STUDIES ON MDO OF ENGINE DESIGN PARAMETERS WITH MISSION, NOISE AND EMISSION CRITERIA AT SSBJ ENGINE CONCEPTUAL DESIGN

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Abstract

The feasibility of a supersonic business jet (SSBJ) at the engine conceptual design level is mainly defined by the optimal matching of engine design variables with mission and environmental requirements to SSBJ.

It is well known that the impact of engine thrust schedule control (thrust management) at takeoff and initial climb on community noise is significant for SSBJ. Cruise emission is also one of the most important environmental performance of SSBJ.

The studies performed in the scope of the Integrated Project HISAC of 6th European Framework Programme are dedicated to the joint Multidisciplinary Optimization (MDO) of engine design variables(EDV) and thrust management (TM) parameters under range, noise and emission criteria at the conceptual design of SSBJ propulsion system. It was shown that the joint MDO may significantly increase the feasibility of SSBJ project and reveal the effective ways to meet stringent market requirements to SSBJ. The EDV and TM parameters such as bypass ratio, overall pressure ratio, temperature throttle ratio, takeoff thrust throttle ratio, wing loading, cruise speed, flight altitude of start of TM, rate of thrust throttling, variation of engine nozzle throat area have been optimized.

1 Introduction

The environmental requirements that directly depend on the propulsion system (the community noise and emission level) hold the important place in the set of contradictory requirements to SSBJ. Optimal matching of SSBJ design variables with environmental requirements mostly defines the feasibility of SSBJ project. Engine cycle parameters (bypass ratio, overall pressure ratio, temperature throttle ratio), wing and thrust loading, cruise speed are related to main engine design variables influencing on mission and environmental performance of SSBJ at conceptual design of propulsion system (PS). Under given requirements to takeoff performance (i.e. takeoff field length), thrust takeoff throttle ratio (TR) can be also taken as the EDV.

Optimization of TM at initial climb may give an important reserve to improve noise performance of SSBJ. A variable engine nozzle with a variable throat and exhaust area is often used as a component of supersonic PS. Optimization of nozzle throat variation for jet noise reduction may significantly increase the environmental friendliness of SSBJ.

According to the noise certification procedure for subsonic aircraft, lateral noise level must be estimated at the full engine power, and flyover noise level must be defined taking into account the impact of the engine throttling after reaching minimal acceptable flight altitude of engine cutback (300m for twin airplane)[1].

Altitudes of start of TM both higher and less than minimal altitude are considered in the studies. The lateral noise is predicted taking into account the impact of TM at initial climb. Such approach to the certification noise prediction extends the understanding of the efficiency of earlier engine TM for supersonic civil transport. It may result in necessity of making changes in the current noise certification procedure for SSBJ taking into account flight safety.

Moreover, low noise TM may be realized as one of the embedding engine schedule controls automatically providing required control of engine fuel flow and nozzle throat area.

Use of smoother thrust throttling, that allows reaching of minimal engine power at the altitudes close to 300m, may keep the flight safety level at the low flight altitudes. For this reason, the optimization of rate of TM at initial climb has been conducted in the studies.

Therefore, the joint optimization of SSBJ EDV and TM at initial climb may significantly facilitate the problem of meeting the contradictory market requirements to SSBJ.

2 Problem statement

These studies have been carried out since 2005 in the scope of Integrated Project HISAC of 6th European Framework 9n collaboration with Russian and European partners, including SCA, TsAGI, Dasssault Aviation and other [2,3,4].

MDO of SSBJ EDV under two main criteria (maximum range and minimum cumulative lateral and flyover noise) with additional estimation of third criteria (cruise nitrous oxides NOx) is considered in these studies.

Calculation of mission performance is performed for the supersonic business jet with fixed takeoff weight taking into account the flight segments, such as takeoff, initial climb, climb, supersonic cruise, descent, approach, landing, and NBAA alternate. Flight profiles for climb and descent were given by TsAGI.

The noise is estimated by the cumulative, lateral and flyover jet noise levels. It is well known, that jet noise is dominant source for SSBJ, because of low BPR and high efficiency of used acoustic liners.

Cruise NOx emission per km of range D_{NOx}/R is considered as a parameter of SSBJ cruise emission performance.

The MDO is carried out with a set of the given restrictions, such as maximal takeoff and landing weight, maximal field length, minimal noise level (the flyover and lateral noise levels have to meet the ICAO Stage 3 requirements [1]).

Considered SSBJ engines are mixed turbofan of conventional architecture with variable supersonic nozzle (without using any acoustic nozzle). The novel LPP (lean-premixed-prevaporised) combustor with super low NOx emission level is considered in the studies.

The following SSBJ parameters were taken as design variables to be optimized: main engine cycle parameters (ECP) – bypass ratio BPR, overall pressure ratio OPR, takeoff turbine rotor temperature T41TO, other EDV - takeoff thrust throttle ratio (ratio of engine takeoff thrust to full power thrust $TR_{TO}=FN/FN_{max}$), takeoff wing loading W/S and cruise flight speed (cruise flight Mach number M_{cr}).

Engine size (and the corresponding SLS thrust and thrust loading) is iteratively defined for each value of W/S from the balanced takeoff condition and given balanced field length BFL_{ref}= 1983m. The minimal one engine inoperative (OEI) climb gradient at the altitude of 10.7m and landing field length were taken as the constraints.

It should be noted, that in the considered case and problem statement (at given BFL) engine thrust throttle ratio TR was considered as engine design variable because of its impact on the engine size.

Variation ranges of the optimized EDV are presented in Table 1.

Variables	Units	Minimum	Maximum
BPR	-	1.5	3.5
OPR	-	20	35
T41TO	K	1450	1700
TR_{TO}	-	0.85	1.0
W/S	kg/m^2	350	450
M_{cr}	-	1.5	2.0

Table 1. The variation ranges of engine design variables.

The main considered parameters of thrust management influenced on the noise has been revealed in the previous study [2]. Therefore, the efficiency of variation of different TM parameters is evaluated in the studies during MDO. The considered TM parameters include nozzle throat area, the altitude of TM start and rate of TM at initial climb.

3 Main input data

The used main aerodynamic and weight performance of aircraft, designed by SCA jointly with TsAGI, are presented in [3, 4].

The aircraft with the takeoff weight TOGW=56t, with wing area $S=150m^2$, engine SLS thrust FN_{TO}=16.5t, and M_{cr} = 1.8 is considered as reference. The main SLS engine parameters of reference aircraft are: BPR = 2.4, OPR = 27, T41TO = 1550K.

The lateral (3rd certification measurement point), flyover (2nd certification measurement point) and cumulative lateral and flyover noise levels are estimated by the corresponding margins of jet noise levels relative to the Stage 3 requirements $\Delta EPNL_3$, $\Delta EPNL_2$ and $\Delta EPNL_{32}$ (the negative values correspond to the exceeds, the positive values correspond to the deficits).

The flight range is characterized by the relative range $R_{rel} = R/R_{ref}$.

As mentioned above, main constraints in the optimization problem were concerned to the meeting of Stage 3 requirements in both certification measurement points, minimal OEI climb gradient at the flight altitude of 10.7m and at TM during initial climb.

Flight range of reference aircraft was taken as reference range R_{ref} ($R_{rel} = 1.0$).

The cruise NOx emission was estimated by the relative NOx emission per a 1 km of range $(D_{NOx}/R)_{rel} = (D_{NOx}/R) / (D_{NOx}/R)_{ref}$. Value of D_{NOx} is calculated by the cruise NOx emission indices $EINOx_{cr}$ and cruise fuel consumption WF_{cr} :

$$D_{NOx}=EINOx_{cr} * WF_{cr}$$

EINOx was calculated by the NOx emission correlation model of LPP combustor. The NOx emission correlation model is currently being validated.

The rate of TM is presented by the relative thrust changing (throttling) per second in percents dFN/dt.

The used engine performance model allows calculating all engine performance at different engine schedule control, including the case of using optimal variation of engine nozzle throat area A8.

The TM with constant A8 (A8 = const), TR_{TOref} = 0.9, start of TM after reaching of the distance of $L_{stm\ ref}$ = 5200m, the rate of TM dFN/dt_{ref}=1.25%ps is considered as reference TM (ref TM).

The following ways of optimal (low noise) TM are also considered in the studies:

- A8=opt - use of the optimal variation A8 that keeps air flow constant and gives additional reduction of exhaust jet velocity and jet noise;
- $H_{stm} = H_{stm\_opt}$- start of TM after reaching of optimal altitude H_{stm_opt}.

The engine rating with extended (up to 10%) engine maximal thrust in case of OEI was used for the computation of continued takeoff performance.

4 Optimization of engine design variables with mission and noise criteria using reference TM at initial climb

The influence of throttle ratio TR on cumulative, flyover and lateral noise (Fig.1) and range (Fig. 2) for reference aircraft using reference TM are shown in Fig.1 and Fig.2.

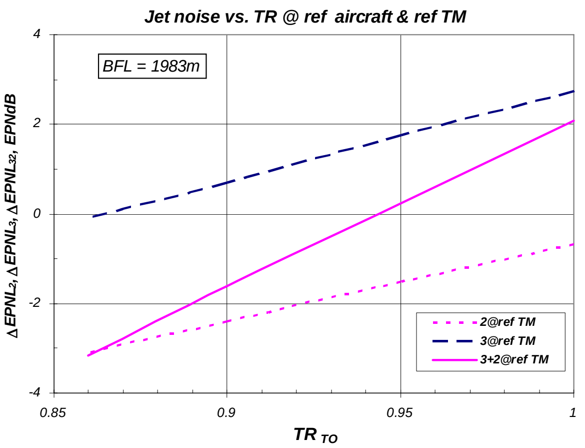

Fig. 1. The influence of TR on $\Delta EPNL_3$, $\Delta EPNL_2$ and $\Delta EPNL_{32}$ at A8=const.

The flyover and lateral jet noise levels are reduced with decreasing of TR due to the significant decreasing of the exhaust jet velocity (the lateral and flyover jet noise each is reduced by 1.7-2 EPNdB at the decreasing of TR by 10%).

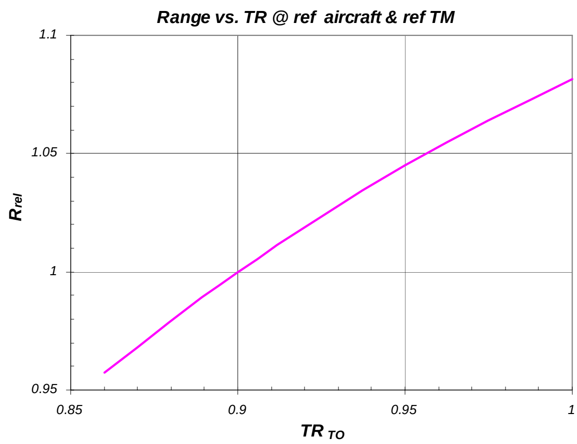

Fig. 2. The influence of TR on R_{rel} at A8=const.

The change of range at change of TR is connected with the change of engine size (and accordingly engine weight and nacelle drag), required to provide given BFL (decrease of TR by 13-14% causes decrease of range by 12-12.5%).

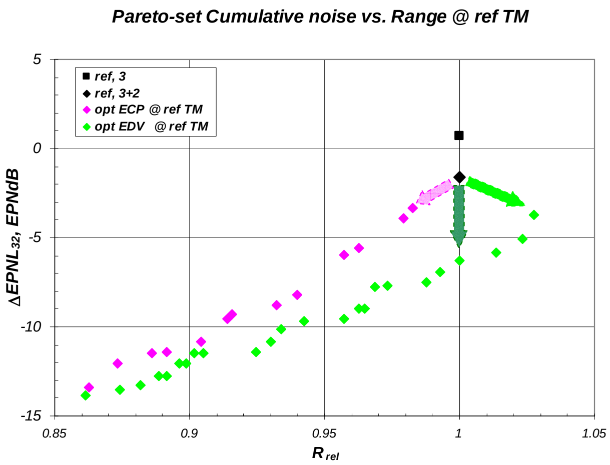

Fig.3. Pareto fronts of MDO of design variables at the reference TM.

Main MDO results in case of usung reference TM are presented in Fig. 3 as the different Pareto fronts of cumulative noise $\Delta EPNL_{32}$ vs. range R_{rel}, which were obtained by the optimization of EDV, such as the engine cycle parameters ECP (BPR, OPR, T41TO) and the values of TR, W/S and M_{cr}.

The points related to the reference aircraft are also shown in Fig. 3 (the reference cumulative noise is marked by a black rhomb, the reference lateral noise is marked by a black square). In spite of the margin of the cumulative noise, the reference aircraft does not meet Stage 3 requirements of lateral noise.

Optimization of engine cycle parameters ECP (the pink points of Pareto fronts in Fig. 3) does not allow preserving the reference range with simultaneous satisfaction of the minimal noise requirements: the minimal range loss may be up to 1.7% (shift by pink arrow in the Fig. 3).

In the case of joint optimization of engine cycle parameters and the other design variables (TR, W/S, M_{cr}) (see the green points of Pareto fronts) the range may be increased by 2.8-3.0%, and the margin on the cumulative noise level may be increased up to 1.5-2 dB (shift on light green arrow).

It must be noted that the maximal reduction of the cumulative noise by MDO of all design variables with the preserving of reference range may be up to 5 dB (shift by deep green arrow).

5 Joint optimization of design variables and TM parameters

5.1 Optimization of the altitude of start of TM and the rate of TM at initial climb

Fig. 4 and Fig. 5 show the influence of altitude of start of TM H_{stm} and the rate of TM dFN/dt on the cumulative, flyover and lateral noise (Fig. 4) and on the altitude of reaching of minimal engine power at initial climb H_{mt} (Fig. 5) for reference aircraft in case of reference A8=const.

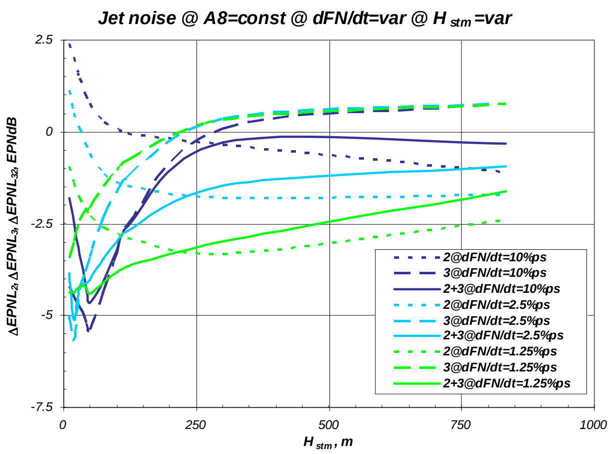

Fig. 4. The influence of H_{stm} and dFN/dt on $\Delta EPNL_3$, $\Delta EPNL_2$ and $\Delta EPNL_{32}$ at A8=const.

It is seen from Fig. 4 that the lateral noise is approximately constant during decreasing of

H_{stm} up to the altitudes of 250-300m, and it is reduced by 4.5-6.0 dB at decreasing of H_{stm} lower than 300m. The flyover noise is increased by 3 dB with the increasing of H_{stm} lower than 200-250m. The change of flyover noise when H_{stm} is higher than 250m depends on dFN/dt (at the increased values of dFN/dt the flyover noise is reduced by 2 dB, at the decreased values of dFN/dt it is increased by 2 dB). Due to contradictory change of lateral and flyover noise with H_{stm} variation the cumulative noise has minimum at H_{stm}=25-50m.

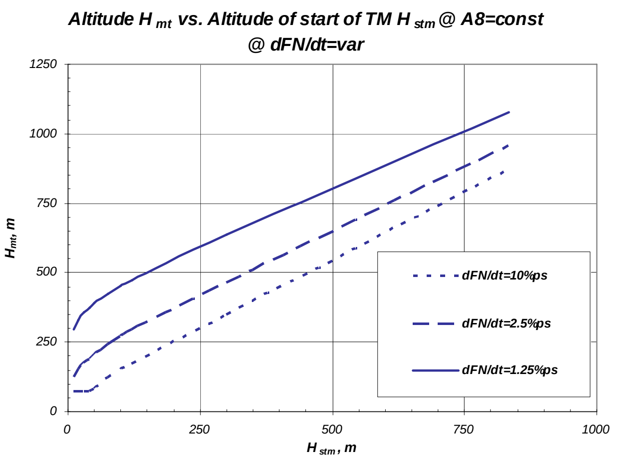

Fig. 5. The influence of H_{stm} and dFN/dt on H_{mt} at A8=const.

It is seen that decrease of dFN/dt from 10 to 1.25%ps (i.e. in 8 times) may significantly increase the altitude H_{mt} (up to 300m and even higher) (Fig.5), that could in its turn increase flight safety at the lower flight altitudes.

The results of joint MDO of design variables and the TM parameters in case of reference control of A8 (A8=const) are presented in Fig. 6 as the Pareto fronts of cumulative noise $\Delta EPNL_{32}$ vs. range R_{rel}, which were obtained by optimization of the design variables (see green points of the Pareto fronts) and by joint optimization of design variables H_{stm} and dFN/dt (see red points of Pareto fronts).

The joint optimization of design variables and TM parameters such as H_{stm} and dFN/dt may increase range by 8.5-9% at the simultaneous satisfaction of the minimal noise requirements (shift by red arrow).

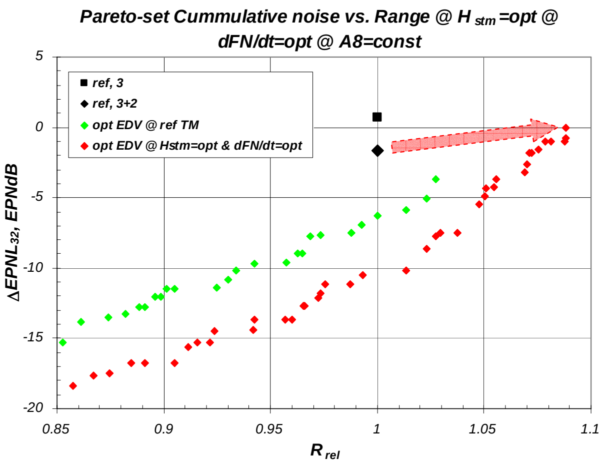

Fig.6. Pareto fronts, obtained by joint optimization of design variables with TM parameters at A8=const.

5.2 Using special (low noise) nozzle variation at the initial climb

Thrust management with variation of the nozzle throat area A8 which provides constant air flow (and additional decrease of exhaust jet velocity), is the optimal (low noise) way to throttle the thrust of engine with variable throat area A8 [2].

Main obtained MDO results in the case of optimal variation A8 (A8=opt) are shown in Fig. 7 as the Pareto fronts of cumulative noise $\Delta EPNL_{32}$ vs. range R_{rel}.

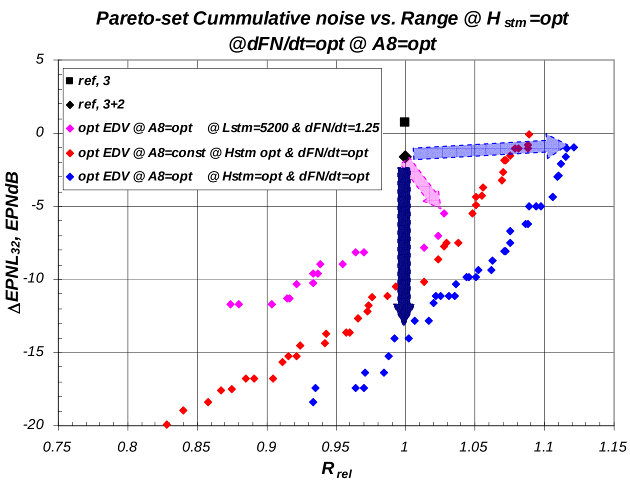

Fig.7. Pareto fronts, obtained by MDO at A8=opt.

Pink points of Pareto fronts are related to the case of using reference start of TM ($L_{stm\ ref}$ =5200m) and rate of the TM dFN/dt=1.25%, blue points are related to the case of using optimal H_{stm} and dFN/dt (H_{stm}=opt, dFN/dt=opt). The best Pareto front in case of reference A8 control (A8=const) is also presented in Fig. 7 (orange points) for comparison. It is seen that maximal benefit of range on condition of meeting Stage 3 noise requirements may be only 3% in first case (shift by the pink arrow), and 11.5-12% in second case (shift by the blue arrow). It should be noted that maximal reduction of cumulative noise by the joint optimization of design variables and all TM parameters (A8, H_{stm} и dFN/dt) keeping the same reference range may achieve 12-12.5 dB (shift by dark blue arrow).

5.3 Comparative estimation of efficiency of the joint optimization

The results of optimization of design variables and the TM parameters are shown in Fig. 8 as the Pareto fronts of range R_{rel} vs. noise $\Delta EPNL_{32}$ for four cases. The description of the cases is presented in Table 2.

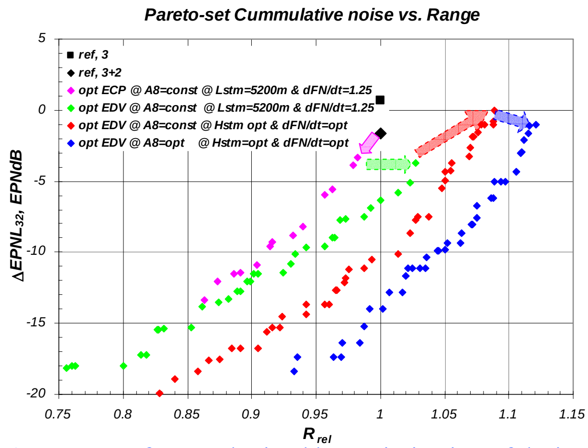

Fig.8. Pareto fronts, obtained by optimization of design variables at different TM.

N	ECP	Other EDV	A8	H_{stm}, dFN/dt
0	ref	ref	ref	ref
1	opt	ref	ref	ref
2	opt	opt	ref	ref
3	opt	opt	opt	ref
4	opt	opt	opt	opt

Table 2. Main cases of optimization of design variables and TM.

It is seen, optimization of only ECP in case of reference TM may allow meeting of noise requirements with a little losses of range (shift by the pink arrow). Additional optimization of other design variables may result in insignificant increasing in range. The joint optimization of design variables and TM parameters (H_{stm} и dFN/dt) may additionally increase range by 5-6% in the case of A8=const (shift by the red arrow), and by 3-4% in the case of A8=opt (shift by the blue arrow).

Table 3 presents the reference and optimal values of design variables and TM parameters for five cases described above.

N	BPR	OPR	T41, K	TR	W/S, kg/m^2	M_{cr}	H_{stm}, m	dFN/dt, %ps
0	2.4	27	1550	0.9	380	1.8	838	1.25
1	2.6	25	1550	0.9	380	1.8	838	1.25
2	3.0	25	1550	1.0	380	1.7	838	1.25
3	2.6	27	1600	1.0	380	1.7	20	1.25
4	2.2	29	1600	1.0	390	1.7	30	2.5

Table 3. Reference and optimal design variables and TM parameters.

It is seen, the optimal values of engine cycle parameters T41TO and OPR are in following ranges: T41TO = 1550-1600K, OPR=25-29.

Pareto-optimal values of takeoff TR fit to the engine full power rating (TR_{TO}=1.0) in all cases. This demonstrates the dominant influence of the range increasing over the noise increasing during increasing of the TR_{TO}.

Optimal values of BPR are higher than reference BPR and fall in range of 2.6-3.0 in case of reference TM. Higher BPR may be explained by the need of significant noise reduction (to meet Stage 3 requirements) after optimal increasing of takeoff rating. Optimal values of BPR are lower than reference BPR and fall in narrow range of 2.1-2.2 in the case of optimal TM.

Lower BPR may be explained by need of increasing range by the decreasing of BPR (and accordingly specific fuel consumption) compensating associated noise losses by the use of optimal TM.

The optimal TM corresponds to lower values of H_{stm} and dFN/dt ($H_{stm\ opt}$ = 20 - 30m,

dFN/dt_{opt}=1.25-2.5%ps), which is conducted with the optimal redistribution of noise levels between lateral and flyover certification points.

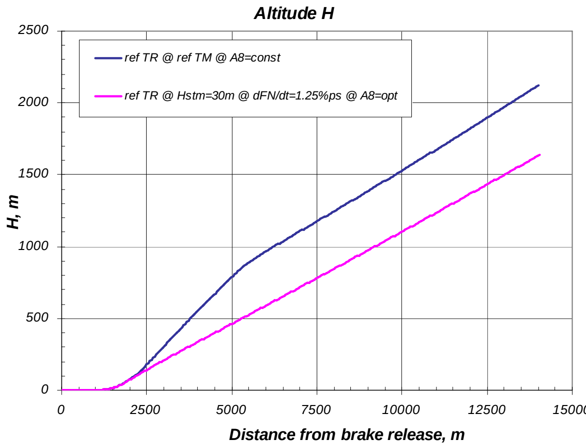

Fig. 9. The trajectories of initial climb at reference and optimal TM.

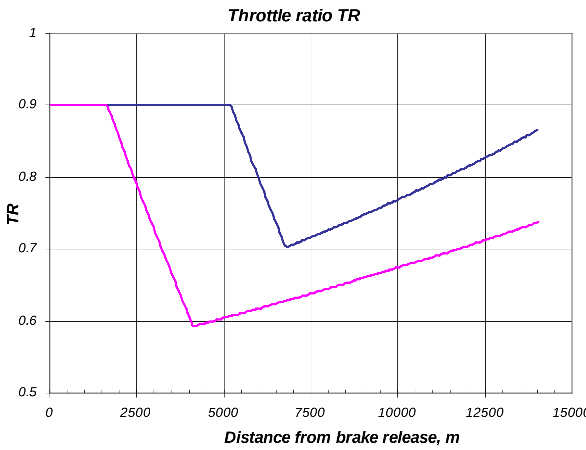

Fig. 10. Change of thrust throttle ratio TR along the trajectory of initial climb at reference and optimal TM.

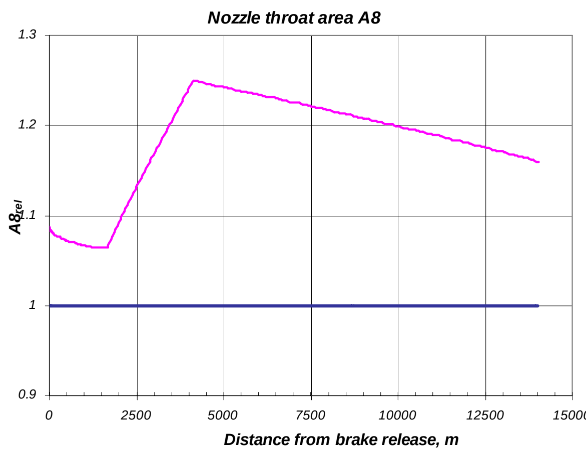

Fig. 11. Change of relative A8 along the trajectory of initial climb at reference and optimal TM.

Changes of main parameters along the trajectories of initial climb are shown in Fig. 9-12. The trajectories of initial climb (Fig.9), change of engine throttle ratio TR (Fig.10), relative nozzle throat area $A8_{rel}=A8/A8_{min}$ (Fig. 11), jet velocity V9A (Fig. 12) are presented for reference and optimal (low noise) TM.

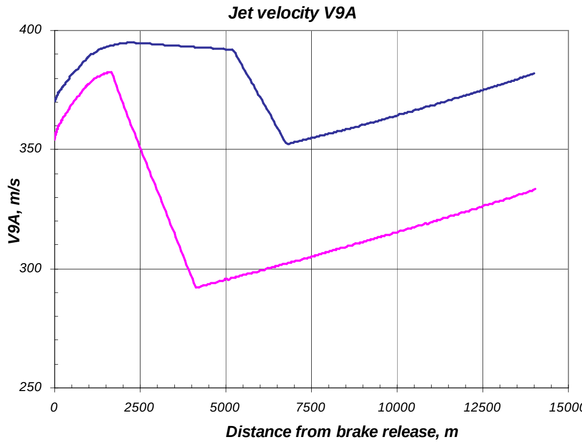

Fig. 12. Change of jet velocity V9A along the trajectory of initial climb at reference and optimal TM.

Start of TM at lower altitude leads to significant lowering of flight altitudes above flyover point, nevertheless it brings reduction of cumulative noise due to significant decrease of jet velocity (Fig. 12). Using smooth thrust reduction at TM from lower altitudes may allow reaching the minimal engine thrust after the flight altitudes of 300m (Fig. 10). Maximum of thrust reduction at the optimal TM may be achieved by 40-45%. The increase of thrust after reaching of the minimal engine power at initial climb is connected with increasing of the thrust required to provide the minimal OEI climb gradient.

Maximum of increasing of nozzle throat area A8 may achieve 25-30% (Fig. 11). Such range of increasing of A8 usually used in supersonic PS to prevent suger of fan at idle, therefore, use of the range of A8 variation does not require significant losses of nozzle weight.

Amounts of additional reduction of jet velocity due to using low noise TM depends on engine thrust throttling (Fig. 12). For example, reduction of takeoff TR by 10% results in decrease of jet velocity by 10-15m/s, reduction of TR at initial climb by 40% leads to decrease of jet velocity by 40-50m/s (Fig.12).

6 Selection of optimal engine design variables of SSBJ taking into account NOx emission

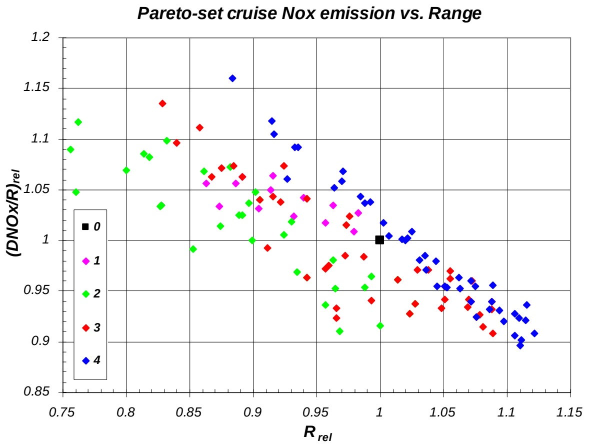

Fig.13. Cruise NOx emission vs. range for points of Pareto fronts of $\Delta EPNL_{32}$ vs. R_{rel} at different TM.

The level of DNOx/R is defined by the values of three main parameters – cruise NOx emission indices, cruise fuel consumption and range. The computation shows that flight range has dominant influence on DNOx/R, and minimum of DNOx/R corresponds to the range maximum in the most cases.

The relative values of $(D_{NOx}/R)_{rel}$ vs. relative values of optimal range $R_{rel\ opt}$ are presented in Fig. 9 for the points of Pareto front of noise $\Delta EPNL_{32}$ vs. range R_{rel}. It is seen that minimum of $(D_{NOx}/R)_{rel}$ is reached in area with R_{rel}=max.

It can be noted that minimal values of (D_{NOx}/R) (by 9-10% lower than reference values) is reached by optimization only ECP.

7 Conclusion

The joint MDO of engine design variables (BPR, OPR, turbine rotor temperature at takeoff T41TO and throttle ratio TR_{TO}, wing loading W/S, cruise Mach number M_{cr}) and TM parameters at initial climb (including altitude since start of TM H_{stm}, rate of TM dFN/dt and nozzle throat area A8 variation) is performed under two main criteria (flight range and cumulative flyover and lateral jet noise) for the SSBJ with given takeoff weight 56t and given restriction on field length and noise (BFL=1983m, jet noise is less than Stage 3 requirements).

The optimization is shown:

- Only joint optimization design variables and TM may give maximum benefit on range with noise requirements satisfaction. Such optimization may significantly reduce cumulative jet noise if there are no strong requirements to range increasing
- Optimal values of design variables and TM parameters obtained by the optimization are as follows: BPR=2.2, OPR=29, T41TO=1600K, TR_{TO}=1.0, W/S=380кг/м^2, M_{cr}=1.7, H_{stm} =20-30м, dFN/dt=2.5%ps
- Minimal values of additional criteria i.e. cruise NOx emission per 1 km of flight range are good agreed with maximal values of range
- The optimal TM using altitudes lower than 300m (minimal altitude of cutback according current noise certification rules for subsonic airplanes) may be realized as one of the embedding engine schedule controls automatically providing required control of engine fuel flow and nozzle throat area variation. Reaching of the minimal engine power at the altitudes close to 300m may be provided by choice of optimal rate of thrust throttling.

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