STUDIES ON REQUIRED PERFORMANCES OF ADVANCED SUPERSONIC CIVIL AIRCRAFT AND THEIR PROPULSION SYSTEMS FOR 2020¬2035 TIMEFRAME

A. Mirzoyan*, L. Mirzoyan**
***Central Institute of Aviation Motors, Moscow, Russia, ** Moscow Aviation Institute, Moscow, Russia**
mirzoyan@ciam.ru; lola-mai@mail.ru

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Abstract

Analysis of required fuel and thrust performance of propulsion system is conducted to generate requirements to novel engines of supersonic civil transport for 2025 – 2030 timeframe. The analysis includes the following design cases:

- *safe takeoff and landing using runway restricted by given field length;*
- *super-/subsonic cruise flight providing given flight range;*
- *transonic acceleration at given flight level;*
- *safe initial climb taking into account takeoff noise requirements (in lateral and flyover reference points).*

Estimation of influence of super-/subsonic cruise speed on mission performance is also carried out.

1 Introduction

Economical viability of supersonic civil transport (SCT) is connected with increased productivity, its capability to carry more passengers in the same time (in comparison with subsonic aircraft). Increased operating costs and environmental restrictions on sonic boom, noise and emission are main technological obstacles on the road to SCT development [1].

Up to now Tupolev 144 and Concorde are the only SCT which were in service. Their development has led to essential technical break in many advanced aviation technologies. However low profitability and environmental restrictions have not allowed these first generation SCT become real typical economic model for the further development and expansion of SCT fleet. Despite it, researches on advanced SCT were and are performed on present time both in the USA and Europe, as well in Russia [2-6].

At the end of XX century world aviation industry came to conclusion that the small, less high-speed and less expensive airplane is more comprehensible in term of simplification solving of mentioned problems and decrease of risks. In the early 1990s Sukhoi design bureau with Gulfstream worked on the project of supersonic business jet (SSBJ) S-21. Some US companies (AERION, SAI and others) are working on the similar SSBJ projects. International project HISAC (High Speed AirCraft) of 6th European Framework Program with participation of the European and Russian companies, carried out in 2005 - 2010 timeframe, was devoted to studying environmentally friendly SSBJ. 2015 - 2018 timeframe was considered in the mentioned projects as prospective time for entry in service (EIS).

In 2005 NASA has engaged the US industry for a new estimation of the future commercial supersonic airplanes, environmental target indicators, and also identification of key enabling technologies. Two teams from the industry and the universities, headed by Boeing and Lockheed Martin, have investigated SCT of 2020 – 2025 (N+2) and 2030 – 2035 (N+3) timeframes [7,8].

NASA technical and environmental target indicators for the future SCT are mainly related to sonic boom, community noise and cruise emissions reduction, increase of fuel efficiency.

2 Problem statement

Main principles of advanced SCT development concept (ASCT DC) for 2020 - 2035 timeframe were formulated in the studies.

By hypothesis of ASCT DC the 4-engined Supersonic Airliner (SA) with 100 - 130pax and twin engine SSBJ with 8 - 12pax may be developed in considered timeframes.

ASCT DC includes the following base development trends:

- the SCT fleet segmentation on passenger and business aviation sectors;
- maturation of TRL of SA up to level 6 to 2020 – 2025 and EIS after 2030 – 2035;
- maximizing commonality of SA and SSBJ as well their Propulsion Systems (PS);
- 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.

The following requirements to advanced SCT and its PS were accepted in ASCT DC:

- flight range is no less than 8600km for SA and 7400km for SSBJ;
- maximal takeoff weight W0 is less than 160t for SA and 60t for SSBJ;
- Field Length (FL) is less than 3000m for SA and 1800m for SSBJ;
- climb time is less than 25min;
- margin of cumulative noise level relative to Stage 3 requirements is no less than 20 - 30 EPNdB;
- takeoff thrust T0 is about 10 - 15tf;
- engine jet velocity at initial climb (at “low noise” engine rating) V_j is to be about 320 - 340m/s at flight Mach number $M = 0.25$ and flight altitude $H = 100$m and is to be about 220 - 240m/s at $M = 0.3$;
- supersonic cruise (SPCR) conditions:
  - M_{SPCR} = 1.6 - 2.0; H_{SPCR} < 17km (for emission reduction)
  - low installing engine specific fuel consumption $SFC_{ins.SPCR}$;
- subsonic cruise (SBCR) conditions:
  - M_{SBCR} = 0.9 - 0.95; H_{SBCR} = 12km
  - low $SFC_{ins.SBCR}$
  - flight range is no less than range for flight profile with SPCR;
- transonic acceleration (TR) conditions:
  - flight level H_{TR} = 8 – 14km
  - high installing engine thrust $T_{ins.TR}$;
- FAR-33 certification requirements plus specific conditions for SCT.

The following main design cases are considered to generate principal requirements to PS:

1. Safe takeoff and landing using runway with restricted field length:

- definition of minimal required takeoff installing engine thrust T0 at $H = 0$, $M = 0$ and Design Atmospheric Conditions (DAC) (deviation of atmospheric pressure from ISA $\Delta p_H = 0$, deviation of atmospheric temperature from ISA $\Delta T_H = +15^o$);
- restriction of maximal drop of engine thrust with a raise of speed at takeoff ($M = 0 – 0.4$).

2. Supersonic cruise at M_{SPCR}= 1.6 – 2.0 :

- definition of the minimal required installing engine thrust $T_{ins.SPCR}$;
- restriction of maximum of average supersonic cruise altitude H_{SPCR} (H_{SPCR} < 17km for emission reduction);
- definition of minimal $SFC_{ins.SPCR}$ providing given total flight range.

3. Subsonic cruise at M_{SBCR} = 0.8 - 0.95:

- definition of the required installing engine thrust $T_{ins.SBCR}$;
- definition of minimal cruise installing engine specific fuel consumption $SFC_{ins.SBCR}$ providing given total flight range.

4. Transonic acceleration at flight level H_{TR} = 8 – 14km, including definition of minimal required installing engine thrust T_{TR} at M_{TR}=1.1.

5. Initial climb with restriction of maximal takeoff noise level (in lateral and flyover reference points):

- for Lateral Reference Point (LRP): restriction of maximal jet velocity V_j = 320–330m/s and minimal required thrust loading $(T/W)_{min}$ at $M = 0.25$, $H = 100m$;

- for Flyover Reference Point (FRP): restriction of maximal jet velocity $V_j = 220–240m/s$ and $(T/W)_{min}$ at $M = 0.3$ and $H = 600m$ (for SA) or $H=1300m$ (for SSBJ).

2 Requirements at design flight conditions

2.1 Supersonic Cruise

Generation of main requirements to supersonic cruise of advanced SCT is carried out at the following assumptions:

- flight range is 9120km for SA and 7400km for SSBJ;
- $M_{SPCR} = 1.8$; $H_{SPCR} = 17km$.

Fig.1 and Fig.2 show in relative form the influence of airframe aerodynamic improvement characterized by airframe aerodynamic efficiency $K_{SPCR.rel}$, airframe weight improvement characterized by change of operational weight $\Delta W_{OP.rel}$ and PS fuel efficiency characterized by $SFC_{ins.SPCR.rel}$ on mission performance of advanced SA and SSBJ. All relative values are referred to corresponding values of SCT of N+1 timeframe (SCT N+1) as reference points.

The reference points are marked on the Fig. 1-4 by dashed circles, the points of SCT N+3 are marked by solid circles, the points of pragmatic level of parameters of SCT for 2025 - 2030 timeframe (SCT2025,SA2025, SSBJ2025) are marked by grey circles and red arrows.

It is seen that best value of SCT N+3 fuel efficiency from the NASA target range (qt = 54.5 – 70 g/pax.km) at minimal W0 and given flight range is provided by simultaneous improvements of $K_{SPCR.rel}$ and $SFC_{ins.SPCR.rel}$ by 15-17% and $W_{OP.rel}$ by 0.5- 1% (dashed arrows).

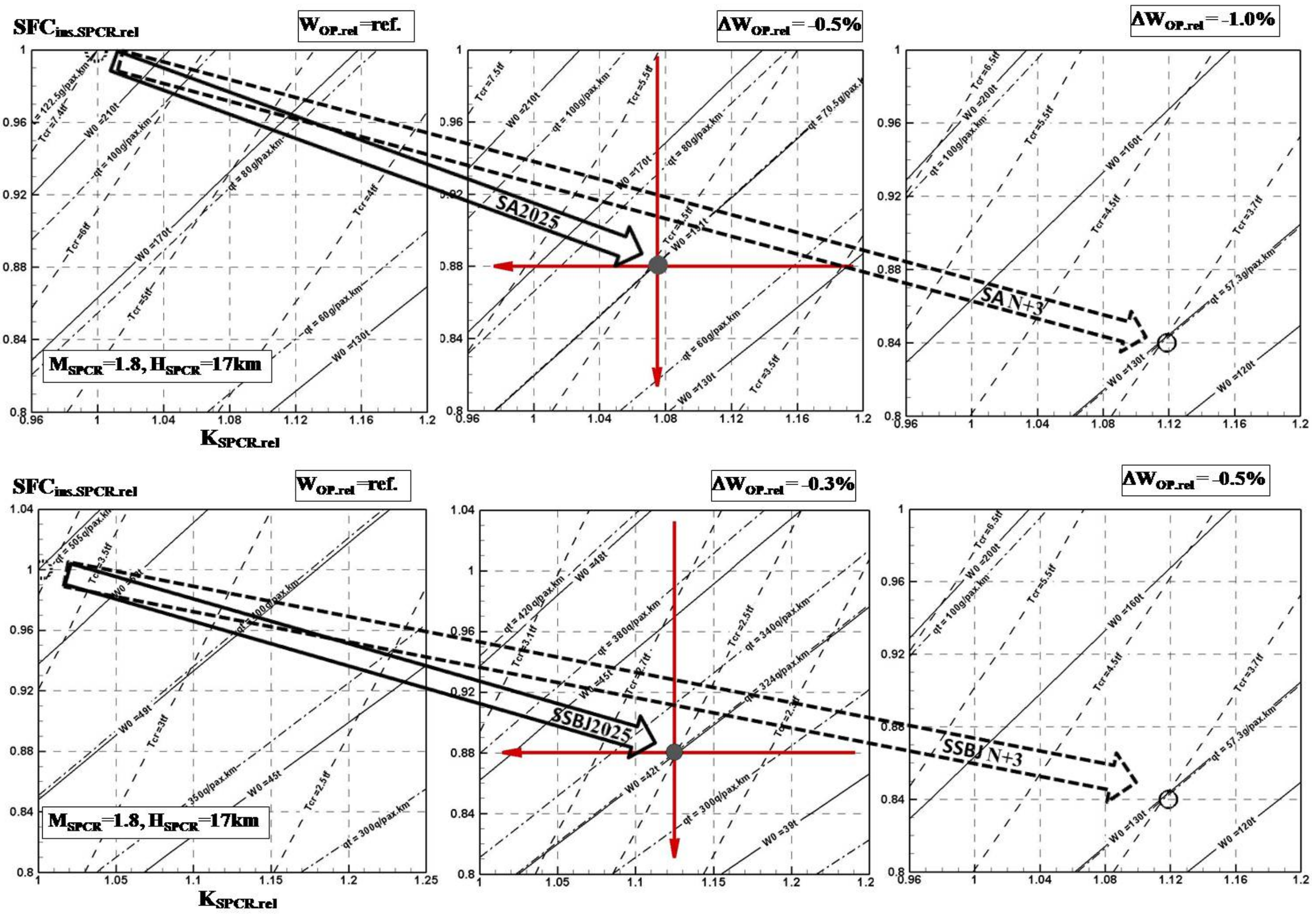

Fig. 1. Impact of $K_{SPCR.rel}$, $SFC_{ins.SPCR.rel}$ and $\Delta W_{OP.rel}$ on qt, W0 and $T_{ins.SPCR}$ for advanced SA and SSBJ

SA N+3 W0 is 125 – 130t, required installing engine thrust in SPCR $T_{ins.SPCR}$ is 3.5-4tf.

In case of such improvements of $K_{SPCR.rel}$, $SFC_{ins.SPCR.rel}$ and $W_{OP.rel}$ W0 of SSBJ N+3 is decreased from 56t (SCT N+1) up to 35 – 38t, $T_{ins.SPCR}$ is about 2tf and qt is approximately 270 - 280g/pax.km (Fig. 2).

More realistic improvements of $K_{SPCR.rel}$ and $SFC_{ins.SPCR.rel}$ by 11 - 13% and operating weight by 0.3-0.5% are assumed for SCT2025 (solid arrows on Fig.1-4). In this case qt, W0 and $T_{ins.SPCR}$ are 70 – 71g/pax.km (satisfies to minimum of NASA N+3 target range), 150 - 153t, 4.5 - 5.0tf for SA2025 and 320 – 330 g/pax.km, 42-43t, 2.5 - 3.0tf for SSBJ2025.

2.2 Subsonic cruise

According to accepted requirements to SCT the flight range of profile with SBCR has to be no less than the one with SPCR.

Generation of requirements to SBCR is carried out for the following conditions:

- flight range is 9120km and 7400km for SA and for SSBJ correspondingly;
- M_{SBCR} = 0.95; H_{SBCR} = 12km.

Fig.3 and Fig.4 show in relative form the influence of $K_{SBCR.rel}$, $SFC_{ins.SBCR.rel}$ and $W_{OP.rel}$ on mission of advanced SCT.

It is seen that improvements of $K_{SBKR}/SFC_{ins.SBCR}$ by 11-17% provide the same W0 as for SCT N+3 with SPCR. And improvements of $K_{SBKR.rel}$ and $SFC_{ins.SBCR.rel}$ by 9-13% provide the same W0 as for SCT2025 with SPCR and $T_{ins.SBCR}$ in range of 1.5-3tf.

2.3 Safe takeoff and landing

Generation of requirements to takeoff and landing performance of PS is carried out for the following conditions:

- takeoff at DAC: $\Delta T_{н} = +15$, $\Delta p_{н} = 0$;

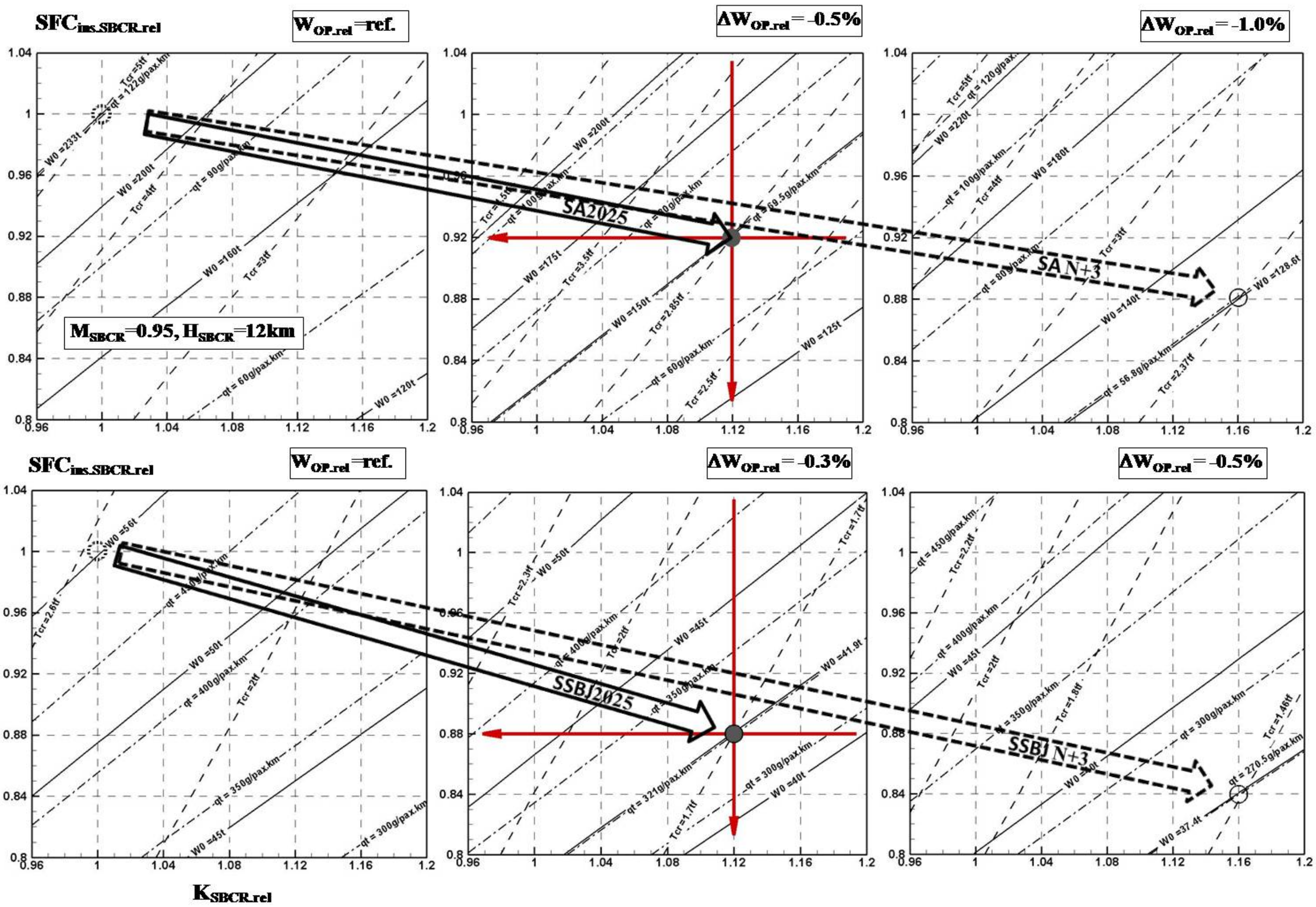

Fig. 2. Impact of $K_{SBCR.rel}$, $SFC_{ins.SBCR.rel}$ and $\Delta W_{OP.rel}$ on qt, W0 and $T_{ins.SBCR}$ for advanced SA and SSBJ

- FL is 3000m for SA, 1800m for SSBJ;
- wing loading $W0/S_w$ is 360 kg/m^2;
- drop of installing engine thrust with a raise of speed from M=0 to M = 0.4 is no more than 20%;
- restrictions of minimal climb gradients (according to FAR-25);
- maximal approach speed is 83m/s;
- degree of installing thrust increasing of operating engines at OEI $T_{ins.OEI.rel}$ is limited by 20%.

Required takeoff thrust loading $(T/W)_{0.min}$ and installing engine thrust T0 at H = 0, M = 0 are presented on Fig.5 and Fig. 6.

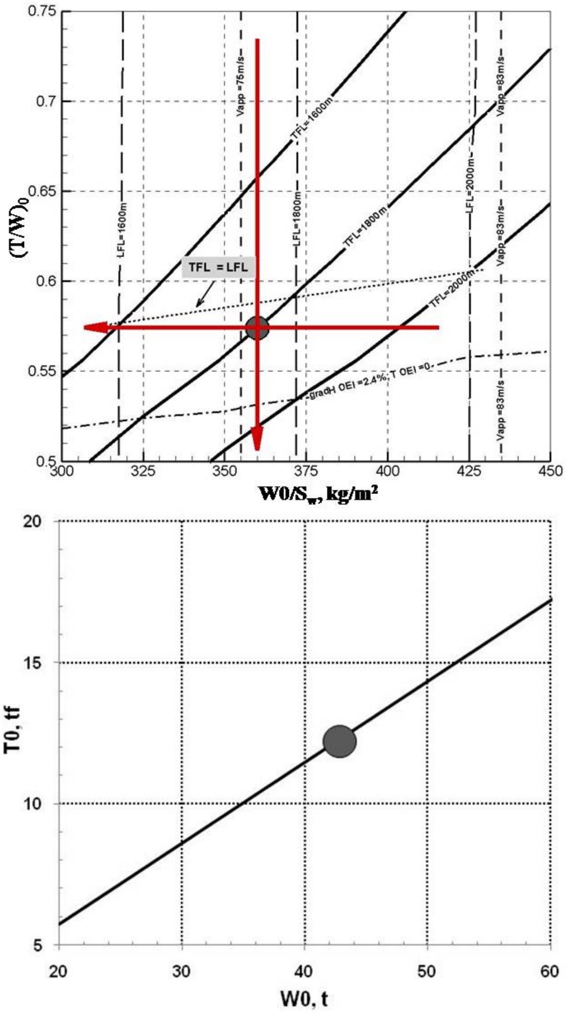

Fig. 5. Requirements to takeoff performance of PS for SSBJ2025

The lines corresponding to required Takeoff Field Length (TFL) and Landing Field Length (LFL), equaled to 1600m, 1800m, 2000m, takeoff with OEI at minimal climb gradient $gradH_{OEI}$ without use of increased thrust of operating engine ($T_{ins.OEI.rel} = 0$), takeoff and landing with the TFL=LFL are shown on Fig. 5.

It is seen that $(T/W)_{0.min}$ for SSBJ2025 providing FL of 1800m is not defined by $gradH_{OEI}$ and is defined only $W0/S_w$.

Therefore use of increased thrust of operating engine at OEI is inefficient for SSBJ2025 because it does not decrease $(T/W)_{0.min}$, which is required to provide FL of 1800m, and remains on the level of 0.56 - 0.58.

Required $(T/W)_{0.min}$ providing FL no more than 3000m for SA2025 is limited by minimal $gradH_{OEI}$ (Fig.6) . If $T_{ins.OEI.rel} = 0$, $(T/W)_{0.min}$ is 0.38 - 0.39, otherwise if $T_{ins.OEI.rel} = +20\%$, $(T/W)_{0.min}$ may be decreased up to 0.32.

The influence of W0 on T0 providing $(T/W)_{0.min}$ is shown on the bottom plots of Fig.5 and Fig.6. It is seen that T0 is about 12.0-12.5tf at obtained W0 for SA2025 and SSBJ2025.

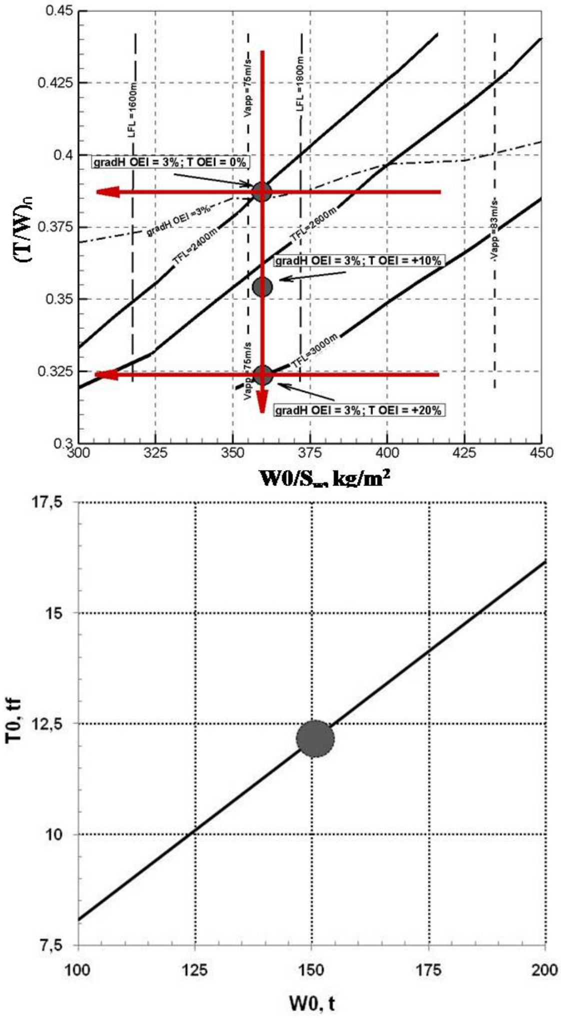

Fig. 6. Requirements to takeoff performance of PS for SA2025

2.4 Transonic acceleration

Generation of requirements to PS at TR segment is carried out at the following assumptions:

- acceleration of airplanes is realized on the fixed flight level H_{TR} =8 -14km;
- most crucial flight conditions, where minimal thrust excesses are reached, correspond to flight point with M = 1.1.

Minimal required installing engine thrust at transonic acceleration at flight level H_{TR}, corresponding to H = 11km and M = 1.1, $T_{TR,H=11km}$ for SA2025 and SSBJ2025 is presented on Fig.7.

It is seen that $T_{TR,H=11km}$ is increased dramatically with a raise of H_{TR}: from 2.5 to 8tf for SA2025 and from 2.5 to 4tf for SSBJ2025.

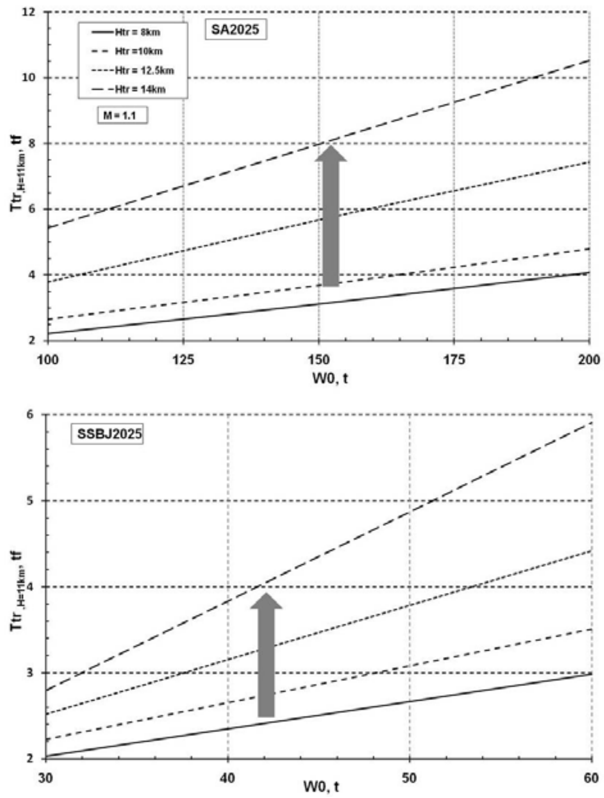

Fig. 7. Requirements to PS performance at transonic acceleration of SA2025 and SSBJ2025

2.5 Takeoff noise

Generation of requirements to PS performance at takeoff and initial climb taking into account of meeting community noise restrictions is carried out for the following conditions:

- takeoff noise in LRP and FRP is mainly defined by jet noise with reserve of 2-3 EPNdB for other nondominated noise sources (fan, core, airframe etc.)
- 2/3 of cumulative noise margin is provided by takeoff noise, 1/3 of takeoff noise margin is provided by noise in LRP
- takeoff jet noise is mainly defined by jet velocity in the region close to reference points
- minimal climb gradients at initial climb correspond to FAR-25 and FAR-36.

Results of takeoff jet noise predictions showed that:

- maximum of lateral jet noise is reached in LRP located at the side of initial climb point with M = 0.25 and H = 100m
- FRP is located on distance of 6.5 km from brake release under initial climb point with M=0.3 and H=600m for SA2025 and H=1300m for SSBJ2025
- required margin of lateral noise relative to Stage 3 providing meeting of NASA N+3 goal is equal to 7 EPNdB and corresponds to V_j of 320 - 330m/s
- required margin of flyover noise relative to Stage 3 providing meeting of NASA N+3 goal is equal to 18 - 20 EPNdB and corresponds to V_j of 240-350m/s.

Results of estimation of $(T/W)_{min}$ providing safe initial climb for SCT2025 are presented on Fig.8. Corresponding minimal required engine thrust $T_{ins.min}$ in dependence on takeoff weight W0 is shown on the Fig.9.

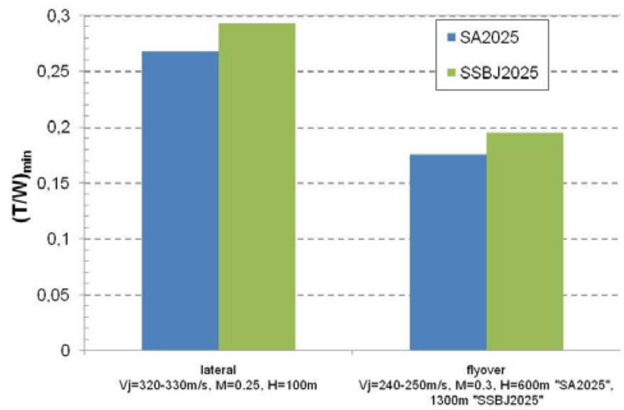

Fig. 8. $(T/W)_{min}$, providing meeting of takeoff noise requirements

$(T/W)_{min}$ and $T_{ins.min}$ at M = 0.25 and H = 100m are 0.268 and 10.0 - 10.5tf for

SA2025 and 0.293 and 6.5 - 7.0tf for SSBJ2025, at M = 0.3 and H = 600m they are 0.176 and ~6.5 - 7.0tf for SA2025, at M = 0.3 and H = 1300m are 0.196 and ~4.0 - 4.5tf SSBJ2025 (Fig. 9).

2.6 Influence of change of SPCR and SBCR speeds on mission of advanced SCT

Studies of influence of cruise speeds on total range at given fixed takeoff weight W0 are carried out for SSBJ2025.

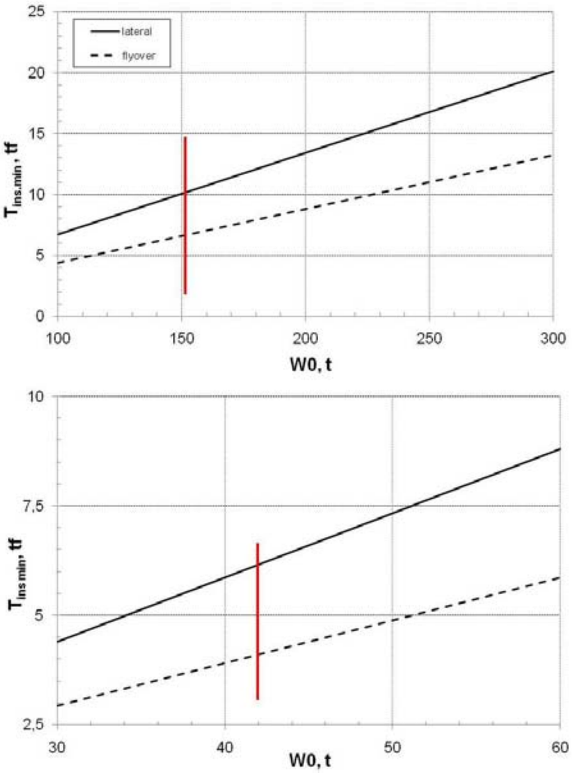

Рис. 9. $T_{ins.min}$ providing meeting of requirements to takeoff noise

Fig.10 shows in relative form the assumed dependences of $K_{SPCR.rel}$, $K_{SBCR.rel}$, $SFC_{ins.SPCR.rel}$, $SFC_{ins.SBCR.rel}$, cruise speeds $V_{SPCR.rel}$ and $V_{SBCR.rel}$ on M_{CR} in two ranges: 0.8 - 1.0 and 1.6 - 2.0. These data are typical for SSBJ N+1.

It is seen that change of $K_{SBCR.rel}$ has maximum at M_{CR} = 0.9, the decrease of $SFC_{ins.SPCR.rel}$ is slowed at M_{CR} < 1.7 due to increase of intake and nozzle losses.

Fig.11 in relative form presents change of flight range in the raise of cruise speeds.

It is seen that change of M_{CR} in the range of 1.7-2.0 influences on flight range insignificantly.

This is connected with cancellation of influences of K_{SPCR}, $SFC_{ins.SPCR}$ and V_{SPCR} on K*V/SFC.

Range extreme in the raise of speed at M_{CR}=0.9 is connected with maximum of K_{SPCR} (Fig. 10).

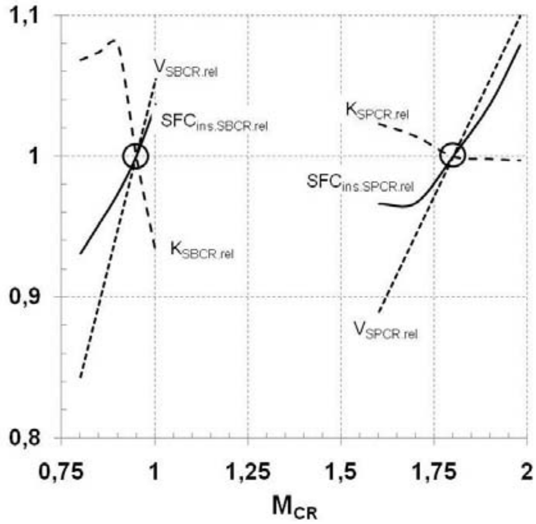

Fig. 10. Influence of change of M_{CR} on changes of $K_{SPCR.rel}$, $K_{SBCR.rel}$, $SFC_{ins.SPCR.rel}$, $SFC_{ins.SBCR.rel}$, $V_{SPCR.rel}$ and $V_{SBCR.rel}$

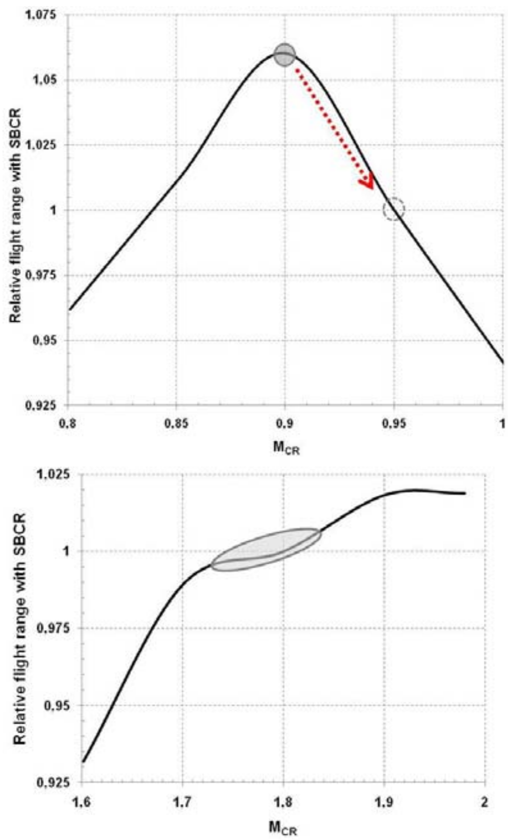

Fig. 11. Influence of M_{CR} on relative flight range

Thus if the dependences of $K_{SPCR.rel}$, $K_{SBCR.rel}$, $SFC_{ins.SPCR.rel}$ and $SFC_{ins.SBCR.rel}$ on M_{CR} for SCT2025 will little differ from the same dependences for SCT N+1, SPCR speed will not be depended on mission requirements but will be mainly defined by compromise between flight time and engine life time. Optimal SBCR speed M_{CR} is 0.9 from mission point of view, but competition with advanced subsonic airliner with cruise speed 0.75 - 0.85 may require to increase the optimal M_{CR} up to 0.95.

Main parameters of SSBJ N+1 and SCT 2025 are shown in the Table 2 for comparison.

Table 2. Main parameters of SCT 2025 in comparison with SSBJ N+1

Parameter	**SSBJ N+1**	**SSBJ2025**	**SA2025**
Takeoff weight, t (%)	56	42 (-25)	151
Field length, m	1980	1800	3000
Flight range, km	7400	7400	9120
Passenger capacity, pax	8	8	120
Supersonic cruise Mach number	1.8	1.8	1.8
Aerodynamic efficiency K_{SPCR} (M = 1.8, H= 17km), %	100	112.5	107.4
SBCR Mach number	0.85	0.95	0.95
Aerodynamic efficiency K_{SBCR}(M=0.95, H=12km) (%)	100	112	112
Relative operating weight	0.507	0.527 (-0.5)	0.417
Fuel fraction (% of change)	0.48	0.46 (-5.0)	0.511
Engine takeoff thrust (without intake losses), tf	14.7	12.1	12.2
Number of engines	2	2	4
Takeoff thrust loading (% of change)	0.5	0.57 (+15)	0.323
Relative $SFC_{ins.SPCR}$ (M = 1.8,H = 17km), (%)	100	88	88
Relative $SFC_{ins.SBCR}$ (M = 0.95, H = 12km), (%)	100	88	87.4
qt with SPCR, g/pax.km (% of change)	505	324 (-36)	70.3
qt with SBCR, g/pax.km (% of change)	507	321 (-36)	69.2
Required $T_{ins.SPCR}$ (M=1.8, H =17km), tf (% of change)	3.8	2.5 (-34)	4.5
Required $T_{ins.SBCR}$ (M = 0.95, H = 12km), tf		1.7	2.8
Minimal thrust loading (thrust , tf) providing safe initial climb at M=0.25, H=100m and V_j=320-330m/s		0.293 (~6.2)	0.268 (~10.1)
Minimal thrust loading (thrust , tf) providing safe initial climb at M = 0.3, H = 100m (for SSBJ2025) or H = 1300m (for SA2025) and V_j = 240 - 250m/s		0.196 (~4.1)	0.176 (~6.6)
Minimal thrust loading (thrust, tf) at H=11km, M = 1.1 providing transonic acceleration on flight level H_{TR} H_{TR} = 8km H_{TR} = 14km		 0.12 (~2.5) 0.19 (~4.0)	 0.08 (~3.0) 0.21 (~8.0)

3 Conclusion

- Main principles of advanced SCT development concept for 2020 - 2035 timeframe have been identified. The 4-engined SA (SA2025) with 100 - 130pax and twin engine SSBJ (SSBJ2025) with 8 - 12pax are considered
- It was shown that NASA SCT N+3 goals on fuel efficiency of 54.5 – 70 g/pax.km at given flight ranges may be reached by simultaneous increase of supersonic cruise (SPCR) aerodynamic efficiency

K_{SPCR} and specific fuel consumption $SFC_{ins.SPCR}$ by 12 - 14% relative to SCT N+1 level

- Requirements to minimal levels of engine thrust at crucial flight conditions are generated for SSBJ2025 and SA2025 in case of assumption of pragmatic predictions of airframe aerodynamic and base PS performance improvements, and include:
  - minimal required takeoff thrust equal to about 12tf providing safe takeoff from runway restricted by given field length;
  - minimal required installing engine thrust equal to 3.0 - 3.5 tf for SA2025 and to 1.5 - 2.0 tf for SSBJ2025 at SPCR (M=1.8, altitude H = 17km);
  - minimal required installing engine thrust at H=11km and M=1.1 is dramatically increased from 3 to 8.5 tf for SA2025 and from 2 to 3.5tf for SSBJ2025 in the raise of flight level of transonic acceleration from 8 to 14 km;
  - minimal required installing engine thrust at M = 0.25 and H = 100m is equal to 12 - 12.5 tf for SA2025 and to 5.0 - 5.5 tf for SSBJ2025, meeting minimal lateral noise requirements with jet velocity level of 320 – 330 m/s; minimal required installing engine thrust at M = 0.3 and H = 600m is equal to 7.0 - 7.5 tf for SA2025 and at M = 0.3 and H = 1300m is equal to 3.0 - 3.5 tf for SSBJ2025, meeting minimal flyover noise requirements with jet velocity level of 240 – 250 m/s
- Studies of influence of super- and subsonic cruise speeds on the range of SA2025 and SSBJ2025 assuming that the dependences of $K_{SPCR.rel}$, $K_{SBCR.rel}$, $SFC_{ins.SPCR.rel}$ and $SFC_{ins.SBCR.rel}$ on cruise speeds will be slow differ from same dependences of SCT N+1 are shown:
  - SPCR Mach number M_{CR} is slow influence on the flight range;
  - optimal subsonic cruise Mach number M_{CR} is equal to 0.9, but competition with advanced subsonic airliner may require to increase optimal subsonic M_{CR} up to 0.95.

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