# STUDY OF INFLUENCE OF ENGINE CONTROL LAWS ON TAKEOFF PERFORMANCES AND NOISE AT CONCEPTUAL DESIGN OF SSBJ PROPULSION SYSTEM

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## Abstract

*Engine control laws (CL), their effect on engine altitude-airspeed and throttle performances, field length (FL) and certificated jet noise in reference points under given SSBJ engine design parameters were studied in this paper.*

*Two simplest and complicated CL were examined at the study. Calculation of altitude-airspeed and throttle engine performances has been made in a wide variation range of control parameters (nozzle throat area and turbine rotor temperature). FL and low noise trajectories with possible combinations control parameters were defined.*

*Engine limitations effect on noise and takeoff - landing performance were also considered. Possible reserves for reduction of jet noise and/or reduction of FL were found.*

*Basic principles for making up of the optimal engine control laws were developed.*

## 1 Introduction

The study continues of researches of low noise engine & A/C schedule at takeoff and landing. Presently there are not enough studies on development of rational takeoff CL, optimized in terms of requirements to FL, takeoff noise reduction, and provision of minimal engine oversizing. At the same time results of previous researches illustrate that influence of chosen CL is often a main factor which defines engine altitude-airspeed and throttle performances effecting on the takeoff field length (TOFL) and takeoff noise.

## 2 Problem statement

### 2.1 Subject of study

The test subject is a twin engine supersonic business jet (SSBJ) with takeoff weight TOW=56 t, wing area A=150 m$^2$, flight range R=7000 km. Reference engine has takeoff thrust T=16…17 t, bypass ratio BPR=2.5…3.0. The turbine rotor temperature T41 and nozzle throat area A8 were examined as main engine control parameters. Reference CL (RCL) of engine T41=1540…1570 K, A8=1.2 m$^2$ provides the A/C takeoff with TOFL=2000 m. Only jet noise was estimated in this study because it is a dominant noise source of the SSBJ.

### 2.2 Reference operating conditions of engine performance

Two simplest CL were examined at the first stage of the study:

1. (T41=const)+(A8=const) – the CL from the takeoff to the engine throttle point at initial climb. The law effects on the takeoff FL and lateral noise. The CL is defined by combination of relative parameters T41$_{rel}$ and A8$_{rel}$, varying in range of 1.0…0.66 and 0.8…1.5 respectively.

2. (T$_{min}$)+(A8=const) – the CL at initial climb (throttle law TL1) and approach effects on flyover and approach noise (T$_{min}$ – minimal engine thrust). The TL1 is defined by the combination of T41$_{rel}$=var and A8$_{rel}$=0.8…1.5.

Separation of these CL is caused that engine throttle must not influence on lateral noise at certification.

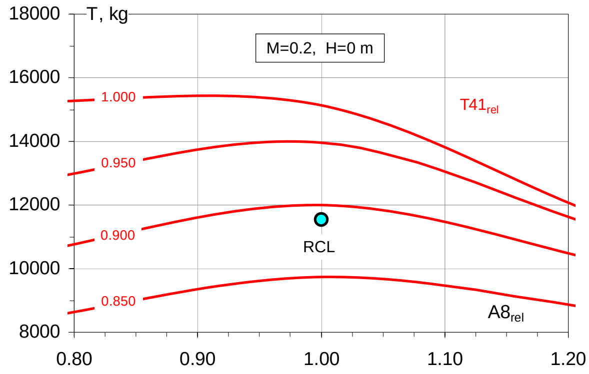

**Fig. 1.** Dependence of engine thrust from engine control parameters

Calculation of altitude-airspeed and throttle engine performances in a wide variation range of nozzle throat area ($A8_{rel}$=0.80…1.5) and temperatures ($T41_{rel}$=1.0…0.66) is necessary to study the influence of different CL on noise and FL.

Figure 1 shows dependence of the engine thrust from $A8_{rel}$ and $T41_{rel}$ at M=0.2 and H=0 m. It can be seen on the plot that the maximal thrust is reached at $0.9<A8_{rel}<1.1$

Engine altitude-airspeed and throttle performances were calculated taking into account bleed and power extractions for A/C needs and air conditioning system.

## 2.3 Trajectory generation for FL and noise estimation

A/C takeoff and landing performances were performed according to aviation standards (FAR-25, CS-25, AP-25 and FAR-36, CS-36, AP-36) for reference design takeoff and landing weights in the atmospheric conditions:

1. ISA+15 C– for FL calculation;
2. ISA+10 C– for noise calculation.

The key condition for selection of engine failure speed is the equality of continued and interrupted takeoff distances.

A part of T41 and A8 combinations was eliminated at FL calculation since it did not provide a requirement takeoff thrust level (the minimal climb gradient of 2.4% on the flight altitude of 10.7 m was not satisfied).

Low noise trajectories at possible combinations T41 and A8 were defined taking into account limitations of noise certification standards (FAR-36, CS-36, AP-366) and passengers comfort.

Upon reaching the throttle distance of 5000 m (according initial altitude of throttle ($H_{in.thr}$) of 700…1000 m) the thrust is reduced to maintain a climb gradient of 4% or flight level with one engine inoperative whichever thrust is greater ($T_{min}$). $T_{min}$ after $H_{in.thr}$ is increased to provide the conditions described above.

# 3 Analysis of study results

## 3.1 First stage

Figure 2 shows the dependence of the required calculated FL from combination of engine control parameters T41 and A8.

The strong curves minimum is connected with thrust change (see Fig. 1).

The margin of noise level relative to ICAO Chapter 3 level (ΔEPNdB Ch.3) is the basic noise parameter at analysis of acoustic characteristics.

Figure 3 shows dependence of margin of lateral, flyover and approach noise levels from control parameters. It can be seen that noise levels are reduced with decrease of the T41 and A8. It is connected with decrease of jet velocity (V8).

Figure 4 shows dependence of lateral noise ΔEPNdB Ch.3 from FL and control parameters T41 and A8. This plot is most interesting due to optimal combinations of $T41_{rel}$ and $A8_{rel}$ are a Pareto set. It can be seen that lateral noise reduction requires decrease of requirements to FL up to maximal value. There is a minimum takeoff distance which is connected with the maximum thrust value at initial climb.

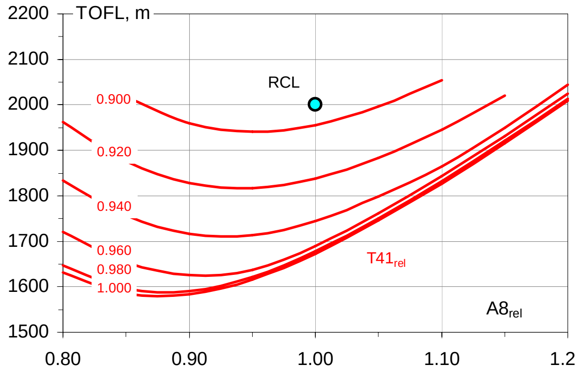

**Fig. 2.** Dependence of required FL from engine control parameters

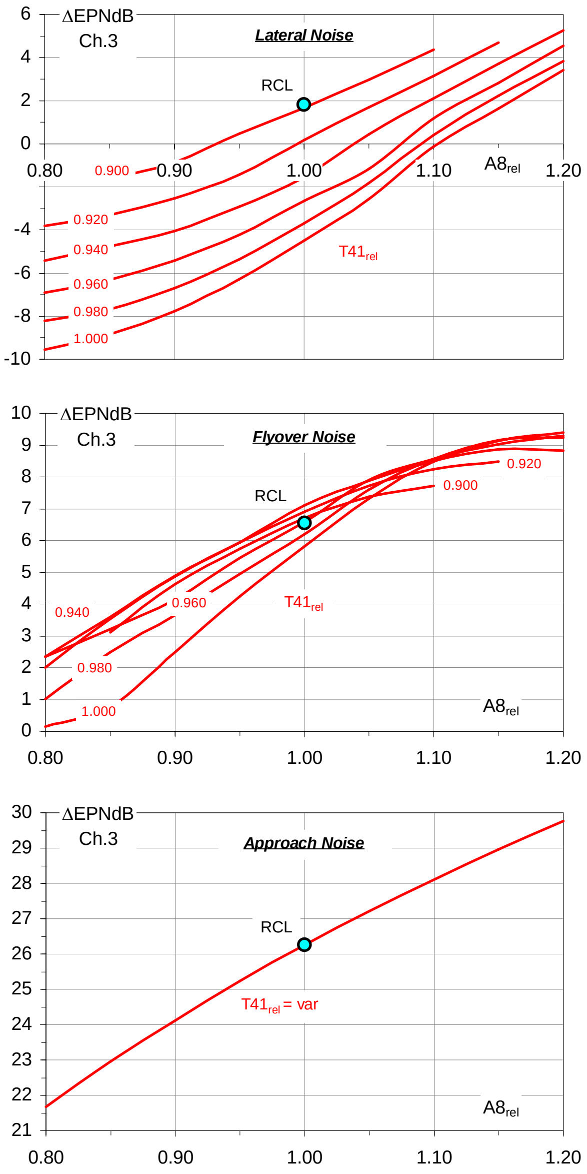

**Fig. 3.** Dependence of jet noise from engine control parameters

The combination of control parameters results in maximum lateral noise due to maximum jet velocity. It can be also seen on the plot that use of optimal CL can allow reducing of FL by ~130 m (6…7%) with the same lateral noise or reducing lateral noise up to ~3 EPNdB with reference initial FL equal to 2000 m.

Similar situation can be seen on analogous plot for the flyover noise (Fig. 5). In spite of the fact that FL in this case has only indirect influence on perceived flyover noise level, noise advantage for this reference point (r.p.) can also reach up to ~3.0 EPNdB.

It should be noted that maximum advantage of lateral and flyover noise of Pareto sets can not be received simultaneously at fixed FL.

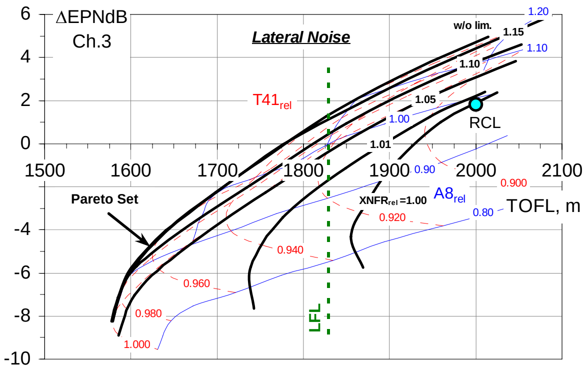

**Fig. 4.** Dependence of lateral noise from required FL and engine control parameters

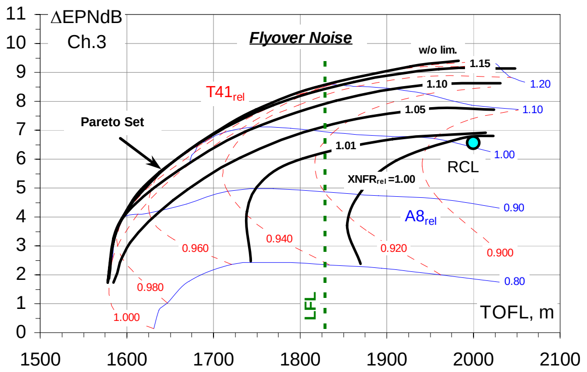

**Fig. 5.** Dependence of flyover noise from required FL and engine control parameters

However, the points for CL providing minimum lateral noise are also near the Pareto set for flyover noise and has maximum of noise levels in comparison with the basic CL point.

## 3.2 Second Stage

The influence of engine and A/C limitations as well as a new and more complicated throttle law (TL2) at initial climb was examined at the second stage of the study. Parameters such as maximal of turbine rotor temperature ($T41_{max}$), relative corrected fan ($XNFR_{rel}$) and compressor ($XNHR_{rel}$) speeds were considered as engine limitations. Curve $T41_{rel}$=1.0=const corresponds with maximal $T41_{rel.max}$ (Fig. 4 and 5). The landing FL (LFL) 1830 m was considered as an A/C limitation.

If maximum $XNFR_{rel}$ were considered equal 1.0 ($XNFR_{rel}$=1.0) for RCL then obtained with respect to limitations at $XNFR_{rel}$ Pareto sets can be plotted on areas considered (Fig. 4 and 5). This was based on the fact that $XNFR_{rel}$ are the dominant limitations (in relation to $XNHR_{rel}$).

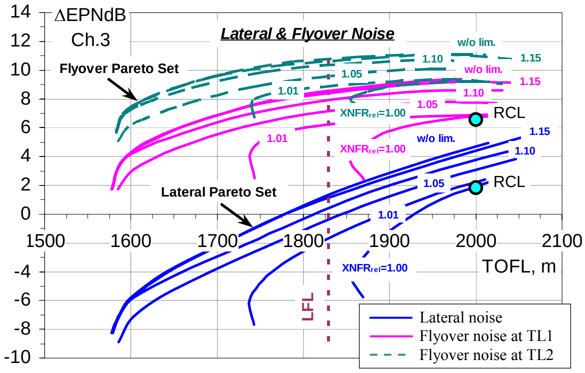

**Fig. 6.** Influence of limitations on noise in calculated areas of possible decisions

The study of a more complicated throttle law TL2: $(T_{min})+(V8=V8_{min})$ ($V8_{min}$ – minimal V8), which is characterized by a combination of T41=var and $A8=A8_{V8=V8min}$ ($A8_{V8=V8min}$ – A8 at $V8_{min}$), allows extra improvement flyover noise by 1.5…2.5 EPNdB.

The influence of considered limitations in calculated areas of possible decisions for two TL is shown on Fig. 6. It can bee seen that the best solutions are in area with $XNFR_{rel}>1.0$ for lateral and flyover r.p. and for FL more 1830 m.

The result can be explained by Fig. 7, which shows a “cross-section” of possible solutions area at minimum requirements to FL (TOFL=2000 m). The Figure shows influence of A8 on a change of engine parameters related to parameters of reference CL. Values of parameters relative jet velocity $V8_{rel}$, corrected air flow $W1AR_{rel}$ and $T41_{rel}$ characterizing flyover noise are correspond to point of the trajectories above flyover r.p.
Limitations values $XNFR_{rel}$, $XNHR_{rel}$ correspond to throttle starting point on $H_{in.thr}$. TL2 provides $V8_{min}$ by greater $W1AR_{rel}$ (dashed line).

Figure 8 shows dependence of noise related to noise of reference CL from $A8_{rel}$ for considered CL at TOFL=2000 m. Minimum jet velocity in this case provides the lowest lateral noise. This means that search of an optimal CL at fixed FL should be defined with condition of minimal lateral noise as the most complicated case in term of noise requirements satisfaction. It can be seen that reduction of jet velocity and lateral noise to minimal value (at $A8_{rel}$=1.17) is accompanied by increasing of $XNFR_{rel}$ up

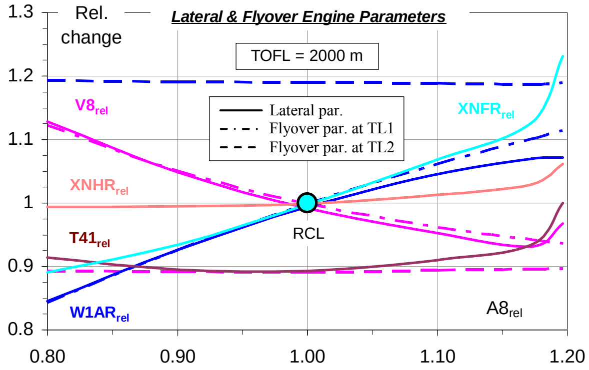

**Fig. 7.** Dependence of engine parameters related to parameters of reference CL from A8 at fixed FL

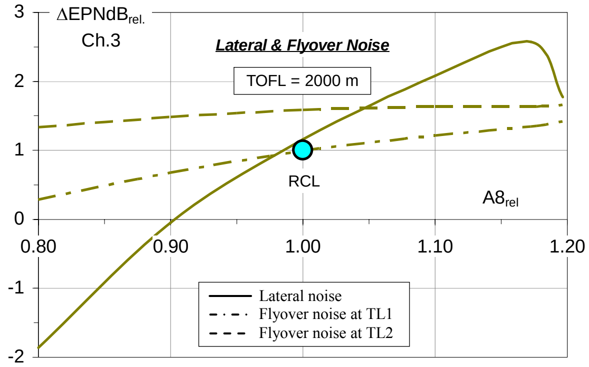

**Fig. 8.** Dependence of jet noise related to noise of reference CL from A8 at fixed FL

~12…13% (see Fig. 7). It should be taken into account on the stage of defining engine parameters and the CL. A jet velocity minimum in this range $A8_{rel}$=1.15…1.2 is connected with features of fan characteristic, as well as with choice of design engine regime.

Influence of $V8_{rel}$ on lateral and flyover noise is shown in Fig. 9. As it was expected, the noise change is in direct proportion to V8 in point above of the lateral and flyover r.p. for TL1 (at A8=const). Using of such CL can allow significant decreasing of noise level in both r.p. by ~7…8 EPNdB in comparison relative to

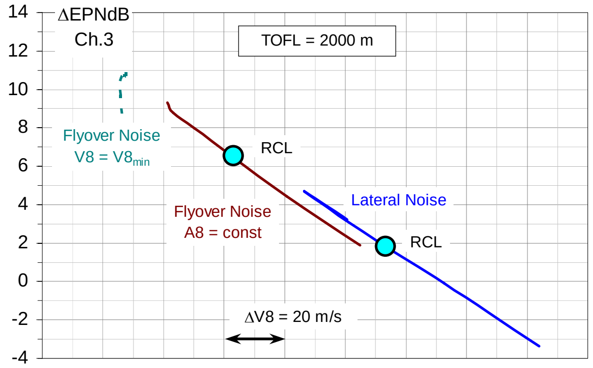

**Fig. 9.** Dependence of noise from V8 and different LC

using RCL. A more complicated TL2 (at $V8=V8_{min}$) provides almost constant minimal jet velocity and extra flyover noise reduction by ~2 EPNdB. It allows making a conclusion that a minimum throttle regime with minimal V8 provides minimal possible flyover noise. It can be seen in the plot also advantages of noise reduction be expected at using of optimal TL2.

### 3.3 Third Stage

Figure 10 shows influence of $H_{in.thr}$ on a change of engine parameters ($V8_{rel}$, $W1AR_{rel}$) and flyover noise ($\Delta EPNdB_{rel}$ Ch.3) related to parameters of reference CL. Slight change of main noise parameters $V8_{rel}$ and $W1AR_{rel}$ at change $H_{in.thr}$ from 300 to ~800 m leads to change flyover noise up to ~1…1.5 EPNdB. It means that flyover noise has low sensitivity to change of $H_{in.thr}$ in range specified above. It should be noted that the altitude of ~800 m approximately corresponds the end of compensation area of flyover noise connected simultaneous change of throttling and $H_{in.thr}$.

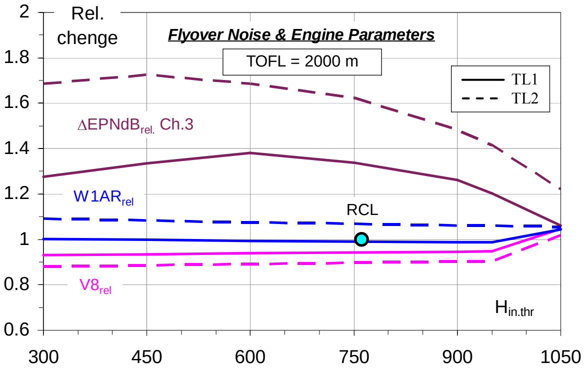

**Fig. 10.** Dependence of flyover noise from initial altitude of throttling and different LC

This allows making a conclusion on optimality TL2 (at $V8=V8_{min}$) with other conditions being equal. More than that, a quite flat maximum of noise curve for this law is shifted to lower $H_{in.thr}$. It has a positive effect on operating noise since early throttle (at $H_{in.thr}$=300 m) will reduce lateral noise and improve the noise in the airport area. Noise insensitivity to the $H_{in.thr}$ allows defining also its optimal value, from the noise minimization of other sources (e.g. a fan).

Based on the results, an approach to optimal engine CL will be available in terms of meeting requirements on FL and minimum noise levels in the r.p. for a specified A/C and an engine.

1. An optimal CL at specified requirements to the FL should be developed on the basis of a requirement of minimal lateral noise as the most complicated requirement to be satisfied.

2. A minimal throttle regime with maintaining of minimum values of parameters which define engine noise (jet velocity and/or fan speed) provides the minimum possible flyover noise. This condition defines an optimal TL.

3. The $H_{in.thr}$ should be chosen taking into accounts requirements on noise minimization in the flyover r.p. or on noise contour reduction in an area where it should be reduced as much as possible.

The described above approach is reasonable to apply at a conceptual design stage not only for supersonic but also for subsonic A/C that have fan noise as the main noise source.

## 4 Conclusion

1. Simplest CL (T41=const)+(A8=const) and ($T_{min}$)+(A8=const) examined in this study effect significantly on FL and noise in the r.p.

2. Change of T41 and A8 in a wide range will requires sufficient reserves of project parameter for engine elements providing their physical structure at engine's maximum regimes.

3. In contrast to the RCL ($XNFR_{rel}$=const=1.0, $A8_{rel}$=const=1.0), optimal CL can reduce the FL by 6…7% or reduce noise in the lateral r.p. by 2.5…3.5 EPNdB.

4. Noise advantage for the flyover r.p. can make up to ~3.0 EPNdB at TL1 ($T_{min}$)+(A8=const). A more complicated TL2 ($T_{min}$)+($V8=V8_{min}$) allows improving this advantage in this r.p. by ~2.0 EPNdB.

5. The flyover noise at considered TL has low sensitivity to changes of $H_{in.thr}$. The altitude variation from 300 to ~800 m results to noise change up to ~1…1.5 EPNdB.

6. Three basic principles of optimal engine CL were developed in the context of meeting the A/C requirements and minimum possible noise for the specified A/C and engine.

7. Optimal CL for any A/C configuration should be chosen from minimum engine size conditions to satisfy FL performance and noise requirements. That allows best matching the A/C and the engine characteristics. The choice of efficient CL is necessary to carry out at the stage of the A/C and engine conceptual design taking into account of all noise sources (engine and A/C elements).

8. It is resalable to continue the study of more complicated CL application for perspective supersonic and subsonic A/C engine with a variable A8. It will allow making up more effective engine CL as well as improve efficiency of matching the engine and the A/C parameters.

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