29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

STUDIES ON POSSIBLE UNIFICATION OF ENGINES FOR ADVANCED SMALL AND MEDIUM SUPERSONIC CIVIL AEROPLANES

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Keywords: *advanced supersonic civil transport, propulsion system*

Abstract

Analysis of required thrust and fuel efficiency of turbofan of supersonic small jet (supersonic business jet) (SSBJ2030) and supersonic medium jet (SSMJ2030) with EIS by 2030 is performed accounting provision of given requirements to noise and cruise NOx emission.

General technical design of unified turbofan for the aeroplanes are elaborated, studies on estimation of mission and environmental performances are carried out.

1 Introduction

By hypothesis of advanced supersonic civil transport (SCT) development concept, supersonic civil aeroplane (SCA2030) will come into service by 2030 and be based on 4-engined supersonic medium jet (SSMJ2030) with 100-120 pax and twin engine SSBJ (SSBJ2030) with 8 pax. (Fig. 1) [1].

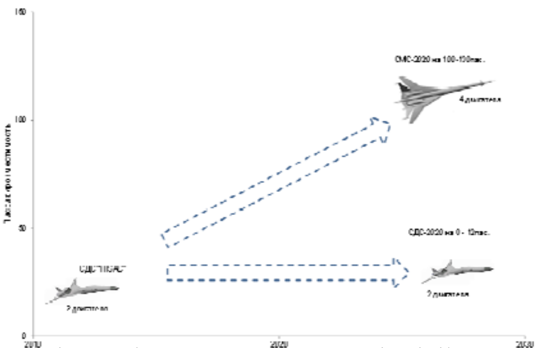

Fig. 1. The concept of supersonic civil transport development of supersonic civil aeroplane (SCA2030).

The concept of SCA2030 development accounts following base trends [1]:

- the SCT fleet segmentation on passenger and business aviation sectors;
- maximizing engine unification;
- pragmatic prediction of levels of airframe aerodynamic and weight improvements and decreasing of engine specific fuel consumption (SFC);
- demand for SCT operations in main and business aviation airports, and flights on transcontinental routes.

2 Requirements to general technical design and required thrusts for SSBJ2030

Generated requirements to SSBJ2030 and its Propulsion System (PS) corresponding to the SCA2030 concept are presented in Table 1.

The required thrusts of SSBJ2030 PS were generated at following design conditions:

- Minimal required takeoff installed engine thrust providing field length less than 2000m at Design Atmospheric Conditions;
- Minimal required installed engine thrust in supersonic cruise (SSC) conditions at Mach number M = 1.8 and maximal supersonic cruise altitude H_{SSC} = 17 km taking into account given maximal acceptable level of installed SFC SFC_{SSC};
- Minimal required installed engine thrust in subsonic cruise (SBC) conditions at flight Mach number M = 0.95 and subsonic cruise altitude H_{SBC} = 12 km taking into account given maximal acceptable level of installed SFC SFC_{SBC}
- Minimal required installed engine thrust at transonic acceleration (M = 1.1 and H_{TR} = 8 -14 km;

Table 1. Generated requirements to SSSBJ-2030 and its PS

Requirement	Value
Range by supersonic flight profile, km	> 7400
Range by subsonic flight profile, km	> 7400
Aircraft takeoff mass, t	< 55
Field length, m	< 2000
Noise (margin relative to Chapter 4), EPNdB	> 10
Cruise NO_X emission, g/kg fuel	< 10
Subsonic cruise conditions	M = 0.95; H =12km
Altitude of transonic acceleration, km	> 8
Supersonic cruise conditions	M = 1.8; H ≤17km
Number of engine	2
Passenger capacity, pax	≥ 8
Fuel efficiency, g/pax-km	< 380

- Minimal low noise thrust at M = 0.25, H=100 m taking into account maximal jet velocity of 340-360 m/s (in Lateral Reference Point - LRP)
- Minimal low noise thrust at M = 0.3, H=1000 m taking into account maximal jet velocity of 250-275 m/s (in Flyover Reference Point - FRP).

Required level of thrusts and installed SFC for design conditions are given in table 2.

Besides of flight altitudes H and flight Mach number M, intake pressure recovery values σ_{intake} are indicated in the table. The values correspond to use of advanced 3D intake [1].

The values of minimal required installed takeoff thrust at start point as well as lift-off conditions (H=0, M=0.25) are submitted in the table. The submitted values define in fact requirements to decline rate of thrust at lift-off conditions, i.e. takeoff thrust speed T = f (M) at H = 0.

The values of minimal installed thrust required at transonic acceleration on flight altitude of 8 - 14 km are given in the table for transonic flight conditions, $T_{ins\ TR\ H=11km}$ is required installed thrust corrected (recalculated) for altitude of 11 km, $T_{ins\ TR}$ is required installed thrust at altitude of transonic acceleration. All transonic data are given for flight Mach number 1.1, which as a rule correspond to minimal thrust excess.

The values of minimal required low noise engine thrust at LNCP and FNCP are defined under condition of providing maximal acceptable exhaust jet velocities V_{jet} = 340 – 360 m/s (for LNCP) and 250 – 275 m/s (for FNCP). The level of jet velocities may provide meeting of accepted noise requirements (margin of 10 EPNdB relative to Stage 4 ICAO Annex 16, Vol I). More detail description of noise prediction procedure is presented in Chapter 5.

3 Elaboration of general technical design of turbofan for SSBJ2030

Mixed turbofan with variable common nozzle is considered as engine for propulsion system of advanced SCA-2030. The turbofan, optimized for SSSBJ, i.e. satisfying requirements (Table 2) with minimal margins is considered in the paper.

Cycle parameters (turbine entry temperature TET and overall pressure ratio, OPR), engine components efficiencies, cooling air flow rates corresponds expected level for SCT engines entering into service in 2020-2030 time period. All engine calculation are conducted accounting customer power and air offtakes.

Cruise BPR is defined by matching of engine parameters at cruise and low noise takeoff conditions. Thrust, TET and OPR are given for engine design conditions (cruise at H = 17 km, M = 1.8, ISA). Thrust, TET and OPR are given for engine design conditions (cruise at H = 17 km, M = 1.8, ISA).The values of required thrust and maximal exhaust jet velocity are given at low noise takeoff conditions (it corresponds to FRP, H = 1000 m, M = 0.3, ISA+10°).

Table 2. Required installed thrust and SFC at different design conditions for SSBJ2030 PS

Required thrust/SFC	Calculation conditions			Value
	H, km	M	σ_{intake}	
$T_{ins\ SSC}$, tf	17	1.8	0.9	2.5 – 3.0
$SFC_{ins\ SSC}$, kg/kgf.h	17	1.8	0.9	1.0 – 1.02
$T_{ins\ SBC}$, tf	12	0.95	0.935	1.5 -2.0
$SFC_{ins\ SBC}$, kg/kgf.h	12	0.95	0.935	0.80 – 0.85
$T_{ins\ TO}$, tf	0	0	0.92	12
$T_{ins\ lift\text{-}off}$, tf	0	0.25	0.929	10.5
$T_{ins\ TR\ H=11km}$, tf	8	1.1	0.936	2.4
	10			2.7
	12.5			3.3
	14			4.0
$T_{ins\ TR}$, tf	8	1.1	0.936	3.8
	10			3.2
	12.5			2.6
	14			2.53
$T_{ins\ min\ LRP}$, tf	0.1	0.25	0.929	6.0 - 6.5 (at V_{jet}=330 - 350m/s)
$T_{ins\ min\ FRP}$, tf	1	0.3	0.931	4.0 - 4.5 (at V_{jet}=250 - 275m/s)

Fan surge margin ΔK_{fan} was limited at low noise takeoff conditions by 40%, and at other conditions ΔK_{fan} = 20%.

Scaled generalized maps of the engine components were used. Jet nozzle is considered as nozzle with full expansion and variable throat and nozzle exit. Nozzle efficiency φ_C was equal to 0.97 and taken into account nozzle inner losses as well as losses related to partial mixing of core and bypass airflows.

Optimal parameters of unified turbofan for SCA2030 were defined taking into account the mentioned above assumptions (table 3).

Table 3. Main parameters of optimal UE for SCA2030

Engine parameter	Value
$BPR_{takeoff}$	2.65
$OPR_{takeoff}$	20.8
$TET_{takeoff}$, K	1530.5
$T_{takeoff}$, t	12.8
D_{fan}/M_{engine}, m/t	1.4/3.04
$SFC_{ins\ SSC}$, kg/kg.h	1.02
$SFC_{ins\ SBC}$, kg/kg.h	0.78

4 Requirements to SSMJ2030

Requirements to SSMJ2030 generated according to the concept of SCA2030 are presented in Table 4.

Table 4. Generated requirements to SSMJ-2030

Requirement	Value
Range by supersonic flight profile, km	> 8160
Range by subsonic flight profile, km	> 8160
Aircraft takeoff mass, t	< 110
Field length, m	< 2400
Noise (margin relative to Chapter 4), EPNdB	> 10
Cruise NO_X emission, g/kg fuel	< 10
Subsonic cruise conditions	M = 0.95; H = 12 km
Altitude of transonic acceleration, km	> 8
Supersonic cruise conditions	M = 1.8; H ≤ 17 km
Number of engine	4
Passenger capacity, pax	≥ 94
Fuel efficiency, g/pax-km	< 70

5 Assessment of mission, takeoff and environmental performances of SCA2030 with unified advanced turbofan

5.1 Mission performance

Optimal engine obtained for SSBJ2030 was applied for SSMJ2030 and hereinafter called as unified engine (UE).

Assessment of required levels of aerodynamic and mass performances of SSBJ2030 shown that to meet requirements (Tables 1 and 2) at using of UE following improvements of reference aircraft are necessary: operating weight W_{op} by 0.3%, aerodynamic efficiency in supersonic cruise K_{SSC} by 1.2% (concurrently required cruise thrust T_{SSC} is decreased up to 3.0 t, aircraft takeoff mass W_0 is reduced from 56 t to 45.3t, and fuel efficiency q_{SSC} may account 375 g/pax.km).

The same improvements for SSMJ2030 providing meeting of appropriate requirements (Table 4) are equal: for W_{op} – 4%, for K_{SSC} - 12% (concurrently T_{SSC} is decreased also up to 3.0 t, W_0 is reduced up to 105.8t, and q_{SSC} may account 60.6 g/pax-km).

Results of estimation of maximal altitude of transonic acceleration for SSBJ2030 and SSMJ2030 are presented on Fig. 2. The minimal required thrust at transonic acceleration was defined at flight segments with minimal thrust excess (it corresponded flight speed at M = 1.1. Change of minimal required thrust for SSBJ2030 and SSMJ2030, and available thrust of UE is shown depending on altitude of transonic acceleration H_{TR}.

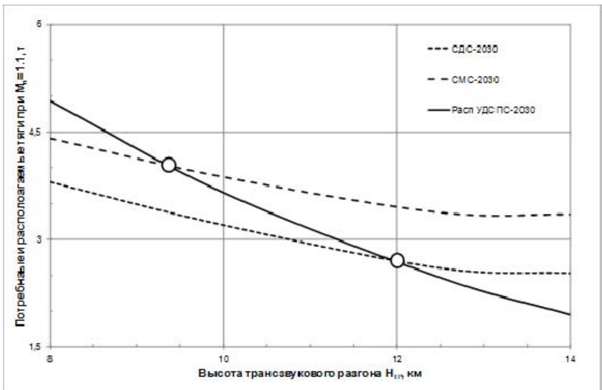

Fig. 4. Change of required and available thrust depending on altitude of transonic acceleration H_{TR} at M = 1.1

It is seen, that H_{TR} may account 12 km for SSBJ2030 with UE, and about 9 km for SSMJ with UE).

5.2 Estimation of takeoff-landing performance

Estimation of takeoff/landing (TOL) performance is carried out under following assumptions:

• Design Atmospheric Conditions (DAC): ΔT_H = +15°C, Δp_H = 0.

• takeoff wing loading $(W/S)_{TO}$=360 kg/m^2;

• increased level of takeoff thrust at one crucial engine inoperative is not applied;

• minimal initial climb gradients at altitude of 10.7 m are accounted as requirements of AR-25/FAR-25.

Main results of takeoff/landing modeling are presented on Fig. 5 and 6 as dependences of minimal required takeoff thrust loading $(T/W)_{TO}$ on takeoff wing loading $(W/S)_{TO}$ at different Field Length(FL) at takeoff L_{TO} and landing L_{land} for SSBJ2030 (Fig. 5) and SSMJ2030 (Fig.6).

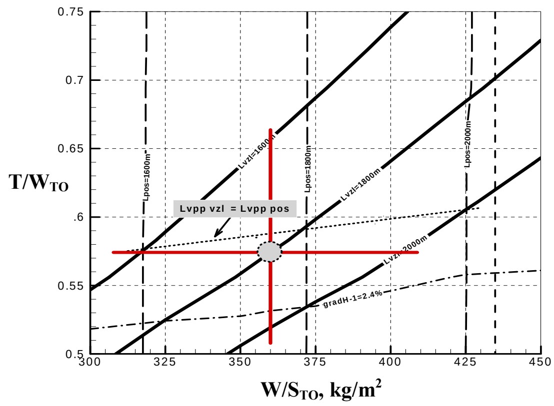

Fig. 5. TOL performance of SSBJ2030 with UE

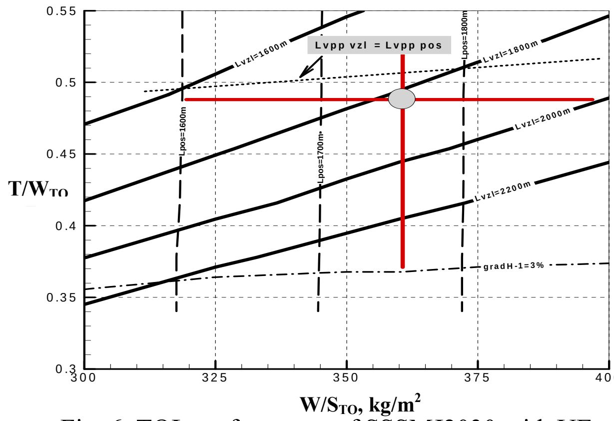

Fig. 6. TOL performance of SSSMJ2030 with UE

The curves with $L_{TO} = L_{land}$ are presented on the plots, area under the curves corresponds to $L_{TO} > L_{land}$ (FL is defined by L_{TO}), and area upper curves corresponds to $L_{TO} < L_{land}$ (FL is defined by L_{land}).

Besides the curves corresponding to minimal climb gradient gradH-1 (2.4% for SSBJ2030 and 3% for SSMJ2030) are also shown here, area under the curves is unacceptable.

As it is seen from Fig.5 and 6 according to available takeoff thrust and corresponding thrust loading the FL for SSBJ2030 and SMJ2030 with UE may account 1800 m, i.e. may meet given requirements.

At that calculated pints for both SSBJ and SSMJ are located close to boarding line $L_{TO} = L_{land}$, i.e. in case of growing stringency of requirements to FL the meeting them will be complicated due to FL will be defined by landing field length L_{land}.

5.3 Estimation of environmental performance

5.3.1 Evaluation of jet noise levels at takeoff

Modern world level of development of acoustic liners (AL), design methods and aids of low noise fan allow hoping that fan noise of future SCT will be significantly reduced and will not be dominated in total engine noise. Additionally, SCT engines have medium BPR 2.5…3.5 and also have enough space (in distinct of subsonic engines) into long supersonic intakes and nozzles to arrange AL. Therefore significant attention in the work is paid to the jet noise reduction. Further researches should be carried out taking into account fan noise and AL application to predict community total noise more correctly.

Important parts of noise assessment are takeoff/landing flight path and jet noise in the source calculation. Therefore flight profile is generated by solving of differential equation system of aeroplane motion as material point. It allow to meet necessary requirements and noise certification conditions.

Methodology of source jet noise prediction is based on semiempirical theory using gasdynamic and geometric jet parameters in nozzle exit section.

One of possible way of SCT takeoff noise reduction by optimal noise takeoff thrust management (so called low noise thrust management) is considered in the work. The capabilities of the such thrust management is limited by conditions of actual noise certification procedure [3,4], of airworthiness standards (AP-25, CS-25, FAR 25) [5], and of stringency of requirements to runway length.

Low noise takeoff thrust management at initial climb, considered in the work, assumes the application of early start of thrust reduction at flight altitude lower than one accepted by actual noise certification procedure for subsonic aircraft (300 m for twin engine aeroplanes, 260 m for tree-engine aeroplanes and 210 m for four-engine aeroplanes [3,4]).

Such approach to noise estimation extends the understanding of necessity and efficiency of early SCT engine throttling. Obviously, it may require modifying of actual noise certification procedure taking into account flight safety requirements. Besides, current aeroplane and engine control systems use widely electronic devices, including on-board computers, which allow to implement such low noise thrust management not by direct impact on engine control lever but by embedding of the control program into the on-board computer and by providing it with engine electronic control system. Besides, keeping of flight safety at low flight altitude may help using of slower thrust reduction, at which maximal throttling (i.e. minimal thrust) is achieved at altitude higher than minimal acceptable one.

Assessment of acoustical performance taking into account meeting noise requirements (see Tables 1 and 4) was carried out at following conditions:

- aircraft takeoff noise is defined by lateral and flyover jet noise with small margin (2 - 3 EPNdB) accounting fan noise;
- 2/3 of total noise margin is provided in Lateral (LRP) and flyover (FRP) reference points;
- it is assumed that landing noise requirement may be provided by application of AL and special variation of intake throat area;
- restrictions of minimal acceptable climb gradients at initial climb is taken into account

(according to AP 25, FAR-25 and AP-36, FAR-36) [3-5].

Following results were obtained based on preliminary assessment of takeoff jet noise:

• maximal lateral jet noise of SSMJ and SSBJ2030 is observed in control point located opposite the flight profile point with M = 0.25 и altitude H = 100 m;

• FRP is located on distance of 6.5 km from break release approximately close to flight profile point with M = 0.3 и altitude H = 1000 m;

• required jet noise margin in LRP providing noise goal is equal to 2 - 8 EPNdB (relative to Stage 3 level) and corresponds jet velocity Vjet = 340 – 360 m/s; required jet noise margin in FRP providing noise goal is equal to - 8 - 15 EPNdB (relative to Stage 3 level) and corresponds jet velocity Vjet = 250 – 275 m/s;

• for **maximal jet velocity reduction** at engine thrust throttling combined schedule of thrust throttle which included firstly engine throttling at constant fan speed up to fan surge margin of 40%, and then thrust decrease providing fixed fan surge margin of 40%.

Four low noise takeoff thrust management schedules were investigated in the work:

1. Using of maximal engine thrust at the start, takeoff and initial climb up to achievement of minimal acceptable altitude of start of engine throttling (close to FRP at distance of 5200 m) with further thrust reduction up to minimal acceptable level (schedule S1);

2. Using takeoff thrust decreased by 10% at start point (90% maximal takeoff thrust, i.e. relative thrust of 0.9), takeoff and initial climb up to achievement of distance of 5200 m with further thrust reduction up to minimal acceptable level (schedule S2);

3.Using of maximal engine thrust at the start, takeoff and initial climb up to achievement of altitude of 30 m with further thrust reduction up to minimal acceptable level (schedule S3);

4. Using takeoff thrust decreased by 10% at start point, takeoff and initial climb up to achievement of altitude of 30 m with further thrust reduction up to minimal acceptable level (schedule S4).

Flight paths at initial climb obtained for SSMJ with UE using different schedules of takeoff thrust management are presented on the Fig. 7.

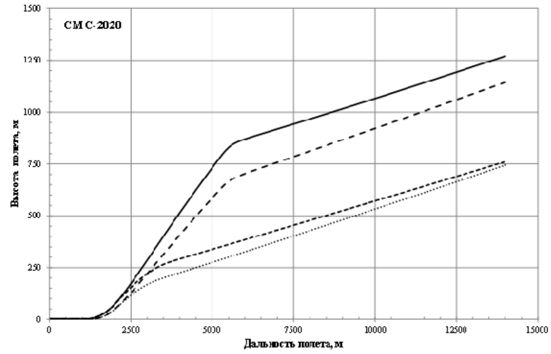

Fig. 7. Flight paths at initial climb of SSMJ with UE using different schedules of takeoff thrust management

It is seen, that starting engine thrust decrease by 10% (schedules S2 and S4) makes initial climb trajectory flatter (due to lower thrust excesses) by 150 m. Thrust throttling up to minimal acceptable level at initial climb decreases flight altitudes more significantly (approximately by 500 m). Lowest trajectory is observed in case of using of schedule S4 (initial climb altitudes is lower by 650 m than altitudes at using of S1).

In general, in spite of using of same UE SSBJ2030 have higher trajectories than SSMJ due to slightly higher thrust loading.

Change of engine modes, characterizing by relative thrust T_{rel}, along the trajectories of initial climb for SSMJ with UE at using of different takeoff thrust management schedules is shown on the Fig.8.

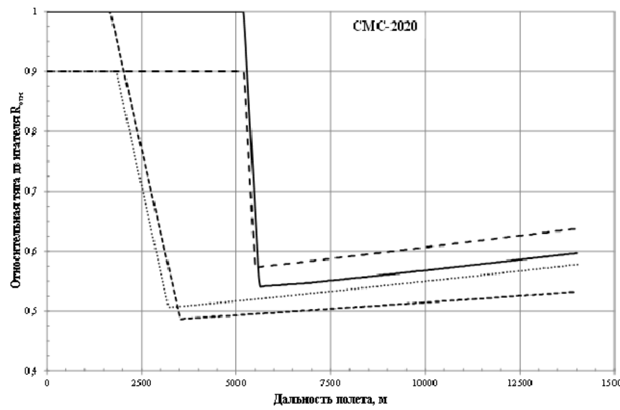

Fig. 8. Change of engine modes (relative thrust T_{rel}) along the trajectories of initial climb for SSMJ with UE

Relative thrust is equal $T_{rel} = T/T_{max}$, where где T_{max} is maximal thrust, T is engine thrust at given engine mode.

It may me noted different rate of thrust reduction at different schedules of takeoff thrust management (S1, S2 and S3, S4). Difference is connected with successful attempt along with noise reduction meeting of actual noise certification requirements according which engine throttling is permitted after achievement of safe altitudes (300 m for SSBJ and 210 m for SSMJ). As a result minimal engine modes at the schedules S3 and S4 is achieved just after reaching of the safe altitudes.

Maximal engine throttling level is defined by requirements to minimal acceptable climb gradients (both at all operative engines and at one engine inoperative) and is equal 58 - 62% for SSBJ, and 48 - 50% for SSMJ. It should be noted that in most cases providing of minimal climb gradients at one engine inoperative is crucial (more stringent).

Starting engine thrust decrease by 10% (schedules S2 and S4) leads to reduction of jet velocity at flying close to LRP and accordingly to reduction of lateral jet noise. However lower flight altitudes leads to increase of flyover jet noise, i.e. in other words, there is redistribution between lateral and flyover jet noise levels. In some cases the redistribution may be useful (e.g. to reduce exactly lateral noise).

Main results of takeoff jet noise assessment are presented in Table 5 for SSMJ and SSBJ with UE using different low noise takeoff thrust management schedules.

In the Table 5 margins of lateral, flyover and cumulative jet noise relative ICAO Stage 3 level are marked as ΔE_{LRP}, ΔE_{FRP}, $\Delta E_{FRP+LRP}$ accordingly. Besides jet noise margins, obtained runway length L_{RW} are also given in the Table 5.

It is seen, that using of low noise takeoff thrust management schedules S1 don't allow to meet even Stage 4 lateral noise requirements for both SSBJ and SSMJ (violation is 0.4 – 0.9 EPNdB, and according Stage 4 requirements margins in each reference points has to be no less than 2 EPNdB relative to Stage 3).

Starting engine thrust decrease by 10% together with engine throttling close to FRP (low noise takeoff thrust management schedule S2) allow to meet noise requirements only SSMJ, and lack of takeoff noise for SSBJ is 3 - 4 EPNdb.

Table 5. Main results of takeoff jet noise assessment for SSBJ and SSMJ with UE

Schedule	Value	SSBJ2030	SSMJ2030
S1	ΔE_{LRP}, EPNdB	-0.9	-0.4
	ΔE_{FRP}, EPNdB	9.4	18.5
	$\Delta E_{FRP+LRP}$, EPNdB	8.5	18.1
	L_{RW}, m	1760	1835
S2	ΔE_{LRP}, EPNdB	2.2	2.8
	ΔE_{FRP}, EPNdB	7.3	17.2
	$\Delta E_{FRP+LRP}$, EPNdB	9.5	20.0
	L_{RW}, m	1860	2030
S3	ΔE_{LRP}, EPNdB	5.3	6.5
	ΔE_{FRP}, EPNdB	9.0	18.8
	$\Delta E_{FRP+LRP}$, EPNdB	14.3	25.3
	L_{RW}, m	1760	1835
S4	ΔE_{LRP}, EPNdB	9.0	10.5
	ΔE_{FRP}, EPNdB	6.6	16.2
	$\Delta E_{FRP+LRP}$, EPNdB	15.6	26.7
	L_{RW}, m	1860	2030

Using low noise schedules S3 and S4 allow meeting noise requirements for SSMJ and SSBJ. At that replacement of S3 on S4 practically don't change takeoff noise, but only leads to redistribution of noise in LRP and FRP. Taking into account that the replacement leads to increase of runway length from 1800 m up to 2000 m, using of S4 may be considered as inappropriate (for SSBJ especially).

6 Approximate assessment of cruise emission performance

Emission assessment has particular importance for SCT flying long time in stratosphere to predict impact of aircraft flight on ozone layer and climate.

Level of cruise nitrogen oxides NOx emission is a one of the parameters defining of the SCT impact. Nowadays there isn't international standards limiting the parameter, but NOx emission level of 10 g/kg fuel accepted in the work is considered as desirable restriction of cruise NOx emission index EINOx.

Validated semiempirical model which is applicable only on early engine design phases (preliminary engine design phases) for investigation of NOx emission of combustor with diffusion combustion was used in the work to approximately evaluate EINOx [6,7].

Change of calculated mean values of cruise NOx emission indices $EINOx_{cr\ mean}$ depending on residence time t_{res} for SSBJ2030 is presented on Fig. 9.

It is seen that required value of cruise EINOx about 10 g/kg fuel corresponds residence time t_{res} about 3.5 – 4.0 ms.

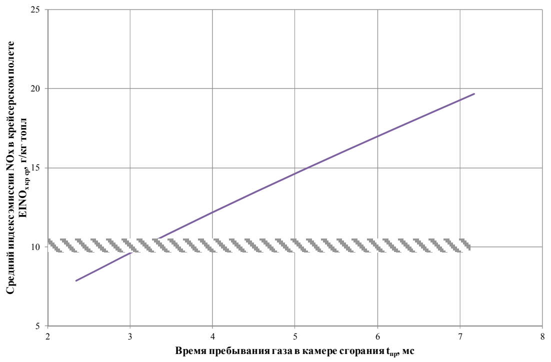

Fig. 9. Mean values of cruise NOx emission indices $EINOx_{cr\ mean}$ depending on residence time t_{res}

Achievement of the values of t_{res} is extremely complicated problem for combustion with diffusion combustion. Further comprehensive investigations of capabilities of realization of low emission combustor for SCT (including combustors like LPP) , providing required level of cruise NOx emission , should be carried out.

7 Conclusion

Studies of capability of unification of engines for advanced small and medium supersonic aeroplanes, providing required mission, noise margins and emission level shown following:

1. PS with unified engine (UE) for SSBJ2030 and SSMJ2030 may be based on using of unaugmented mixed turbofan with variable supersonic nozzle, moderate BPR (~2.65) and OPR (~21).

2. Obtained required maximal levels of SFC, providing together with assumed advanced level of aerodynamic and mass efficiencies of airframe of SCA2030, required range by supersonic and subsonic flight profiles are equal to 1.02 kg/kgf.hour at SSC and to 0.8 kg/kgf.h at SBC. In the case, takeoff mass of SSBJ2030 and SSMJ203 may account 45.3 and 105.8 t accordingly.

3. In case of accounting only jet noise (taking into account additional noise margin for fan noise by 2 – 3 dB) noise requirements for SCA2030 with UE may be meet by using special low noise takeoff thrust management schedules with early start of engine throttling at initial climb.

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