperature was fixed, change of *T41TO* corresponds to change of temperature throttle ratio (difference between the maximal and takeoff turbine rotor temperatures).

Relative flight range R_{rel}, change of jet noise level dE_{max} (in a lateral or flyover reference points depending on which of margins of noise relative to ICAO requirements is less), relative corrected cruise NOx emission $D_{pv\ rel}$ (absolute mass of NOx emission in cruise flight per unit of average flight speed V_f) and relative change in near surface temperature dt_{rel} were included in the vector of optimization criteria (2):

$$Vector\ of\ criteria = \begin{bmatrix} R_{rel} \\ dE_{max} \\ D_{pv\ rel} \\ dt_{rel} \end{bmatrix} \qquad (2)$$

Each criterion is used in a relative form: it is referred to the value of the criterion at the reference combination of DV which corresponds to the maximal range and satisfies minimal noise requirements.

The following main assumptions and restrictions were accepted for DV optimization:

- field length is calculated taking into account the balanced rejected and continued takeoff and landing field length;
- minimal takeoff noise requirements correspond to lateral and flyover jet noise levels not less than Chapter 3 ICAO requirements (that may provide meeting of Chapter 4 requirements [5]);
- flight level of acceleration through transonic speeds is 8-10 km;
- at engine cutback, flight level has to be maintained with one engine inoperative, or 4% climb gradient has to be maintained with all-engines-operating.

3 Emission modelling

Assessment of cruise NOx emission for SSBJ, which flies a long time in stratosphere at the supersonic speed, is very important for prediction of aircraft impact on ozone depletion and climate change. Nowadays international standards for restriction of cruise NOx emission have not yet been accepted.

At the conceptual design when detailed combustor geometry is not defined, the selection of emission models is an important problem since the simplified models-applicants must be validated. In the study the selection and validation of emission correlation models (CM) were based on the comparison of computational results for several existing subsonic engines received by various CM with certification ICAO data and results obtained by detailed emission models.

Some CM for NOx emission calculation using key air flow parameters in the combustor inlet and combustor volume were considered in the study [6, 7].

Five CM of NOx emission assessment for combustor operating in diffusion mode were compared (Table 1):

CM	*EINOx*
CM 1 (GE)	*f(p3, T3, HFL)*
CM 2,3 (MTU,RRD)	*f(p3, T3)*
CM 4 (SNECMA)	$f(t_{res}, p3, T3)$
CM 5 (RR)	$f(t_{res}, p3, T4)$

Table 1. Correlation models for NOx emission assessment.

In the Table 1 $t_{res} = f(V_{com}, p3, T3, W31)$ is combustor residence time; *p3* и *T3* are combustor inlet pressure and temperature correspondingly; *HFL* is atmospheric humidity; V_{com} is combustor volume; *W31* is combustor flow rate; *T4* is combustor exit temperature.

The assessments of *EINOx* at takeoff for several existing engines and at takeoff/cruise for reference engine were carried out to compare and select CM. *EINOx* values calculated for existing engines were compared with corresponding certification test data from ICAO database [8] and are presented in Table 2.

Engine	CM2		CM1		CM3		CM4		CM5	
	EINOx	%	EINOx	%	EINOx	%	EINOx	%	EINOx	%
JT9D-7	20.6	45.6	20.5	45.9	20.9	44.9	36.9	2.6	37.4	1.4
JT8D-17	15.3	25.7	14.6	29.1	15.3	25.7	21.5	-4.4	24.2	-17.5
Olym-pus	14.1	21.8	13.4	25.6	14.1	21.7	18.8	-4.7	23.1	-28.1
V2527-A5	26.4	0.4	26.4	0.4	26.9	-1.5	26.5	-0.1	26.1	1.5
GE90-85B	40.2	22.7	41.1	20.9	40.4	22.3	52.1	-0.1	41.8	19.6
PW 4164	30.1	21.8	30.4	21.2	30.8	20.2	38.6	-0.2	36.0	6.5
BR700-715C1	31.3	0.3	31.6	-0.7	31.9	-1.6	31.5	-0.3	29.6	5.8
AE3007 C1	13.7	32.2	12.9	36.3	14.0	30.7	20.2	-0.1	27.6	-36.5
Trent 556-61	38.3	13.1	39.1	11.3	38.6	12.4	44.1	-0.1	38.4	13.0

Table 2. Comparison of takeoff emission calculated by CM for existing engines.

Values of *EINOx* calculated for SSBJ reference engine were compared with data obtained by high-fidelity emission model (HF EM) [9] and are summarized in Table 3.

Flight condi-tions	HF EM	CM1		CM2		CM3		CM4		CM5	
		EINOx	%	EINOx	%	EINOx	%	EINOx	%	EINOx	%
Takeoff	36.4	19.0	47.8	19.5	46.5	19.9	45.4	37.7	-3.6	39.4	-8.4
Cruise	47	27.3	42.0	27.2	42.1	22.7	51.7	46.6	0.8	23.7	49.6

Table 3. Comparison of takeoff and cruise emission calculated by CM and HF EM for SSBJ reference engine.

As can be seen from the tables, the best results were obtained by CM 4. Error of its *EINOx* assessment is no more than 4-5%. This CM was further used to predict cruise *EINOx*.

Calculation of emission parameters is carried out using average cruise NOx emission index $EINOx_{cr}$ and average flight speed V_f:

$$D_{pv} = EINO_{x\,cr} \cdot \frac{W_{f\,cr}}{V_f},$$

where D_{pv} is corrected cruise NOx emission (absolute mass of cruise NOx emission per unit of average flight speed V_f); $EINOx_{cr}$ is average cruise NOx emission index; V_f is average flight speed; $W_{f\,cr}$ is total cruise fuel consumption.

Calculation of total change in near surface temperature dt is based on the simplified climate functions proposed by DLR taking into account impact of water vapor, CO_2, ozone and methane emission and depending on *EINOx*, $W_{f\,cr}$ and cruise flight altitude H_{cr}:

$$dt = f\,(EINO_{xcr}, W_{f\,cr}, H_{cr})$$

The influence of the *BPR*, *T41TO*, *OPR* and M_{cr} on emission performance is defined by combination of changes of $W_{f\,cr}$, $EINOx_{cr}$, V_f (due to change of range and flight time) and H_{cr}.

The influence of *OPR* and *BPR*, relative takeoff turbine temperature $T41TO_{rel}$ and M_{cr} on $D_{pv\,rel}$ and dt_{rel} are shown in Fig. 2 and Fig. 3.

It should be noted, that there are strong influence of *OPR* on $D_{pv\,rel}$ (change of *OPR* from 23 to 28 results in change of $D_{pv\,rel}$ by 15 - 16 %), strong influence of *BPR* and *OPR* on dt_{rel} (change of *BPR* from 2.2 to 2.7 or *OPR* from 23 to 28 results in change of dt_{rel} by 25-35%), and weak influence of *BPR* on $D_{pv\,rel}$.

These influences should be taken into account at analysis and selection of optimal SSBJ DV.

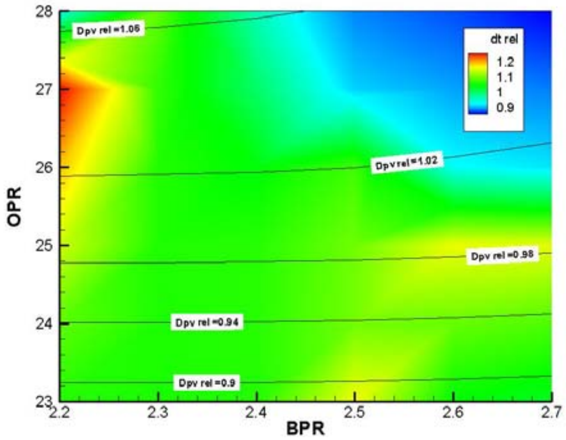

Fig. 2. Influence of *OPR* and *BPR* on emission parameters $D_{pv\ rel}$ and dt_{rel}.

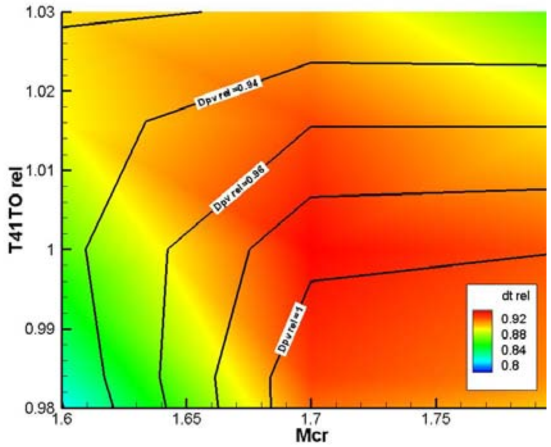

Fig. 3. Influence of *T41TO* and M_{cr} on 'emission parameters $D_{pv\ rel}$ and dt_{rel}.

4 Results of SSBJ DV optimization

The main results of SSBJ DV optimisation under three criteria (range, noise and emission) are presented in Fig. 4, Fig. 5 and Table 4.

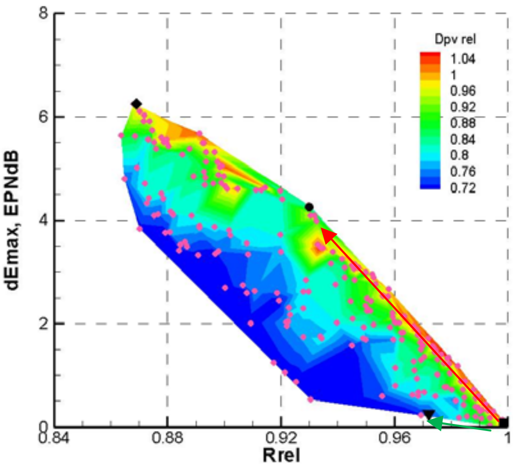

Fig. 4. Optimal relations between R_{rel}, dE_{max} and $D_{pv\ rel}$.

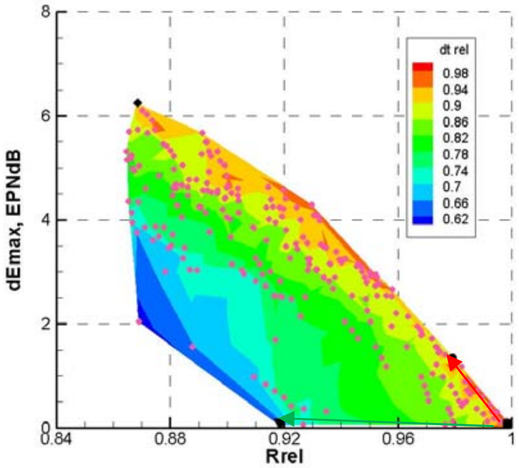

Fig. 5. Optimal relations between R_{rel}, dE_{max} and dt_{rel}.

Criteria	BPR	$T41TO_{rel}$	OPR	$TR_{TO\ rel}$	M_{cr}	W/S, kg/m^2	Change of R, %	Change of dE_{max}, EPNdB	Change of D_{pv}, %	Change of dt, %
R=max (reference)	2.2	1.00	26	1.00	1.8	390	0	0	0	0
D_{pv}=min (2 criteria)	2.5	1	23	0.85	1.8	370	-8	-4.3	-18	-4
D_{pv}=min (3 criteria)	2.2	1.05	23	0.85	1.8	370	-0.2	-0.2	-29	-8
dt=min (2 criteria)	2.6	1	28	1.00	1.7	370	-2	-1.3	5	-11
dt=min (3 criteria)	2.7	1.05	29	1.00	1,8	380	-8	0	-17	-35
dE_{max}=max	2.7	0.95	24	0.95	1.8	390	-14	-6.2	-4	-9

Table 4. Main reference DV and DV optimized under emission and noise criteria.

The optimal interrelations between relative flight range R_{rel}, change of jet noise level dE_{max}, $D_{pv\ rel}$ and dt_{rel} are illustrated in Fig. 4 and Fig. 5 in the form of Pareto optimal set (pink points). Right top points of the set (i.e. extreme right points for each considered noise level) are Pareto optimal set under two criteria - range and noise. Black squares correspond to the reference case, black rhombuses - optimal decisions with minimal noise, black mugs - minimal values of D_{pv} or dt with R_{rel} and dE_{max} criteria, and black triangles – minimal values of D_{pv} or dt with R_{rel}, dE_{max} and D_{pv} or dt criteria.

It is seen, that maximal reduction of D_{pv} with R_{rel} and dE_{max} criteria may reach only 15-18% (in comparison with reference case) and it results in range losses by 8-10% (red arrow in Fig. 4). Optimization of DV under 3 criteria allows reducing D_{pv} by 25-30% with range losses only by 2-3% (green arrow in Fig. 4).

The maximal possible reduction of dt at optimisation under criteria of R_{rel} and dE_{max} may be 10-11% with small range losses (red arrow in Fig. 5) whereas at optimisation under three criteria it may reach 35-40 % with range losses by 6-8 % (green arrow in Fig. 5).

Thus it is possible to draw a conclusion that in case of consideration of only two criteria (range and jet noise), there is no possibility of considerable reduction of emission by DV optimization. Addition of the third criterion (D_{pv} or *dt*) in DV optimization may significantly reduce emission.

Optimal values of SSBJ DV for different Pareto optimal decisions are summurised in Table 4.

The following optimal DV were obtained under range, emission and noise criteria: OPR_{opt} = 23-29, $T41TO_{rel\ opt}$ = 0.95-1.05, BPR_{opt} = 2.2-2.7, TR_{TOopt} = 0.85-1.0, $M_{cr\ opt}$ = 1.7-1.8, W/S_{opt} = 370-390 kg/m^2.

5 Conclusion

Multiobjective optimization of DV including bypass ratio, overall pressure ratio, takeoff turbine rotor temperature, takeoff thrust throttle ratio, takeoff wing loading, cruise Mach number, under three criteria (range, takeoff jet noise and cruise NOx emission) carried out for SSBJ with takeoff weight of 56t and the requirements to field length and minimal noise showed the following:

- developed and validated emission models may be effectively used at conceptual design for calculation of average cruise NOx emission and change in near surface temperature in case of using combustor operating in diffusion mode;
- rational choice of SSBJ DV allows meeting the minimal noise requirements with reduction of the corrected cruise NOx emission by 25-30 % (in comparison with the reference case providing maximal range at meeting minimal noise requirements) without essential flight range losses.

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