Chapter

Estimation of Cumulative Noise Reduction at Certification Points for Supersonic Civil Aeroplane Using the Programmed Thrust Management at Take-off and Approach

Artur Mirzoyan and Iurii Khaletskii

Abstract

The reduction of the cumulative noise level at certification points applying to the supersonic civil aeroplane is estimated in the paper. The reduction is obtained by using an programmed thrust management with Programmed Lapse Rate based on the variation of engine power setting at take-off and approach. The use of proposed programmed reduced noise thrust management requires a change of the conventional noise certification procedures as well as further implementation as fully automated system (Variable Noise Reduction System) into aircraft/engine control system. The main engine noise sources such as the fan and exhaust jet are taken into account in the estimation. It is shown that the cumulative noise level using proposed programmed thrust management is lower by 10.7–12.2 EPNdB than using the conventional engine thrust control as currently applied to subsonic jet aeroplanes at take-off and approach.

Keywords: supersonic civil aeroplane, take-off and approach, engine thrust (power) setting, throttle ratio, bypass ratio, noise certification reference points

1. Introduction

The crucial issue of development of a new generation of supersonic civil aeroplanes (SCA) is to meet environmental requirements like sonic boom level, community noise level during landing and take-off cycle (LTO) and engine/CO_2 emission levels. According to the requirements of Chapter 12 of the current ICAO noise standard, maximal SCA noise levels at certification reference points (RP) should be satisfied the noise limitations for subsonic jet aeroplane at the same maximum certificated take-off mass (MTOM), i.e. to the current requirements of Chapter 14, Annex 16, Volume I [1].

The SCA design features leads to the generation more intense noise during the LTO cycle vs. the noise of the subsonic jet aeroplane with the same MTOM. The estimations of the noise levels applied to advance SCA shown that it is still impossible to meet the requirements at the current level of aviation technologies. The CAEP (Committee on Aviation Environmental Protection) has not yet developed the new standard for SCA noise at RP.

The lack of an international standard for SCA noise and the expectation of the implementation of several USA SCA projects in the current decade motivated the USA Federal Aviation Administration (FAA) to develop national standards. In March 2020, FAA published a preliminary version of the national noise standards for a distinct SCA class. The limit line of USA noise standards locates exactly in the middle between the Chapter 4 and Chapter 14 of the ICAO standard for subsonic jet aeroplanes [2]. The SCA class is limited by the MTOM value of 68 000 kg and by the cruise speed corresponding to the Mach number of 1.8.

NASA and other research centers assessments showed that meeting the FAA's published limits on the SCA noise level, and even more so meeting the requirements of Chapter 14, Annex 16, Volume I, may not be satisfied on the current technology level [3, 4].

The FAA rules also suggest the some changes to the existing noise certification reference procedures applied to the subsonic jet aeroplanes. It is specifically stipulated that the SCA noise certification will use of technical equipment (like Variable Noise Reduction System) that will implement new approaches to the SCA community noise reduction. The capability for SCA noise management during LTO cycle using the engine thrust variation providing engine automatic (programmed) thrust/power throttling was considered in the number of publications [3–8]. The aim of the studies was to assess the maximal SCA community noise reduction using the thrust management at LTO cycle.

2. Problem statement

The take-off thrust (power) throttling has a contradictory effect on the noise levels in each take-off RP, i.e. on the lateral and flyover (cutback) noise levels. On the one hand, the lateral noise level is reduced due to a decrease of the engine exhaust jet velocity as well as fan circumferential velocity. On the other hand, the flyover noise level is increased due to the lower thrust settings are associated with the lower climb path, and therefore the distance from the community noise source to the take-off RP is decreased. Thus, a compromise solution on the engine thrust management (TM) during the take-off is required to reduce the take-off (lateral plus flyover) noise level.

In accordance with the noise certification procedure, the approach noise level is measured at approach using the constant flight speed along the path and the fixed glide slope angle θ which is equal to -3^o [1].

To provide the flight along such path with the constant flight speed and glide slope angle, it is necessary to maintain a certain level of the engine thrust (power setting). The level of the thrust will be uniquely determined by the values of the specified flight speed and glide slope angle. In other words, if an aeroplane is flying along glide slope at a constant speed, there is a direct relationship between the levels of the required engine thrust and the glide slope angle.

The approach RP is determined by the point on the ground, on the extended center line of the runway at the distance L_{app} = 2000 m from the threshold. Therefore, the approach noise level at varying the glide slope angle θ will mainly depend on the 2 factors: the flight altitude above the approach RP and the change of the engine parameters associated with a change in the required engine thrust (i.e. approach power setting).

Therefore, the variation of the approach power setting leading to a change of the glide angle is considered in the paper as a measure of the reduction of the approach noise level.

The paper presents the results of a computational study of the acoustic efficiency of using the programmed reduced cumulative (sum of the lateral, flyover and approach noise levels) noise thrust management with so-called Programmed Lapse Rate (PLR) during the take-off as well as the approach. The approach provides the reduction of the cumulative community noise taking into account the fan and exhaust jet noise.

It is well known that the current ICAO standard, Chapter 14, imposes more stringent requirements for the subsonic jet aeroplane than the previous Chapters 3 and 4 [1]. The intention of the SCA designers to follow the global trend of reducing the impact of aviation on the environment pushes them to consider the propulsion systems based on the turbofan with higher bypass ratio (BPR).

At the same time, there is a cardinal redistribution of the contributions between engine noise sources as increasing BPR. The dominance of the jet noise for the turbofan with lower BPR (~ 0.5…1.5) is replaced with an approximate equality of the fan and jet contributions for the turbofan with mediate BPR (~ 2.5…3.5) and then with predominant fan noise for the turbofan with higher BPR (~ 4.0…5.0).

The comparison of the effective perceived noise levels in case of use of the reference and the proposed programmed reduced cumulative noise thrust management using PLR (from here on programmed TM) is carried out as applied to a notional twin-engine supersonic business jet (SBJ). The SBJ has the range L = 7400 km, seating capacity n = 8 pax and balanced field length BFL = 2000 m.

The considered SBJ propulsion system is based on the turbofan with BPR = 2.5 … 5.0. The values of the range L, the seating capacity n and the balanced field length BFL are kept constant under the BPR variation. The take-off thrust loading is defined under provision of the specified balanced field length value.

The turbofan with BPR up to 5.0 is considered to maximize the SBJ noise reduction. At the same time, it is obvious that it is necessary to find a compromise solution, accounting the contradictory factors like nacelle size/drag, which is increased with increasing BPR.

3. Mission performance assessment for the SBJ at fixed flight range and using of turbofan with different BPR

The calculation of mission performance is performed for the SBJ with fixed flight range taking into account the flight segments like take-off, initial climb, climb, supersonic cruise, descent, approach, landing, and NBAA alternate. The engine size (and the corresponding SLS thrust and the take-off thrust loading) is defined from the balanced take-off condition and the given balanced field length BFL = 2000 m. At the definition of balanced field length the minimal one engine inoperative climb gradient at the altitude of 10.7 m is considered as the constraint [5].

Keeping the specified values of the flight range L, the seating capacity n and the balanced field length BFL with an increase of BPR leads to an increase of the maximum certificated take-off mass MTOM. It is primarily happened due to an increase of the required engine take-off thrust FN_{to} and propulsion system mass W_{ps}.

The **Figures 1** and **2** show the changes of MTOM (**Figure 1**), relative take-off thrust FNto_rel and propulsion system mass Wps_rel (**Figure 2**) depending on the BPR.

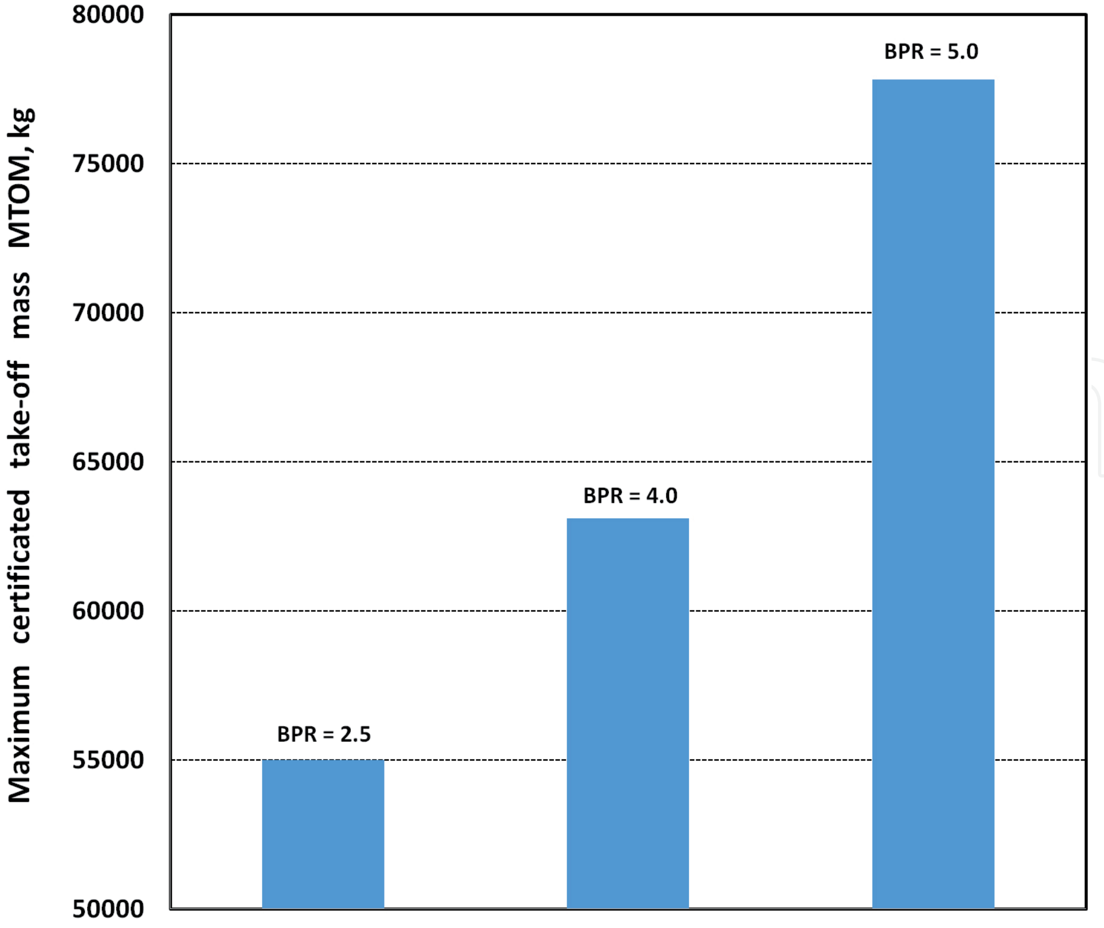

Figure 1.
The change of maximum certificated take-off mass MTOM vs. engine bypass ratio BPR (L = 7400 km, n = 8 pax, BFL = 2000 m).

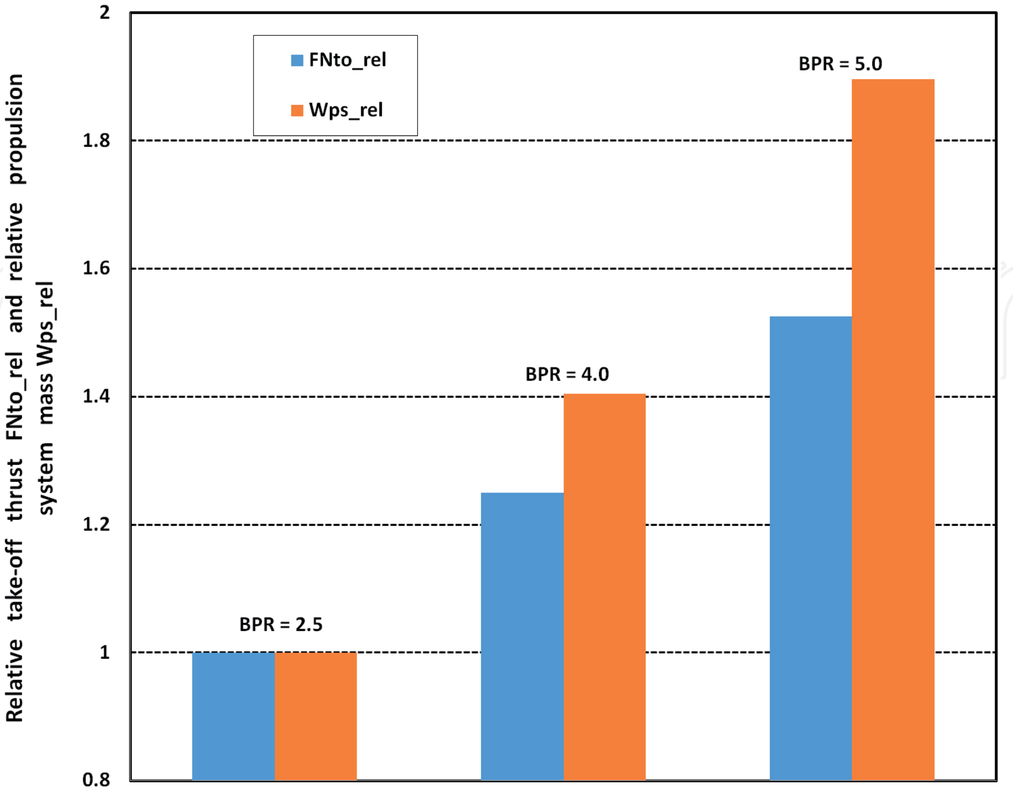

Figure 2.
The changes of FNto_rel and Wps_rel vs. bypass ratio BPR (L = 7400 km, n = 8 pax, BFL = 2000 m).

The relative values of the take-off thrust FNto_rel and the propulsion system mass Wps_rel are equal to:

$$FNto\_rel = FN_{to} / FN_{to\,BPR=2.5}, Wps\_rel = W_{ps} / W_{ps\,BPR=2.5}. \tag{1}$$

where FN_{to}, $FN_{to\ BPR\ =\ 2.5}$, W_{ps} and $W_{ps\ BPR\ =\ 2.5}$ are the take-off thrust and propulsion system mass for the turbofan with current BPR and BPR = 2.5 correspondingly.

It can be seen that as BPR changes from 2.5 to 5.0 with fixed values of L, n and BFL, the take-off thrust FN_{to} and the propulsion system mass W_{ps} increase by 57 and 90%, respectively, while the MTOM increases from 55 000 to 77 000 kg, i.e. on 40%.

A noticeable increase of the MTOM at highest BPR may lead to an increase of the direct operating cost, which could be economically unacceptable. Therefore, the cost efficiency of use of turbofan with the higher BPR should be evaluated in the future activities more detail.

4. The reference and programmed reduced cumulative noise thrust management at take-off and approach

4.1 Take-off

Conventional TM applied to subsonic jet aeroplanes at take-off is considered as reference TM during the take-off. It includes the take-off and cutback power settings.

The proposed programmed TM using the PLR includes 7 flight path segments: take-off power (segment 1), throttling to power setting providing reduced lateral noise (segment 2), power setting providing reduced lateral noise (segment 3), restoring maximum climb power setting (segment 4), maximum climb power setting (segment 5), throttling to power setting providing reduced flyover noise (segment 6) and power setting providing reduced flyover noise (segment 7).

The throttle ratio value TR is equal to TR = thrust/full thrust,

where thrust corresponds to the thrust value for the current power setting;

full thrust corresponds to the thrust value for the maximum power setting at the current flight conditions.

The **Figure 3** shows the changes of the take-off thrust throttle ratio TRto depending on the distance from the brake release point and used take-off TM applied to SCA with MTOM of 55 000 kg and turbofan with BPR = 2.5.

The main purposes of the flight path segments are following:

- reduction of the required balanced field length (segment 1);
- reduction of the lateral noise level (segments 2 and 3);
- increase of the flight altitudes over the flyover RP (segments 4 and 5);
- reduction of the flyover noise level (segments 6 and 7).

The power settings on the segments 3 and 7 correspond to the lower power settings, providing the lateral and flyover noise reduction accounting the airworthiness and noise certification procedure restrictions in term of the minimal climb gradients [6].

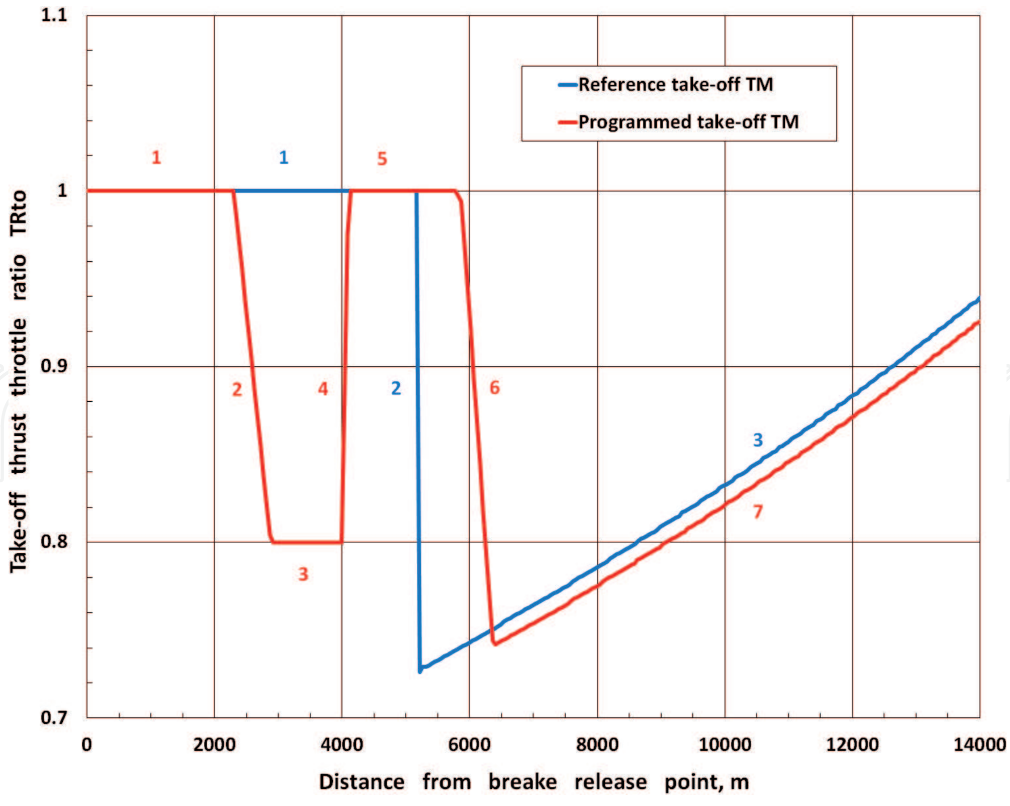

Figure 3.
The change of the take-off thrust throttle ratio TRto depending on the distance from the brake release point for reference and programmed take-off TM.

The proposed programmed TM includes rational choice of the TM parameters like the location of the beginning and end points of the segment 3, the beginning point of the segment 7, the thrust throttle ratio on the segments 3 and 7, the thrust acceleration and throttling rates on the segments 2, 4 and 6 (see **Figure 3**). All parameters are optimized in the paper under the minimum take-off noise criteria.

As seen in the **Figure 3**, the optimal take-off throttle ratio TRto values for the segment 3 and in beginning point of the segment 7 are equal to 0.8 (i.e. the engine power should be reduced by 20% vs. maximum power setting) and 0.74 (i.e. the engine power should be reduced by 26%) accordingly. The optimal distances for location of the beginning and end points of the segment 3 and the beginning point of the segment 7 should be equal to 2300, 4000 and 5800 m respectively. The optimal take-off thrust throttling rates on the segments 2 and 6 should be equal to 15 and 2.5% of thrust per a minute.

The **Figure 4** shows the SBJ flight path for the turbofan with BPR = 2.5 using the reference and programmed take-off TM.

Despite the fact that the use of programmed TM leads to a lower initial climb trajectory (see **Figure 4**), it is possible to recover the altitude above the flyover RP. It is mainly obtained due to the optimal choice of the programmed TM parameters, impacted on the flight above RP.

4.2 Approach

The conventional TM applied to the subsonic jet aeroplanes at approach providing the approach flight path with the glide slope angle $\theta = -3^\circ$ is considered as the reference approach TM. It usually includes use of the engine power setting close or equal to the flight idle.

The proposed programmed approach TM includes the use of the engine power setting lower than the flight idle.

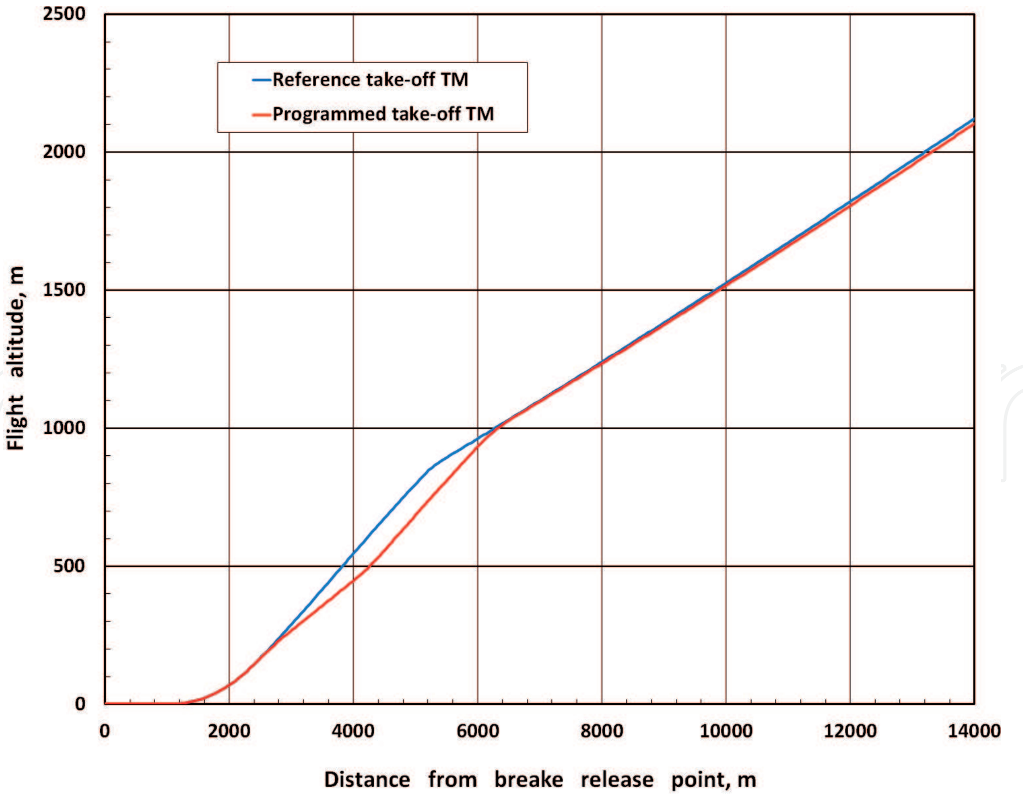

Figure 4.
The SBJ take-off SBJ flight path for turbofan with bypass ratio BPR = 2.5 using reference (green line) and programmed (red line) take-off TM.

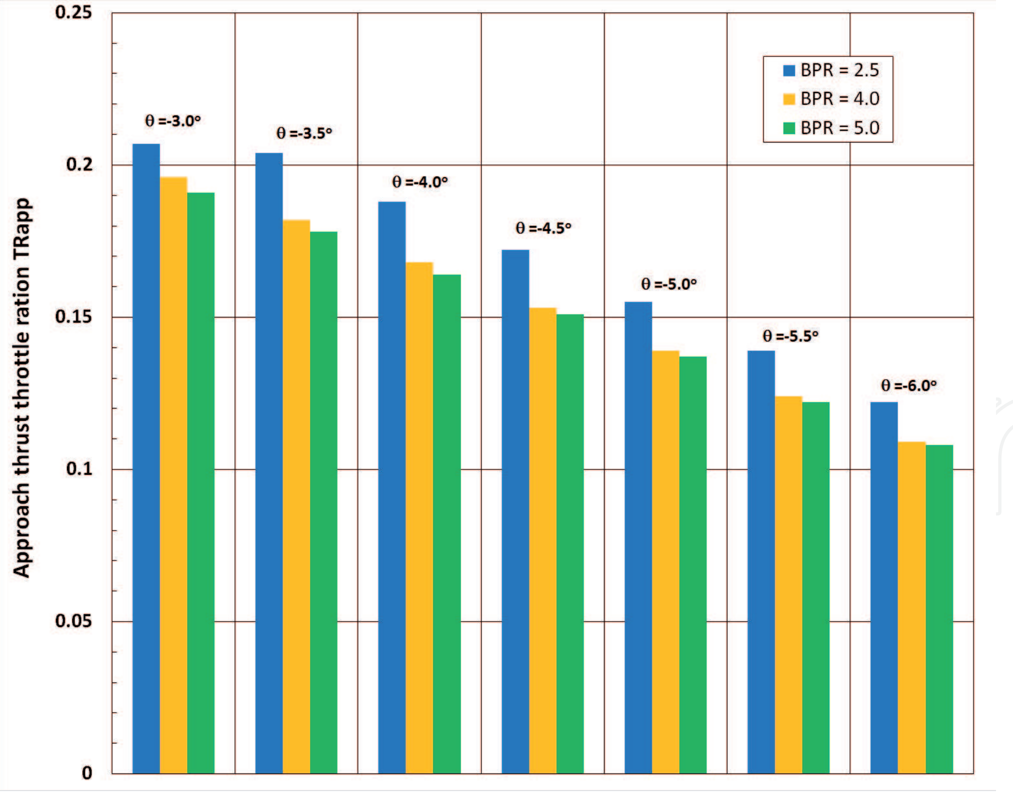

Figure 5.
The change of approach thrust throttle ratio TRapp depending on the glide slope angle θ and bypass ratio BPR for the reference (at θ = −3°) and programmed (at θ higher than -3°) approach TM.

Figure 5 shows the change of approach thrust throttle ratio TRapp depending on the glide slope angle θ and engine BPR.

It can be seen that with an increase in the angle θ from −3 to-6°, the approach throttle ratio TRapp decreases from 0.2 to 0.11–0.12. At the same time, a change

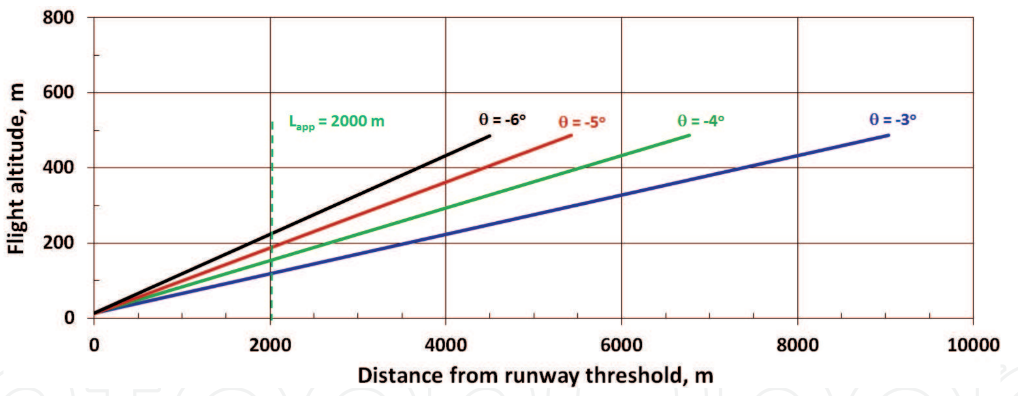

Figure 6.
The SBJ approach flight paths with the different glide slope angles θ for and turbofan with bypass ratio BPR = 2.5.

of BPR in the range from 2.5 to 5.0 practically does not affect the change of the engine power setting.

On the **Figure 6** SCA approach paths with different glide slope angle θ are presented for turbofan with BPR = 2.5. Changing the engine power setting and θ leads to an increase of the flight altitudes above the approach RP, located at a distance of 2000 m from the runway threshold.

The flight altitudes above the approach RP does not change with a change of BPR. And at the same time it significantly increases (by about 100 m) with an increase of the angle θ from −3 to -6° (**Figure 6**).

5. Comparison of SCA noise benefit at using reference and programmed TM

The **Figure 7** shows the comparative acoustic efficiency of using the programmed take-off TM vs. reference take-off TM. Changes of the flyover noise in case of replace of reference with programmed take-off TM does not exceed 1 EPNdB that is associated with the same flight conditions above the flyover RP (see **Figure 4**).

The changes of the lateral noise level are equal to 2.6 to 6.1 EPNdB depending on BPR.

The increase of the noise reduction benefit as increasing BPR is connected with increasing the contribution of fan noise to the total engine noise as well as increasing the influence of engine throttling in the fan noise. As a result, the change of the take-off (lateral plus flyover) noise level using programmed take-off TM instead of the reference take-off TM is equal to 2.3...6.0 EPNdB, depending on the BPR.

The **Figure 8** shows the change of SBJ approach noise level deviation from the approach noise in case of using turbofan with BPR = 2.5 and angle θ = −3.0° depending on BPR.

The changes of the approach noise level in case of replace of reference with programmed approach TM may reach up to 8 EPNdB depending on glide slope angle θ.

The assessment shown the potential effectiveness of a programmed approach TM, which reduces the approach noise level due to higher glide slope angle and flight altitudes above the approach RP.

The use of higher glide slope angle may lead to a more complex approach and landing procedures and requires the mandatory use of an instrumental automatic landing system, which is currently applied to many subsonic jet aeroplanes.

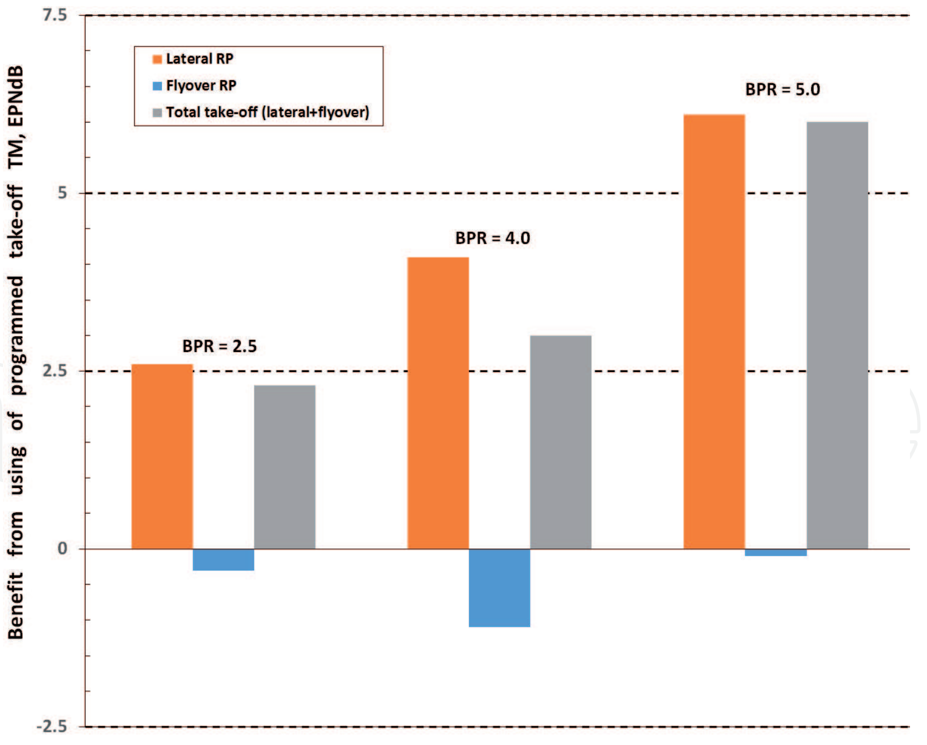

Figure 7.
The benefit of SCA lateral, flyover and total take-off (lateral plus flyover) noise levels from the use of programmed take-off TM depending on the engine bypass ratio BPR.

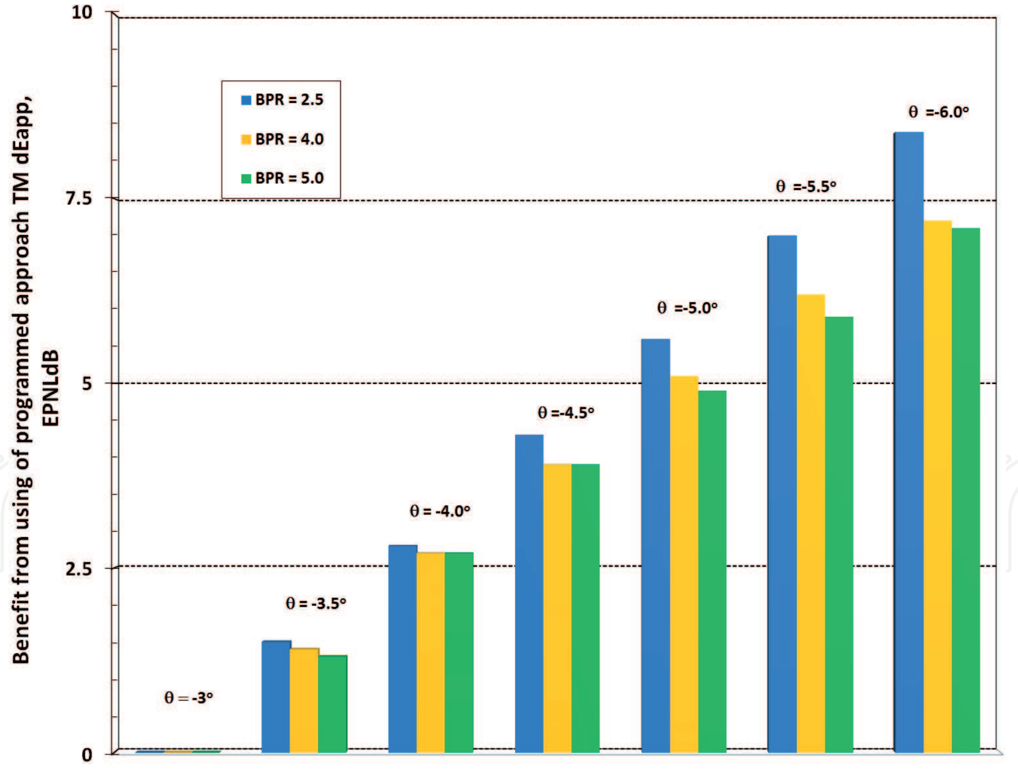

Figure 8.
The benefit of SCA approach noise levels from the use of programmed approach TM depending on the glide slope angle θ and the engine bypass ratio BPR.

6. Conclusions

In connection with the development of a new version of the ICAO international standard for the noise levels of SCA at certification points during the LTO cycle and the introduction of the USA national standard, it becomes relevant to study new opportunities to reduce the noise for such type of aircraft. The use of programmed thrust management (control) at the LTO cycle is evaluated in the paper as a tool for reducing the SCA noise levels. A comparative assessment of effective perceived noise levels in case of using the reference (conventional for subsonic jet aeroplanes) and programmed thrust management is applied to notional twin-engine supersonic business jet (with seating capacity of 8 pax, a range of 7 400 km, and the balanced field length of 2 000 m).

The following main results are obtained:

- the use of the proposed programmed take-off thrust management during the takeoff and initial climb instead of the reference one, reduces the take-off (lateral and flyover) noise level by 2.3–6.0 EPNdB depending on the bypass ratio BPR. It is mainly achieved by lateral noise reduction while flyover noise level is possible to keep unchanged;

- the use of the proposed programmed approach thrust management during the approach is associated with an increase of the glide slope angle due to additional thrust throttling. It is shown that an increase in the glide slope angle leads to reduction of approach noise. As the glide slope angle is changed from -3^{o} to -6^{o}, the SCA approach noise reduction may reach up to 8.4 EPNdB for turbofan with bypass ratio BPR of 2.5, and up to 6.2 EPNdB for turbofan with BPR of 5.0. It should be noted that increasing the glide slope angle relative to the standard value of -3^{o} may lead to the more complex approach and landing procedures and requires the mandatory use of an instrumental automatic landing system, which is currently used on many subsonic jet aeroplanes;

- the use of the programmed thrust management at LTO cycle instead of reference thrust management (i.e. use of cutback around flyover certification point and approach with the with the glide slope angle of -3^{o}) may reduce cumulative noise level by 10.7–12.2 EPNdB depending on bypass ratio BPR;

- as changing the bypass ratio BPR from 2.5 to 5.0 while maintaining the specified aircraft mission performance such as flight range, seating capacity and runway length the aircraft maximum take-off mass is increased from 55 to 77 tons, the take-off thrust and propulsion system mass are increased by 57% and 90% accordingly; a noticeable increase of the aircraft takeoff mass at highest bypass ratio BPR may lead to an increase of direct operating cost which could be economically unacceptable;

- programmed take-off thrust management using Programmed Lapse Rate should include the optimal location of two flight segments with lower power settings in the area of lateral and flyover reference points, optimal lower power settings, optimal thrust throttling rates as well as flight segment with maximal climb power setting between lateral and flyover reference points;

- the optimal values of the parameters of programmed take-off thrust management are following: thrust ratio in the area of lateral and flyover reference points are equal 0.8 (i.e. power reduction by 20%) and 0.74 (i.e. power reduction by 26%) respectively. The optimal distances for beginning and end of flight segment with power setting providing reduced lateral noise and for beginning of flight segment with power setting providing reduced flyover noise are equal to 2300, 4000 and 5800 m respectively. The optimal thrust throttling rates for transition on the power settings providing reduced lateral and flyover noise are 15 and 2.5% of thrust per minute respectively.

The study of programmed thrust management should be continued in the direction of taking into account the effect of noise shielding by airframe elements and the application of acoustic liners in the propulsion system.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this work.

Nomenclature

Abbreviations

BPR	bypass ratio
EPNdB	Effective Perceived Noise level unit
LTO	Landing/Take-Off cycle
NBAA	National Business Aviation Association
PLR	Programmed Lapse Rate
RP	noise certification Reference Point(s)
SBJ	Supersonic Business Jet
SCA	Supersonic Civil Aeroplane(s)
TM	Thrust Management
VNRS	Variable Noise Reduction System
Symbols	
BFL	balanced field length in m
FN	thrust in kN
L	flight range in km
m	meter
M	flight Mach number
MTOM	Maximum certified Take-Off Mass in tons
n	seating capacity
TR	Throttle Ratio
θ	glide slope angle in degree
Scripts	
app	approach
ps	propulsion system
rel	relative
to	take-off

Author details

Artur Mirzoyan* and Iurii Khaletskii
Central Institute of Aviation Motors, Moscow, Russia

*Address all correspondence to: mirzoyan@ciam.ru

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