NOISE SAVING POTENTIAL OF FUTURE APPROACH AND DEPARTURE PROCEDURES

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Abstract

Noise Abatement Procedures (NAPs) for departure and approach have already been designed in the past. Lower engine and higher airframe noise levels and additional possibilities for aircraft guidance and control lead to the fact that existing noise abatement procedures do not exploit the full noise reduction potential.

Prerequisite for any new flight procedure design is to maintain safety standards, like airline standard operating procedures (SOPs), and economical items, e.g. fuel flow, flight time and engine stress. Due to the need for short term solutions, extensive hard- and software changes of onboard and ground equipment should be avoided, since typical legal certifications would prolongate the entry into service of such procedures.

Tradeoffs have to be made to satisfy these oppositional requirements. New departure procedures with equal or higher noise saving potential like existing procedures (e.g. ICAO-A) but reduced flight time and less fuel consumption have been found.

The achievement of noise reduction during the approach is more complicated than in the departure phase. Airframe noise may be dominant, if engines are operated near idle thrust. The main measures on flight procedures for noise reduction are increased height, decreased thrust and delayed configuration change. A continuous descent approach combined with a steep ILS-segment can reduce the maximum noise level of about 3 dB(A) over the full approach phase, compared to a present standard ILS Low Drag Low Power Procedure.

Symbols

C_L	lift coefficient
C_D	drag coefficient
D	drag
$F_{\max}$	maximum thrust
$F_{req.}$	required thrust
F_{idle}	idle thrust
G	weight
g	gravity constant
$\dot{H}$	vertical speed
V	true airspeed
$\dot{V}$	acceleration
V_X	airspeed for best climb angle
V_Y	airspeed for best rate of climb
W	weight
g	flight path angle

Abbreviations

AGL	Above Ground Level
ATA	Air Transport Association
CDA	Continuous Descent Approach
DLH	Lufthansa German Airline
DLR	German Aerospace Center
DOC	Direct Operating Costs
FAA	Federal Aviation Administration
FMS	Flight Management System
ft	feet (= 0,3048 m)
IAH	Intermediate Acceleration Height
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
INM	Integrated Noise Model
kts	knots (= 0,5144 ms^{-1})
$L_{A,MAX}$	Max. A-weighted sound level

L_{AE} , SEL	A-weighted Sound Exposure Level
LDLP	Low Drag Low Power Approach
MONA	Modern Noise Abatement Procedure
nm	nautical mile (= 1852 m)
PANS-OPS	Procedures for Air Navigation Services – Aircraft Operations
SOP	Standard Operating Procedures

1 Low Noise Departure Procedures

1.1 Boundary conditions

The request for a rapid development of improved low noise departure procedures results from the high requirements for the approval of hard and software components for aviation applications. In addition operating time of today's airliners amount up to 30 years and more, hence improvements could become effective on a broad basis in decades. These boundary conditions require flight procedures, which get along with the today's equipment conditions. Such procedures can be regarded as real short term alternatives to current procedures and be used within relatively short time (order of magnitude 5 years from today on).

1.1.1 Safety

During take off and initial departure the engines operate with maximum thrust which is in opposition to the approach phase. Long continuous flight phases under full thrust/weight ratio stress the individual components of the engines substantially, reduce their life span and, particularly safety-relevant, increase the risk of an engine loss in flight. Therefore take off procedures with reduced take off thrust and/or shortly reduction to climb thrust should be examined particularly.

Take off and climb are flight phases, in which 24% of all accidents (take off 11%, initial climb 5%, climb with flaps up 8%) of commercial jet airliners occur [1]. Likewise 67% of all total losses are attributed to the cockpit crew as primary source of error. Therefore new procedures may not increase the work load at all.

Airline Standard Operating Procedures (SOP's) were developed, in order to ensure a reduction of the work load (crew coordination concept), standardization of the operational procedures and improvement of communication in the cockpit (crew resource management). The consideration of these sensitive factors should be also guaranteed by future departure procedures.

1.1.2 Air traffic control

In order to avoid additional stress related to the air traffic conditions at large airports particularly for the operations during day time it is important that new procedures promote the flow of air traffic and generate no further bottlenecks, in order not to further limit the possible number of flight movements per hour per airport.

Procedures with high time need, due to reduced airspeeds should be examined and optimized therefore a priori only for possible operations during night time. The day flying operation requires a suitable compromise between noise saving and preservation of the traffic capacities.

1.1.3 Economic feasibility

During the design of modern noise-reducing departure procedures some constraints should be regarded, in order to make an economic operation possible and to exercise no further rising costs on the airlines.

The costs of fuel at large airlines amount between 18% and 26% of the direct operating cost (DOC's) or related to the annual sales profit e.g. at Lufthansa in the year 2001 approx. 9,7% [2]. A reduction of the fuel consumption during the departure would be from economic view as well as from ecological view desirably, in order to improve the pollutant emission balance further.

Apart from the safety aspects already mentioned before, reduced takeoff thrust and full thrust only during short flight segments is also economically desirable, since this increases the lifespan and allows longer maintenance rates.

1.1.4 Air traffic regulations

Within the recently amended ICAO PANS OPS [3] the boundary conditions concerning the interpretation and execution of low-noise departure procedures are described in detail. In relation to earlier regulations, which provided two exactly defined departure procedures, the new guidelines enable a more flexible design which is only limited by the following safety demands:

- the minimum possible flight altitude for thrust reduction to climb thrust is 800 ft above ground

- the thrust level after reduction may not be smaller, than that level, which is necessary to achieve the minimum climb rate demanded in the certification regulations in case of an engine failure

- it is expected from the airlines that they commit themselves to only one low-noise departure procedure in addition to their standard operation departure procedure.

1.2 Flight mechanics basics

In order to optimize the departure procedure, firstly the main parameters which influence the climbing flight should be regarded. Drag and lift equation of motion together provide the correlation between flight path angle, thrust, drag and acceleration (Eq. 1); maximum thrust without acceleration leads to maximum climb angle. The vertical speed results from the product of flight path angle and airspeed (Eq. 2) [4].

$$(1) \quad \sin(g) = \frac{F_{max} - D}{W} - \frac{\dot{V}}{g}$$

$$(2) \quad \dot{H} = V \sin(g)$$

Fig. 1 shows the achievable rate of climb (vertical speed) as a function of airspeed. The maximum of the curve indicates the maximum of the rate of climb using the airspeed V_Y. The tangent gives the maximum climb angle using the airspeed V_X.

While at V_Y -speed the aircraft operates time and fuel-saving and therefore economical. At V_X -speed the distance to the ground becomes larger, lowering the noise impact and making the departure more ecological.

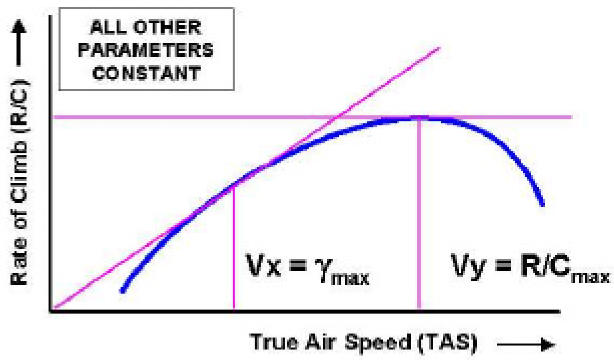

Fig. 1 Rate of climb due to true airspeed

1.3 Optimization approach

Both speeds vary during take-off and climb due to current thrust setting and configurations. Fig. 2 shows height, thrust and speed from the ICAO-A and Modified ATA departure procedure. In addition V_Y and V_X are displayed. Obviously the aircraft cannot follow the optimal speeds because there are steps due to thrust and configuration changes.

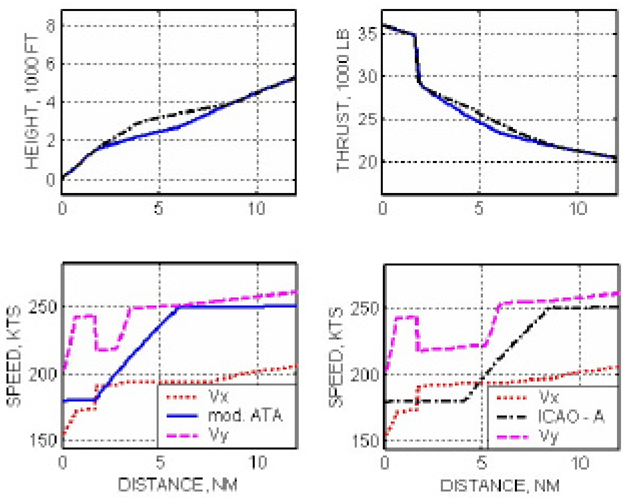

Fig. 2 Analysis of departure procedures in terms of V_Y and V_X

The optimization process has to make a compromise between an ecological departure (operate a long time nearby V_X) and an economic departure (fast come up to V_Y). Safety demands as well as air traffic regulations and standard operation procedures have to be taken into account. The pilot workload should not increase.

1.4 Results

Noise calculations using the Integrated Noise Model (INM), developed by the FAA, as well as the SIMUL software, developed by DLR, shows the dominance of engine noise compared to airframe noise. By reason of negligible airframe noise two parameter influence the noise immission on ground mainly during the departure phase:

- the thrust level
- the height of the aircraft

Long climb segments with constant speed of approximate V_X and late acceleration hold a large noise reduction potential but lead to extended flight time and more fuel consumption.

To meet the boundary conditions based on capacity and economy the acceleration phase from initial climb speed (V_2+10 kts, near V_X) to final climb speed (near V_Y) should start as fast as possible. However, air traffic regulations forbid speeds greater than 250 kts below flight level 100 (approx. 3000 m).

A new noise abatement departure procedure should be operational within short time and therefore feasible by manual flight as well as by automatic flight using today's controller functionality. So the acceleration target will result indirectly from a required vertical speed / rate of climb.

The **MO**dern **N**oise **A**batement Departure Procedure (MONA) is characterized by an intermediate acceleration phase of reduced rate of climb, which is connected directly to the first climb segment of constant speed and take-off thrust. By reaching the intermediate acceleration height (IAH) the rate of climb will be reduced further in order to obtain the higher acceleration values of MOD-ATA or ICAO-A -Procedure.

Fig. 3 shows height and speed over the distance from take-off point by all three departure procedures. Furthermore the differences of the maximum A-weighted sound level ($\Delta L_{A,MAX}$) and the A-weighted sound exposure level (ΔSEL) related to the MOD-ATA – Procedure are shown. Fig. 4 illustrates the effect of an extended intermediate acceleration phase which ends at 5000 ft height.

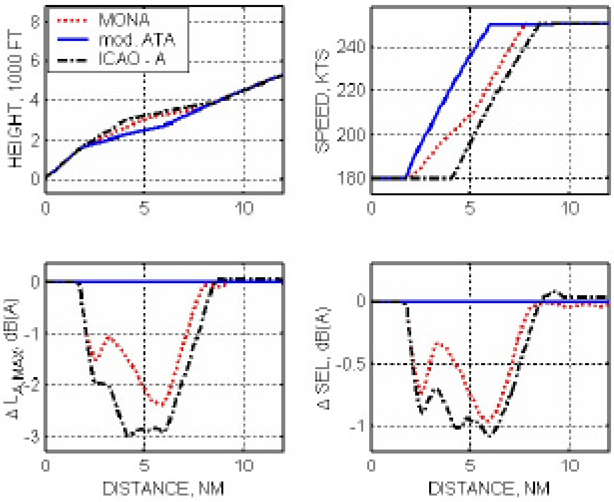

Fig. 3 Comparison of MONA- (3000 ft Intermediate Acceleration Height), MOD-ATA- and ICAO-A- Procedure

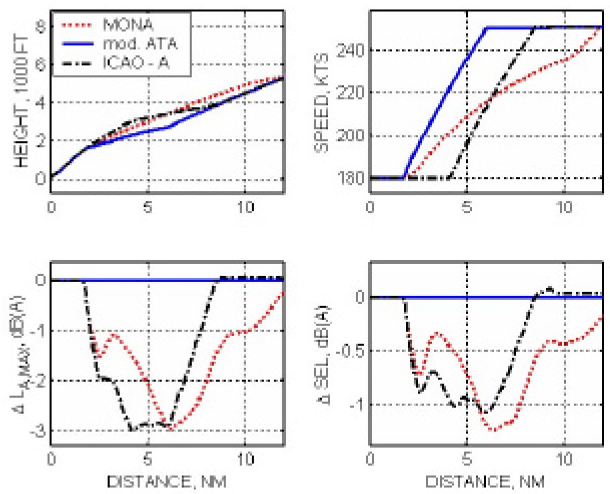

Fig. 4 Comparison of MONA- (5000 ft Intermediate Acceleration Height), MOD-ATA- and ICAO-A- Procedure

The implementation of an intermediate acceleration phase induces the following advantages:

- In the range of 4 until 15 km (2 – 8 nm) after take-off point the distance between noise source and observer related to the MOD-ATA –Procedure is higher and therefore the noise immissions are lower.

- An acceleration phase which takes place earlier than by ICAO-A –Procedure reduces fuel consumption and flight time.
- A noticeable increase of pilot workload does not occur because only an additional height has to be regarded to finish the intermediate acceleration phase and to start the final acceleration. The procedure can be proceed in a manual manner and half automatically using the vertical speed mode by timely selection the appropriate rate of climb.
- Related to specific airport requirements it is possible to select a specific intermediate acceleration height in order to avoid noise impact nearby the airport or far away, as desired.
- An increase of the power reduction height results in additional noise reduction.

Fig. 5 shows the additional fuel consumption of MONA –Procedure (magenta squares) and ICAO-A -Procedure (magenta line) related to the MOD-ATA –Procedure.

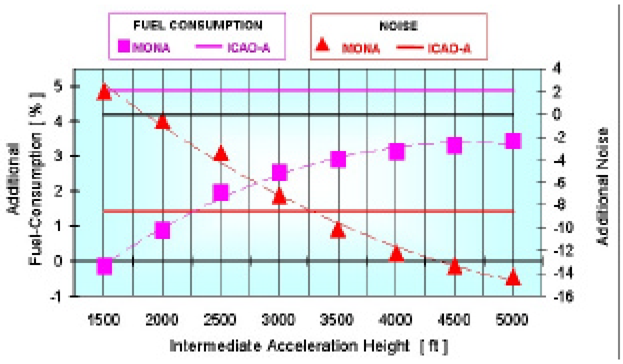

Fig. 5 Noise immission and fuel consumption up to 6000 ft height and 250 kts speed related to the MOD-ATA -Procedure

If the intermediate acceleration height is increased the additional fuel consumption of MONA increases likewise but does not reach the value of ICAO-A. Moreover a value to describe the benefits of the MONA procedure is the additional noise relief (red triangle) obtained by increasing the IAH. (This noise relief value is calculated by the integral of the noise-delta, reference to the MOD-ATA procedure over the length of the departure [dB*m*10^{-3}]). At approx. 3500 ft the additional noise achieves the constant value from ICAO-A (red line). That means MONA is obtaining similar noise savings, while the additional fuel consumption amounts approx. 50%. Coming up to larger IAHs MONA leads to even more noise relief, but does not reach the additional fuel consumption of ICAO-A.

The **S**tudy of **O**ptimization procedURes for **D**ecreasing the **I**mpact of **N**ois**E** around airports (SOURDINE) [5], Fourth European Framework Program, suggest reducing the thrust except for the required minimum climb gradients and then increasing it stepwise. Today's Flight Control Systems (FCS) are not able to perform such a procedure and there is no possibility to select the appropriate values using the Flight Management System (FMS). Therefore only the pilots could try to perform this manually but that would increase the cockpit workload in the critical take of and climb flight phase. May be future FCS will be able to cope with such procedures.

2 Low Noise Approach Procedures

2.1 Boundary conditions

Alternative low noise solutions for the current approach procedures should be realizable within short term. This means that no upgrading of onboard and ground systems shall be required. Though complete usage of the available FMS and FCS performance, including all current modes will be mandatory.

2.1.1 Safety

The approach phase is characterized by reaching the runway threshold with the target speed acquired, while maintaining a safe flight state during the whole approach. Starting from the cruise flight at high altitudes, potential as well as kinetic energy has to be reduced.

The approach and landing phase contains 59% of all commercial jet aircrafts accidents (initial approach 5%, final 7%, landing 47%) according to [1]. Particular during the configuration phase, the approach to the ground, the flare and the deceleration the workload of the crew is very high. Additional work load due to modified procedures shall be avoided.

2.1.2 Air traffic control

To operate an airport at its full capacity the aircraft's arrival time have to be determined as accurately as possible. If new approach procedures do not allow a precise arrival time prediction the separations have to be increased due to safety reasons and therefore airport capacity decreases. That would never be accepted by airport authorities, airlines and ATC, due to economic reasons. Therefore only night- or off-peak time operations would be feasible for such procedures.

2.1.3 Economic feasibility

The economic feasibility of noise abatement approach procedures, compared to departure procedures, is of secondary interest. Generally noise abatement approach procedures will help to reduce fuel consumption.

2.1.4 Air traffic regulations

The ICAO PANS-OPS [3] provides information about the constraints for design and implementation of noise abatement approach procedures. Accordingly the aircraft has to take the final configuration at outer marker position but latest at 5 nm from threshold. Extreme sink rates should not appear during the complete approach phase. If the design of procedures is based on currently available systems and equipment (year 1982) then it is not possible to require flight path angles more than standard 3° ILS glide path angle for the final approach part. However, if an implementation of new systems and equipment allows the realization of noticeable differing approaches, the procedures may and should redesigned.

Furthermore, noise abatement procedures are not permitted, if the runway is not clean and dry, the ceiling is up to 500 ft, the sight is lower than 1 nm, the crosswind component including gusts amounts to more than 15 kts, the tail wind component including gusts is greater than 5 kts and if wind shear during final approach is anticipated.

2.2 Flight mechanics basics

The flight mechanics basics for the approach flight phase can be derived from the drag and lift equation of motion. Assuming that lift is equal to weight, equation (3) provides the flight path angle and/or the aircraft's acceleration due to a given thrust, in this case idle to perform e.g. a descend. If the flight path angle and/or the aircraft acceleration is given, i.e. during flight on glide path, a specific thrust is required (Eq. 4).

$$(3) \qquad \sin(g) + \frac{\dot{V}}{g} = \frac{F_{idle}}{W} - \frac{C_D}{C_L}$$

$$(4) \qquad \frac{F_{req}}{W} = \frac{C_D}{C_L} + \sin(g) + \frac{\dot{V}}{g}$$

Similar to the departure the approach contains several flight phases or segments. At the top of descend the thrust level will be reduced up or near to flight idle and the aircraft passes into descend. During this phase the aircraft's behavior is like a glider plane. By constant speed and idle thrust, the drag to lift ratio C_D / C_L is greater than the thrust to weight ratio F_{idle} / W. Therefore, the flight path angle becomes negative (Fig 6). Deceleration at the same time would lift the flight path angle.

At the intermediate approach altitude the aircraft changes into horizontal flight ($g = 0$) and if no (further) deceleration should be performed, an increase of thrust will be necessary (Eq. 4). After further speed reduction, the approach flap setting can be obtained. The length of this segment is mainly affected by air traffic control. Therefore, the end of the deceleration phase in daily practice is not identical with the glide path intercept point. This requires the thrust to be increased to maintain constant speed and altitude (Fig 6).

After the intercept of the glide path, before the outer marker is passed, the landing gear shall be extended and the landing flap setting chosen. To perform a safe final approach and landing, the aircraft has to be stabilized at 1000 ft AGL, according to airline standard operating procedures. Safe state of flight means constant speed (Final Approach Target Speed), on glide path and final configuration established.

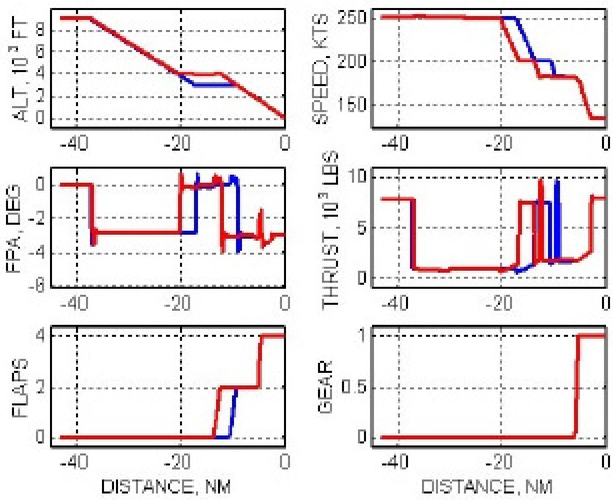

Fig. 6 Low Drag Low Power Approaches using different intermediate approach altitudes

The described preceding procedure is already noise reduced and called "**L**ow **D**rag **L**ow **P**ower Approach (LDLP)". It was established during the seventies by Lufthansa German Airlines at Frankfurt Airport, and is therefore often referred to as "Frankfurt Procedure". Gear and final flap extension on glide path, just before outer marker result in low drag, leading to low thrust levels as well as low noise levels for major parts of the approach. Fig. 7 shows the maximum sound level and the single event sound exposure level of two LDLP-Approaches with different intermediate approach altitudes.

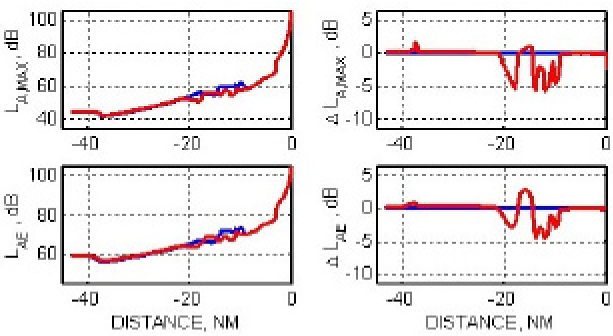

Fig. 7 Noise metrics of LDLP-Approaches with different intermediate approach altitudes (3000 ft and 4000 ft)

An increase of the intermediate approach altitude results in a local noise relief up to -5 dB, compared to a baseline procedure using a typical value of 3000 ft above ground level, for the level flight segment.

2.3 Optimization approach

The noise immission on the ground, directly below the flight path, depends mainly on the distance to observers and the aircraft's noise emission. Airframe noise emissions of today's aircraft may be greater than noise created by engines emissions, especially if the engines are operate near flight idle thrust. Lower noise levels during approach can be achieved by higher flight path altitudes and preferable idle thrust during the whole approach phase. Configuration changes shall be performed as late as possible at the minimum allowed speed for the respective configuration.

2.4 Results

Lifting the vertical flight path in the close surroundings of the airport can only be achieved by steeper descends using increased glide path angles, which can span over the whole ILS-approach range (STEEP APPROACH) [6] or only over an intermediate segment (TWO SEGMENT APPROACH). Fig. 8 shows schematically vertical flight profiles of different approach procedures.

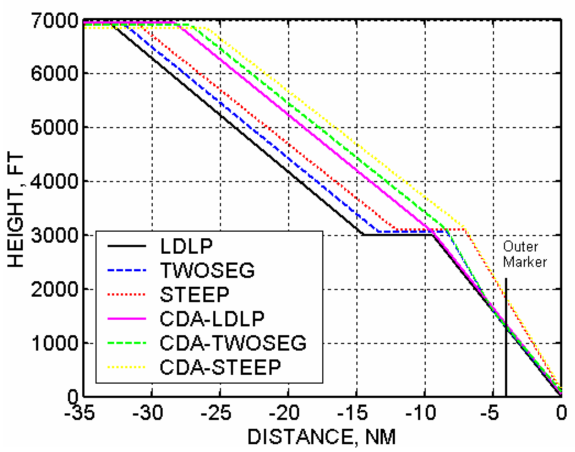

Fig. 8 Vertical flight profiles of different approach procedures

On constant speed conditions with the engine in flight idle conditions the flight path angle is limited by the aircraft's aerodynamic quality (max. C_D / C_L, Eq. 3). Flight path angles below -5° are for the most part stationary not reachable by modern aircrafts due to their excellent aerodynamic performance.

On the other hand airports are not able and not allowed by law to increase the ILS glide path up to 5° or more, without losing their CAT II and CAT III certification. Additionally an intermediate approach segment, using a steeper glide path for a two segment approach, is as well not realizable within near future. Furthermore, pilots do not like steep approaches continuous until the ground and often refer to such procedural suggestions as "controlled crashes". Only the implementation of extended pilot-assisting systems and further training might help to revise this opinion.

Regarding the far field around the airports, the intermediate approach altitude can be lifted and thus enlarge the distance to the noise source. Though the need for increased thrust during this flight phase continues to exist. Hence it makes more sense to waive the intermediate approach altitude and perform a continuous descent including a smooth transition to the ILS glide path. This procedure is called "Continuous Descent Approach (CDA)" (see Fig. 8). One disadvantage of the CDA is the inaccuracy to determine the exact arrival time by air-traffic control. Therefore higher separation minima are to be used. To avoid negative influences on the airport's capacity CDA-procedures are usually only in use during times with low traffic volume, e.g. during night time.

The combination of a CDA and a -4° STEEP APPROACH meets the described optimization approach in a favorable way. The flight path is always higher compared to LDLP-Approaches and the thrust levels mostly lower. Indeed the landing flaps and gear extension take place earlier, in order to be able to perform the steep ILS segment the landing flaps and gear extension take place earlier (Fig. 9).

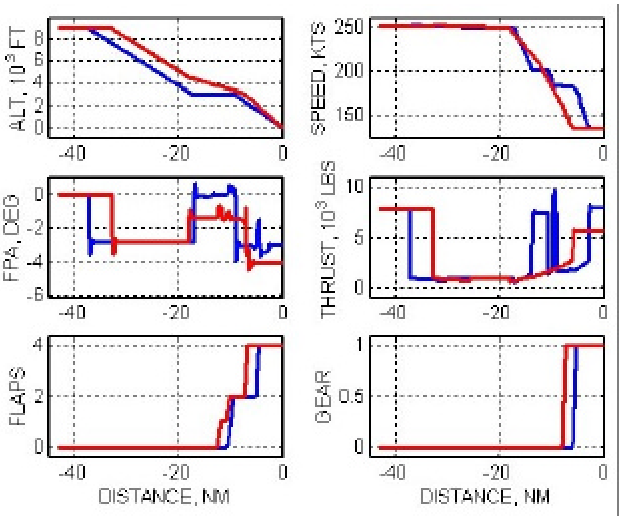

Fig. 9 Combination of CDA- and STEEP-Approach (red line) procedures compared to LDLP- Approach (blue line)

Compared to the LDLP-Approach the combined CDA / STEEP-Approach results in average noise reductions of about 5 dB at a distance between 10 and 20 nm to the runway threshold (Fig. 10). A similar value is reached nearby the airport.

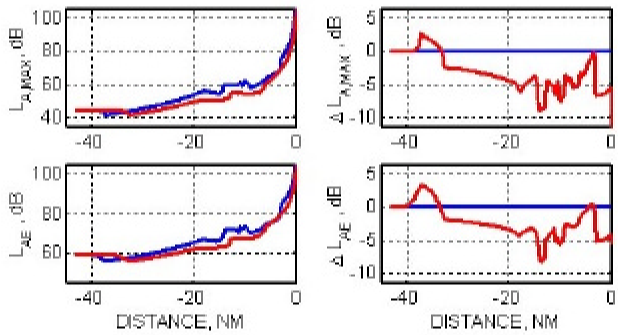

Fig. 10 Noise metrics of a combined CDA / STEEP-Approach procedure (red line) compared to a LDLP (blue line)

As previously explained, steep ILS-Approaches are no feasible short-term solutions for NAPs. The same can be stated concerning steeper intermediate ILS-Segments which would require an additional glide path transmitter. But it is possible to control the aircraft via selected flight path angle (FPA control mode) and than intercept the glide path from above. Fig. 11 shows this kind of noise abatement approach procedure, which could be named **S**egmented **C**ontinuous **D**escent **A**pproach (SCDA). Glide path intercept happens at 2000 ft AGL and the aircraft is stabilized at 1000 ft, according to airline SOPs.

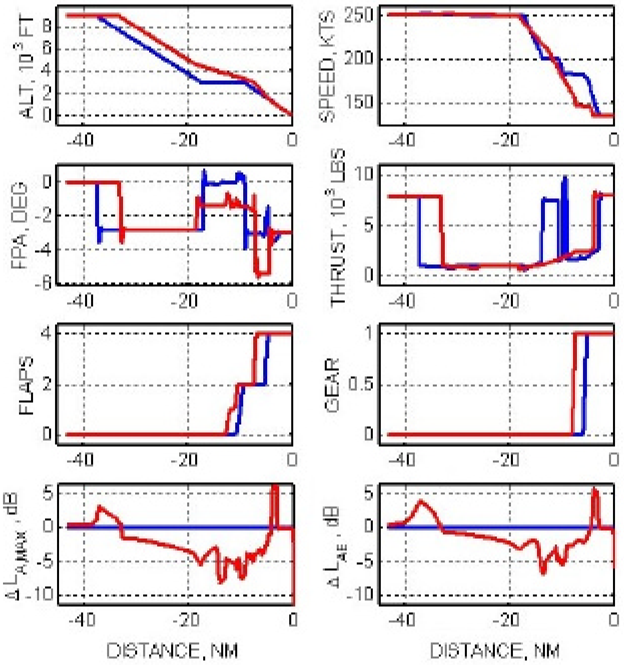

Fig. 11 Segmented Continuous Descent Approach (SCDA) procedure (red line) compared to a LDLP (blue line)

Consequentially, there is no noise reduction compared to the LDLP-Approach nearby the airport within approx. 6 nm distance. Nevertheless this SCDA-Procedure is feasible with today's onboard and ground equipment.

The SCDA-Procedure was flight tested using the Advanced Technologies Testing Aircraft System (ATTAS) (Fig. 12) operated by German Aerospace Center (DLR) at Braunschweig research airport.

Fig. 12 ATTAS aircraft

The standard ILS instrument approach procedure at Braunschweig airport (EDVE) has some local peculiarities e.g. a 3.5° glide path angle instead of a common 3° ILS glide slope and a lowered intermediate approach altitude of only 2500 ft MSL (2200 ft AGL) compared to usual values of 3000 ft AGL or even higher. Fig. 13 shows the flight test demonstration results from a LDLP-Reference-Approach followed by two SCDA-Procedures. The required tops of descent for the SCDAs were pre-estimated by using standard aviation weather forecast including wind speeds and wind directions at different flight levels. All boundary conditions as specified before were met. Single–spot noise measurements, underneath the flight path were conducted at a distance of 8 nm to the runway threshold. Noise relief of up to -8 dB $L_{A,max}$ was metered.

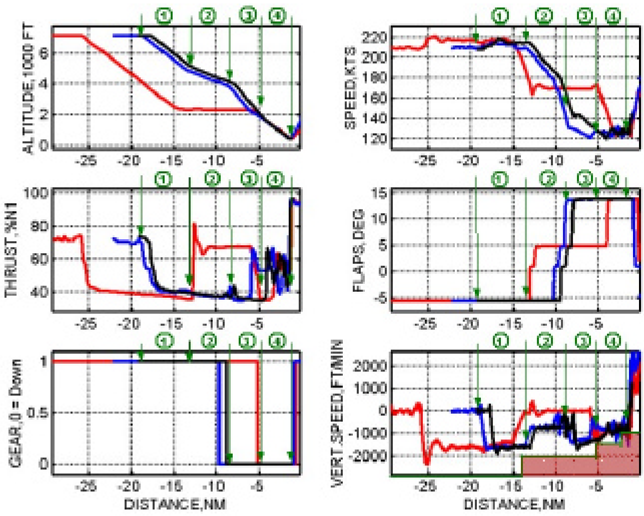

Fig. 13 Flight test results containing one LDLP-Approach (red line) and two SCDA-Procedure (blue and black line)

3 Outlook

A prerequisite for the design of future noise abatement procedures were short-term solutions, without the need to modify the equipment on board the aircraft or on the ground. Furthermore, the standard operation procedures from airlines and air traffic regulations, e.g. from the ICAO have to be met. Extended functionality of the Flight Management System (FMS) and the Flight Control System (FCS) would flatten the way to perform more complex three dimensional trajectories.

A medium-term objective could be the intercept of the glide path from above at a lower height than 2000 ft AGL and to reduce the stabilization height. The FCS has to fulfill requirements derived herein. Today's FMS calculate the aircraft's trajectory and speed schedule without taking into account the wind speed and configuration changes. Future FMS should be able to perform complete specific noise abatement procedures in a managed, fully automatic mode. It is also thinkable that future FMS might directly manage the timing for the extension of the required flap setting and the landing gear. This would reduce the pilot workload during the critical approach phase and therefore might help to increase flight safety.

Another large potential comes from the modeling and prediction of noise immissions. Influences from the atmosphere like wind speed and direction, temperature, air humidity etc. may affect the noise dispersion noticeably. If the FMS could take these effects into account within real time and perform therewith an optimized trajectory, further noise relief can be expected.

4 Conclusions

It has been shown that noise relief around airports can achieved within short-term by applying enhanced noise abatement procedures. Besides the primary objective to reduce the noise levels observed on the ground, attention is turned to meet specific boundary conditions like safety, air traffic control, economical and ecological feasibility and air traffic regulations. By taking into account these objectives and requirements, the achieved results might be acceptable to all involved parties. Hence these procedures could be realized with relatively low effort within short period of time.

The objective of short-term realization requires special procedures which can be executed using today's equipment. The outlined procedures attempt to fulfill these boundary conditions. Furthermore, requirements for future onboard and ground future equipment were presented and an outlook on possible future procedures was given.

Concerning departure procedures, the implementation of an intermediate acceleration segment (MONA- Procedure) leads to significant noise level reductions compared to the MOD-ATA- Procedure, whereas time and fuel consumption do not increase in the same orders of magnitude as by ICAO-A. The MONA- Procedure can furthermore be adapted to local conditions and peak / off-peak operations using different intermediate acceleration heights. Measures like increasing the thrust reduction height additionally helps to reduce the noise impact at observers locations.

Regarding the approach procedures, a CDA combined with a STEEP-Approach provides maximum noise relief possible throughout the whole approach procedure. Since short-term implementation of such a combined procedure will not be possible by using today's equipment a passable way might be the described SCDA procedure, where glide path intercept occurs from above using an intercept-height, which enables an aircraft flight state stabilization before reaching 1000 ft AGL. This procedure does not provide the maximum possible noise reduction. Though it would be feasible after slight adaptions concerning specific FMS functionality (e.g. top of descent calculation by taking into account atmospheric disturbances like wind).

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