EVALUATION OF SIMULATOR AND FLIGHT TESTED NOISE ABATEMENT APPROACH PROCEDURES

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Abstract

Short and middle term solutions are necessary to address the problem of aircraft noise in the vicinity of airports. Several approach procedures leading to noise abatement were designed based on performance calculations and fast time simulations. Two of them, namely the Low-Drag-Low-Power (LDLP) as a reference and the Segmented Continuous Descent Approach (SCDA) with a glide path intercept from above were analyzed on Airbus A320 and A330 full flight simulators with 44 pilots, evaluating pilot workload. Via flight tests two further procedures, a Continuous Descent with a late gear extension (LCDA) and an optimized LDLP procedure with a steep final segment (SLDLP), are investigated on an Airbus A319 aircraft. Noise measurements on ground were performed at 25 locations inside the departure and approach areas. The investigations indicate that consequent practice of flight procedures such as continuous-descent and steep-final-approaches provide adequate noise abatement.

Symbols and Abbreviations

A	Area
CDA	Continuous Descent Approach
dBA	Decibel, A-weighted
DLH	Deutsche Lufthansa
DLR	German Aerospace Center
ECG	Electrocardiogram
EEG	Electroencephalogram
EOG	Electrooculogram
FAA	Federal Aviation Administration
FFS	Full Flight Simulator
GD	Gear down
INM	Integrated Noise Model
L_{Amax}	Maximum A-weighted sound pressure level
LAnAb	German project on noise optimized approach and departure flight procedures
LCDA	CDA with late gear extension
LDLP	Low-Drag-Low-Power
N1	Engine rotor speed
NAP	Noise Abatement Procedure
NASA	National Aeronautics and Space Administration
N_{AWR}	Number of awakening reactions
n_{FRG}	Average population density in Germany
OM	Outer Marker
P_{AWR}	Probability of awakening reactions
POD	Point of descend
RPM	Revolutions per minute
SCDA	Segmented CDA
SEL	Sound exposure level
SIMUL	DLR noise calculation tool
SLDLP	Steep LDLP
SOP	Standard Operation Procedures
TLX	Task load index
u_{Wg}	Horizontal wind speed component
V	True airspeed
ZFB	Zentrum fuer Flugsimulation Berlin
γ	Flight path angle

1 Introduction

The recent decrease of sound emissions from aircrafts' engines, airframe and gear has reduced the single event noise impact during landing approach considerably. But at the same time the number of movements increased, so that aircraft noise remains as a great problem for the people living in the vicinity of airports. A short- up to middle-term contribution to further noise reduction can be expected from new designed flight procedures.

Noise abatement flight procedures (NAPs) for departure and approach have already been designed in the past [1]. Lower engine and higher airframe noise levels and additional possibilities for aircraft guidance and control lead to the fact that existing procedures do not exploit the full noise reduction potential.

Prerequisite for any new flight procedure design is to consider safety standards, like airline standard operating procedures (SOPs), economical items, e.g. fuel consumption, flight time and engine stress, air traffic management and capacity issues and legal requirements. 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 opposite requirements. Steep approach procedures indeed reduce high noise levels but could increase the fuel consumption due to an increased flight time [2].

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 [3].

2 Noise Abatement Flight Procedure Design Process

The design process of noise abatement flight procedures generally contains five steps which are different in complexity and results [4]. The first four steps are loops using demands on noise reduction and operational feasibility as inputs. All loops include a noise calculation and an assessment of operational feasibility if possible and provide outputs into the next loop (Figure 1).

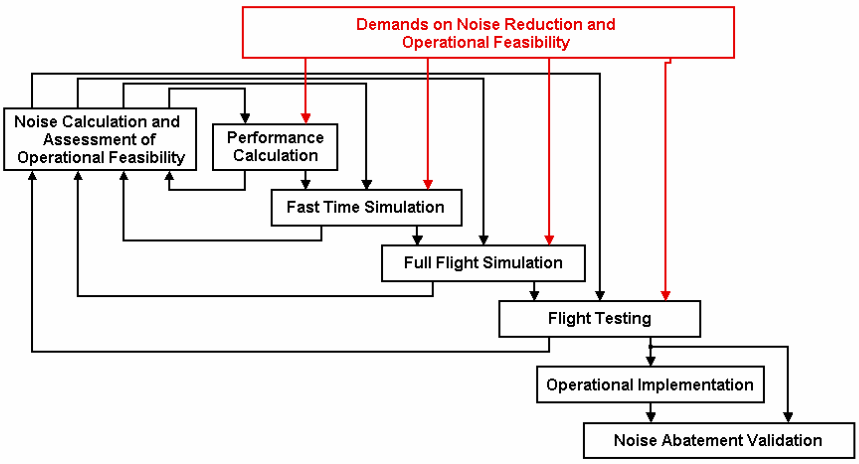

Fig. 1. Steps of the noise abatement procedure design process

The first loop is a basic performance calculation which identifies the aircraft's boundaries in terms of minimum flight path angles and/or maximum deceleration capability related to a specific configuration of slats/flaps and gear. Noise calculation and assessment of operational feasibility have less significance because only constant single segments of the flight path can be regarded. The next step is to set up a computer aided simulation which is faster than real-time (fast time simulation) in order to get the complete approach profile including the transition phase between the segments. In addition to a dynamic model of the aircraft, flight management and flight control algorithms are necessary to simulate the full flight path. Noise calculation can be carried out and compared to a reference procedure. But the results of feasibility and safety considerations strongly depend on the behavior of the implemented flight control laws.

Research into pilot acceptance and workload due to novel flight procedures presupposes full flight simulation which is also needed to prepare flight tests. Full flight simulation provides the performance of the total system containing the aircraft- and engine dynamics, the flight management and control systems and the pilot interaction. A high level assessment of operational feasibility is possible. Flight testing is the last step of the NAP design process. Real weather conditions as wind changes and real traffic conditions and their influences on the procedure design could be investigated. Furthermore, a noise abatement validation can be performed by noise measurements on ground.

For noise level calculation / simulation the SIMUL software developed by U. Isermann [5] was used. This software was introduced in 1988 and has been enhanced continuously within several projects performed by the German Aerospace Center (DLR). SIMUL is based on a separate modeling of engine and airframe noise sources and accounts for directional characteristics as well as for frequency information. The noise calculation is based on the estimation of the noise-time-history at an observer location. In the current version only noise emission calculations for the Airbus A320 aircraft can be performed.

3 Evaluation of Noise Abatement Approach Procedures by Fast Time Simulation

The commonly used approach procedure is the Low-Drag-Low-Power (*LDLP*), which implies late gear and late final flap extension resulting in low drag at the initial part of the glide path and therefore only low power. Starting from a level flight at for example 7000 ft with a speed of 250 kts the aircraft performs a so-called "open descent", which is characterized by idle thrust setting and constant speed (Figure 2). The airplane behaves like a sailplane. Arriving at the intermediate approach altitude, typically 3000 ft, a change to level flight associated with adequate thrust adjustment takes place. To reduce speed for landing, a deceleration is necessary and to maintain lift at lower speeds the extension of flaps and slats is required. Therefore, at the deceleration point thrust is reduced to idle and reaching the minimum clean configuration speed high lift devices (first configuration stage) has to be deployed. The Airbus A320 can engage four configuration stages while approaching which are defined by different slat and flap positions. For the first stage only slats are deployed. After further deceleration the next configuration stage follows. A three degrees glide path will be intercepted from below at about 9 nm distance from the target touch down point. The aircraft decelerates further on glide path while thrust remains at idle condition. At about 2000 ft above ground the landing gear will be extended, directly followed by configuration changes to stage 3 and 4. To maintain landing speed once it is reached, the thrust has to be adjusted. At 1000 ft at the latest the aircraft must be stabilized in flight path, speed and thrust setting. If not possible for some reasons, a go-around has to be performed.

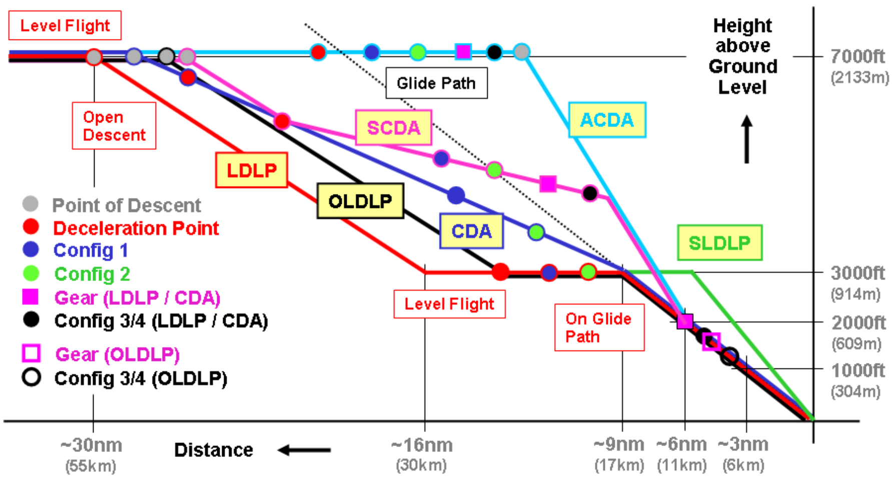

Fig. 2. Different noise abatement flight procedures

Now the question is how to improve the *LDLP*-approach with regard to noise without affecting safety and only minor influences on operational feasibility and economy. The disadvantage of the *LDLP* is among other things the intermediate approach altitude which is often too long due to air traffic control reasons. For an optimized *LDLP* (*OLDLP*) the length has to be reduced to the required deceleration length. Furthermore a reduction of the gear extension height is possible without affecting the stabilization height. To avoid the intermediate approach altitude completely a Continuous Descent Approach (*CDA*) has to be performed. The *CDA* has higher demands on air traffic control and aircraft flight guidance. During continuous descent, deceleration and aircraft configuration changes have to be initiated earlier than for *LDLP*. On glide path the *CDA* performs a late gear extension (*LCDA*) which is the same as for the *OLDLP* procedure.

Figures 3 shows aircraft inputs, states, and maximum noise level for the three described procedures as well as the noise level difference to *LDLP* obtained from the fast time simulation. Figure 4 depicts the corresponding contours of constant maximum noise level. *OLDP* and *LCDA* avoid the thrust adjustment necessary for *LDLP* on intermediate approach altitude. Therefore, as seen from upper plot in Figure 4 the contour area >50 dBA shrinks clearly between 23 and 15 nm distance from touch down. The islands of the >60 and the >65 dBA contours disappear completely (Figure 4, Plot 2 and 3). Due to later thrust adjustment regarding the *OLDLP* and LCDA procedures there is a noise reduction directly below the flight path of about 2 dBA in the region between 6 and 3 nm distance from touch down point (Figure 3) and all displayed contour areas become smaller (Figure 4).

As described before, the *LCDA* procedure avoids the intermediate approach altitude but does not differ from *OLDLP* procedure during the flight on glide path. Therefore, noise reductions at higher levels could only occur at steeper flight path angles (more height) during final approach, but then the aircraft has to be configured earlier since more drag is required. A steep final approach (more than 3° glide path angle) until touch down is not practicable in the near future because equipment on ground and aircraft certification will have to be changed. The appropriate solution is a steep segment down to 1500 ft which ensures that the stabilization height of 1000 ft is maintained. Glide path interception will take place from above with gear down and full flap setting so that aircraft stabilization comprises only of the glide path capture task.

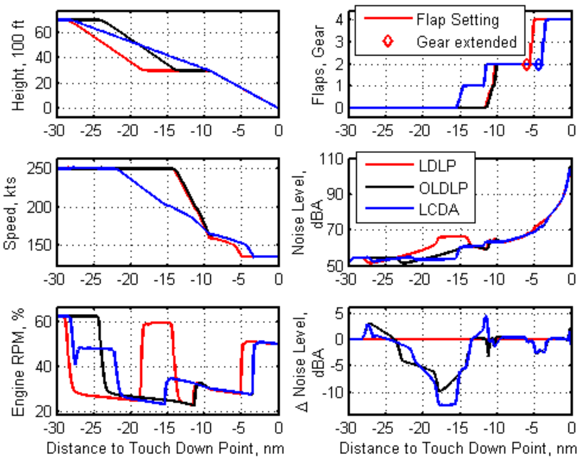

Fig. 3. Flight states and noise level below flight path of LDLP, OLDLP and LCDA

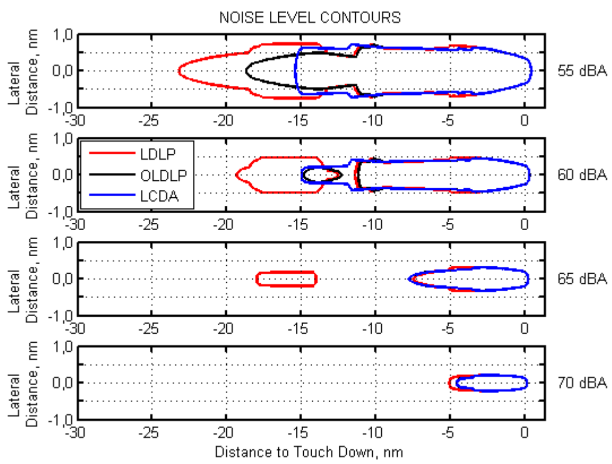

Fig. 4. Noise Contours of LDLP, OLDLP and LCDA

To extend the area of noise reduction two additional CDA procedures are designed with such steep approach segments. Figure 5 shows the Advanced-CDA procedure (*ACDA*) and the Segmented-CDA procedure (*SCDA*). For the *ACDA* the aircraft will be fully configured during the initial level flight which leads to a fast speed reduction and an early steep descent at low airspeed. The *SCDA* consists of multiple segments of an open, a decelerated and a steep descent. The *ACDA* has the most noise reduction regarding the >50 dBA contour. The islands of the >55 dBA contour result from the early deployment of slats/flaps and gear. Compared to the *ACDA* the noise reduction from *SCDA* is not so much (Figure 6).

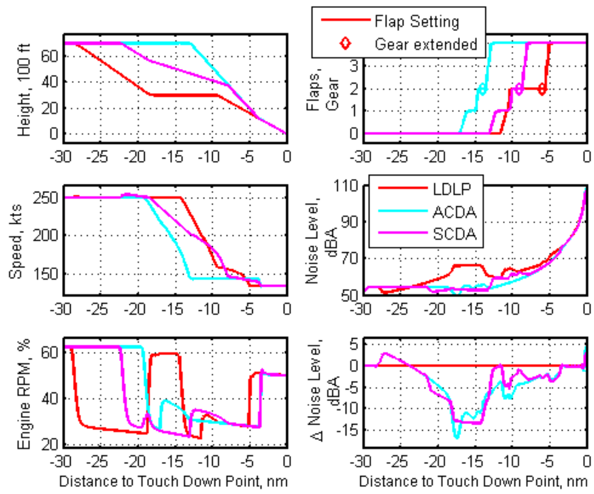

Fig. 5. Flight states and noise level below flight path of LDLP, ACDA and SCDA

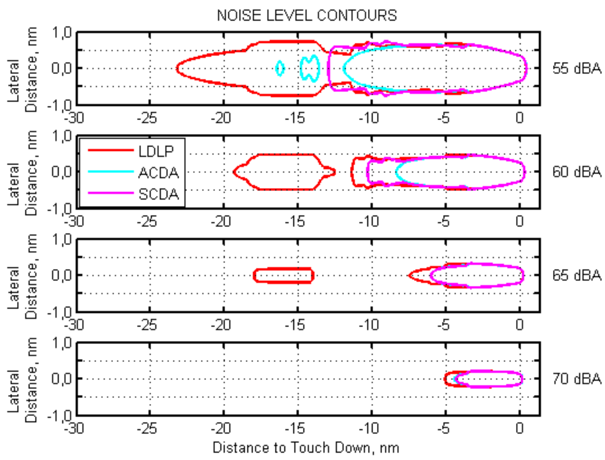

Fig. 6. Noise Contours of LDLP, ACDA and SCDA

Even if a steep approach until touch down is not feasible yet, an investigation of the amount of noise reduction would bring out the benefits of such an approach. Figure 7 shows the Steep-LDLP (*SLDLP*) with a 3.5° glide path angle compared to the *LDLP* and *OLDLP*. The -3.5° flight path angle can only be achieved by earlier stage 3 flap/slat setting, which requires a change in normal flap/gear schedule. Expectedly, a benefit is achieved at higher levels on glide path when thrust has been adapted (Figure 8).

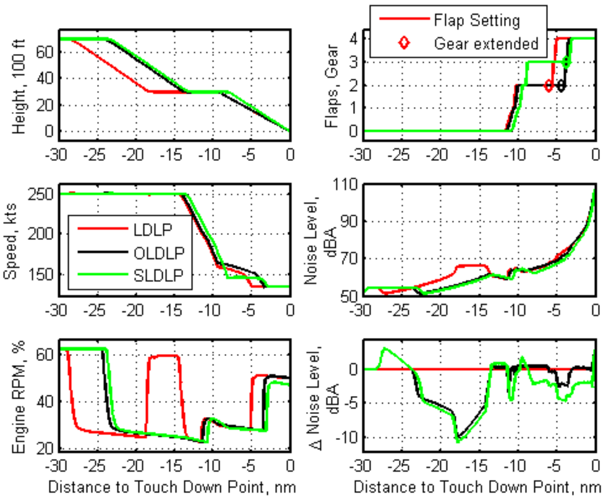

Fig. 7. Flight states and noise level below flight path of LDLP, OLDLP and SLDLP

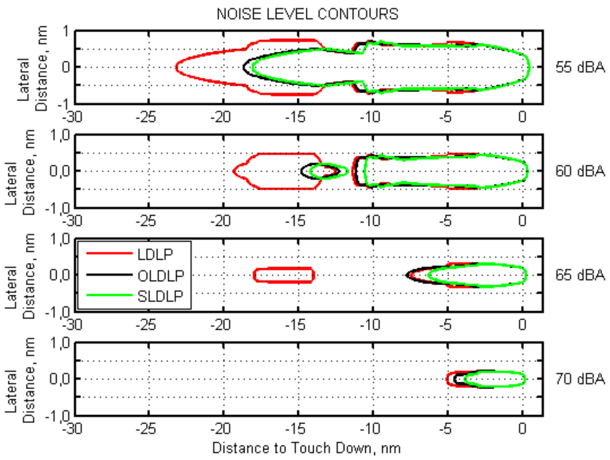

Fig. 8. Noise Contours of LDLP, ACDA and CDA

Figure 9 shows the noise contour areas of all investigated procedures and the differences to the *LDLP* reference procedure. The *ACDA* followed by the *SCDA* gives the best values for the >55 dBA and the >60 dBA contour areas. For higher noise levels (>75 dBA and more) only the *SLDLP* shows significant noise reduction. The slight increase of the >80 dBA contour area for *OLDLP* and *LCDA* maybe a result from lower height compared to the *LDLP*, even if the simulated aircraft is "on glide path".

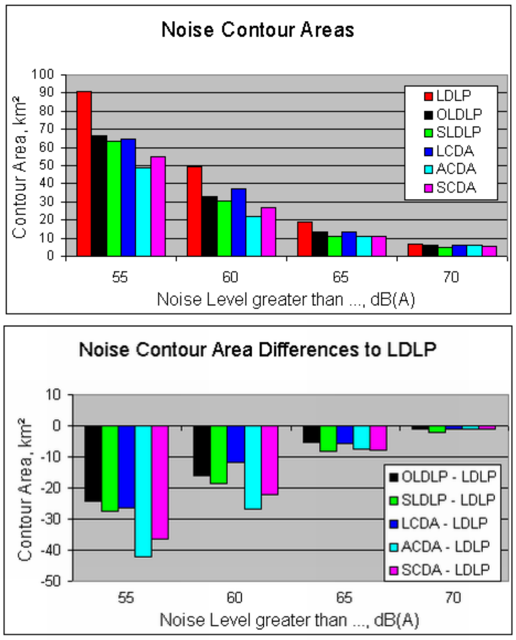

Fig. 9a. Noise Contour Areas from >55 to > 70 dBA

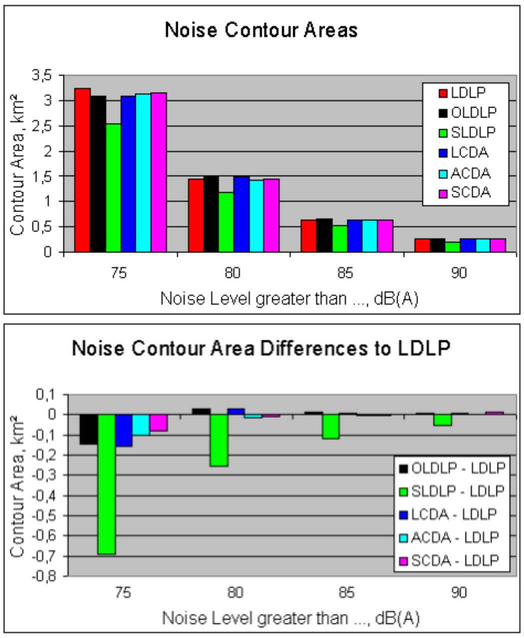

Fig. 9b. Noise Contour Areas from >75 to > 90 dBA

Now the question is, which procedure is the quietest, those which reduce the >55 dBA-contour mostly or those for the >75 dBA-contour? An appropriate answer could be an awakening criterion, developed by DLR as a result of a large polysomnographic field study [6]. Special attention is given there to dose-response relationship between the maximum sound pressure level of an aircraft noise event and the probability to wake up. The awakening criterion is a promising approach to weight noise level contours against each other during night-time operations.

The awakening criterion relates the maximum A-weighted sound pressure level L_{Amax} at the ear of the sleeping person to the probability P_{AWR} to wake up, using following equation (1) as in Ref. [6]:

$$P_{AWR} = 0.0019 L_{Amax}^2 + 0.04 L_{Amax} - 3.3 \qquad (1)$$

The threshold at which an increase in awakenings can be noticed is 32.7 dB. For this calculation, noise calculated by SIMUL is reduced by 15 dB to account for dampening by bedroom walls and windows. To compute the average number N_{AWR} of persons awakened per approach, areas of noise level contours A_i are calculated in 1 dB-steps (beginning at 32.7 dB) and multiplied by the probability $P_{AWR,i}$ at that noise level and by the average population density n_{FRG} = 231 residents per square kilometer in Germany (Equation 2). Of course the population is not evenly distributed in the vicinity of an airport, but in generic approach investigations, the criterion is found to work well for weighting noise levels changes against each other.

$$N_{AWR} = n_{FRG} \sum_i A_i P_{AWR,i} \qquad (2)$$

Figure 10 shows the awakenings resulting from the investigated NAPs. Compared to the *LDLP* all other procedures reduce the number of awakenings by more than 110 residents. The most reduction is achieved by the *SCDA* (156) followed by the *ACDA* (146) and the *SLDLP* (142).

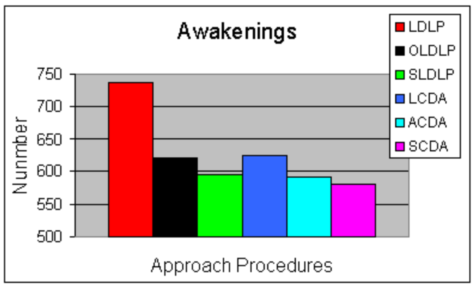

Fig. 10. NAP related awakenings

An economical assessment is possible in terms of fuel consumption and procedure flight time (Figure 11). These values are best for the *SLDLP* and worst for the *ACDA*.

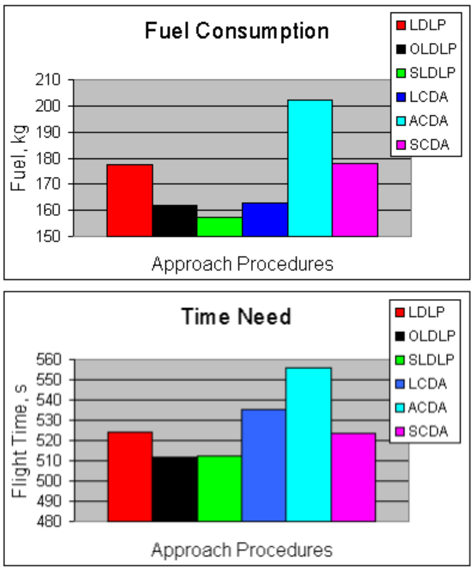

Fig. 11. Fuel Consumption and Time Need

Due to the fact that the *SLDLP* is not feasible today without changing the glide path elevation, the *SCDA* seems to be the best compromise between ecology and economy. But on the other hand it could be expected that the *SCDA* leads to increased workload and hence the procedure's feasibility is not ensured. Full flight simulator tests can resolve this problem.

4 Airbus A320 and A330 Full Flight Simulator Investigations

For the assessment of pilot workload and acceptance, 44 pilots were tested either on an A320-Full-Flight-Simulator (Lufthansa Flight Training) at Frankfurt or on an A330-Test- and Full-Flight-Simulator (Center of Flight Simulation at Technical University) at Berlin during 22 sessions [7] (Figure 12). All simulator sessions were conducted between 11:00 pm and 03:30 am in order to have an initial situation which is comparable to a landing after a long range flight. The crews performed a *LDLP* landing scenario followed by three *SCDA* procedures with captain and first officer alternately in command (8 runs in total). Technical, physiological and psychological data were monitored using Electroencephalogram (EEG), Electrooculogram (EOG), Electrocardiogram (ECG), blood pressure, salvia cortisol, and questionnaires about fatigue, taskload, and acceptance. Noise levels on ground were calculated using the DLR noise simulation software SIMUL for the A320 and the FAA software Integrated Noise Model (INM) for the A330.

Fig. 12. A330/340 Full Flight Simulator from ZFB

Under the conditions investigated (no wind, no turbulence and no other traffic), large deviations from the planned vertical flight paths were observed, especially for the A320 [8] (Figure 13). Main reason was the lack in keeping the appropriate point of descent (POD). To avoid an increase of noise due to too early glide path intercept followed by aircraft stabilization with thrust increase (Figure 14), a high precision of flight path and speed are necessary. This could not be performed by the pilot without additional assistance. So a solution can be the use of an Advanced Flight Management System (AFMS), as developed by DLR [9], which automatically performs the beginning of the descent and the extension of slats/flaps in a timely manner.

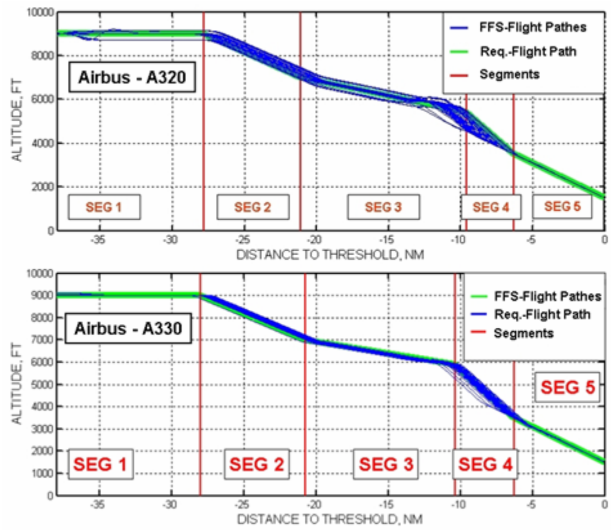

Fig. 13. Deviations from the planned flight path recorded from FFS-Study [8]

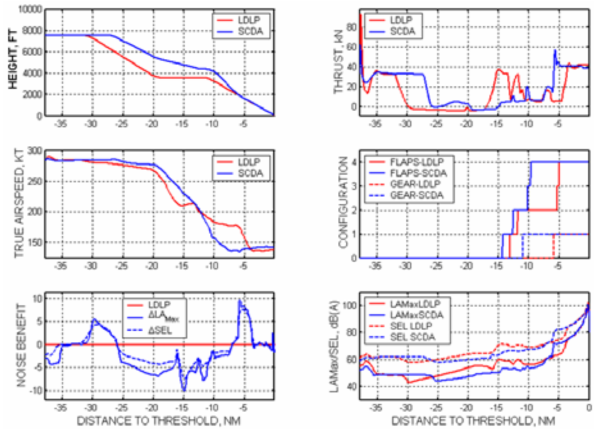

Fig. 14. Example for an A320-Simulator test-run [8]

The Figure 15 shows an example of an A330-Simulator test-run which demonstrate an accurately performed *SCDA* procedure. Compared to the *LDLP* a significant noise reduction can be observed over a wide range. Only small noise increases appear. However these results are from the used INM noise calculation tool, which does not represent airframe noise.

The peaks in thrust for the *LDLP* result from a too fast aircraft deceleration which leads to a too fast arrival of minimum speeds since rate of slat/flap extension is not fast enough. To avoid a fall below minimum speed the thrust increases automatically.

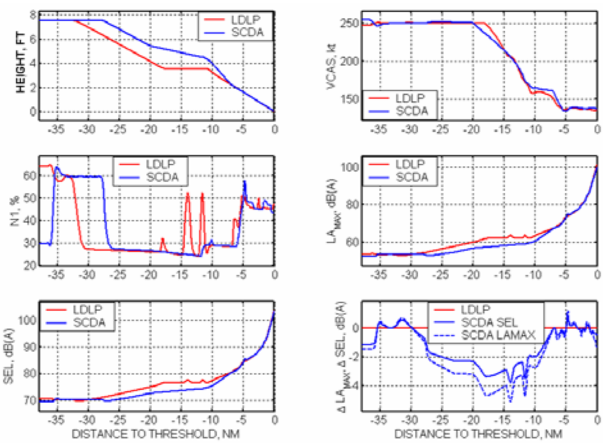

Fig. 15. Example for an A330-Simulator test-run [8]

A rating of fatigue was performed after each test run by means of Samn-Perelli scale [10], indicating no fatigue at zero points and maximal fatigue at 20 points. As expected the fatigue incremented during the simulator session (Figure 16). A correlation between the type of approach procedure and the increment of fatigue was not clearly evident [8, 11].

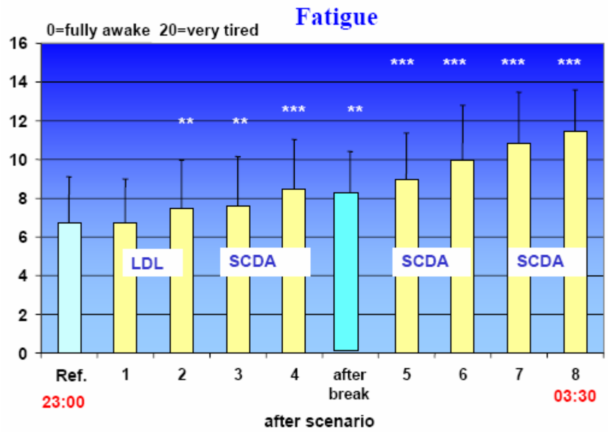

Fig. 16. Fatigue ratings after each simulator run [8, 11]

Also the taskload was assessed at the end of each simulator run by means of the NASA Taskload Index (TLX) [12]. No significant differences between *LDLP* and *SCDA* and between captains and first officers were observed. Obviously, the rated taskload of the pilot flying the aircraft is clearly higher than that of the pilot not flying (Figure 17). Furthermore the effect of training reduces the rated taskload as can be seen from the differences between *SCDA2*, *SCDA1* and *SCDA* Training.

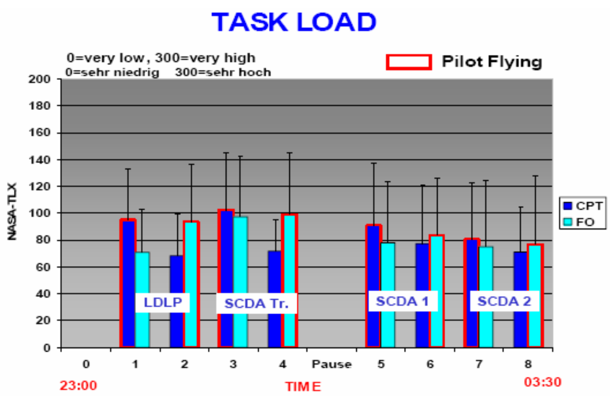

Fig. 17. Rated taskload after each simulator run [8, 11]

Pilots were asked about their common opinion on the *SCDA*. The procedure was rated rather non-problematic after an adequate briefing and the workload was reported to be mainly acceptable. But though there were no safety critical flight states during all simulator runs, the *SCDA* was rated from 14 pilots less safe than the *LDLP* (Figure 18).

Regarding the medical data it can be stated that there were no significant differences in heart frequency, blood pressure, and salvia cortisol concentration.

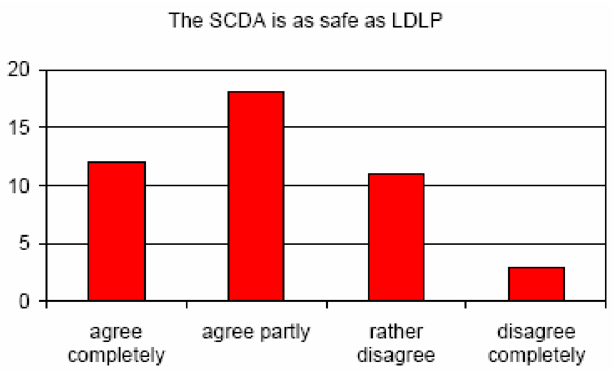

Fig. 18. Assessment of pilots for the safe operability of the SCDA [8, 11]

5 Flight Tests

Although the reported simulator tests help to investigate noise reduced approaches under more realistic conditions compared to fast time simulations, further studies are strongly recommended, e.g. under real flight conditions, before introducing new procedures into practice. For this purpose and to validate the calculated noise reduction, extensive flight tests were performed at Schwerin-Parchim Airport using an Airbus A319 aircraft, as supplied and operated by Lufthansa German Airlines (Figure 19).

Fig. 19. Airbus A319 at Schwerin-Parchim Airport

Four approach procedures were selected from the introduced ones, which were the *LDLP* as reference, the *LCDA*, the *SLDLP* and the *SCDA*. Figure 20 shows the simulated trajectories, airspeeds, engine RPM, flaps/gear positions and the calculated maximum noise level and its difference to the reference procedure *LDLP*.

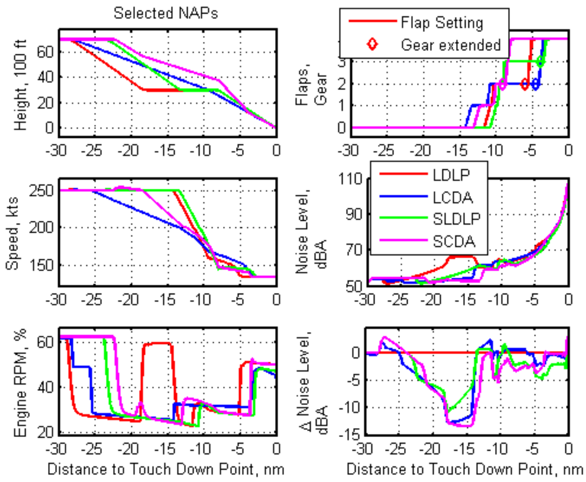

Fig. 20. Selected NAPs for flight testing

In real flight, wind speeds and actual weight affect the precision of the planned procedure and therefore correction to critical parameter have to be made, i.e. to the point of descent.

Due to horizontal wind speed u_{Wg} the flight path angle γ will change during open descend even if thrust remains constant (Equation 3):

$$\sin\gamma = \frac{\sin\gamma_0}{\left(1 + \dfrac{u_{Wg}}{V}\right)} \qquad (3)$$

where γ_0 is the flight path angle without wind.

Headwind leads to a steeper open descent and a shorter deceleration distance, while tailwind increases the flight path angle and extends the deceleration distance (Figure 21). Therefore, a corresponding adaptation of the point of descent (POD) is necessary to avoid a thrust increase for headwind conditions or to avoid a necessary deceleration after glide path intercept for tailwinds. In the first case the additional thrust requirement would generate extra noise, while in the second case the stabilization height at 1000 ft could be missed and thus lead to a go-around. So the POD has to be moved closer to touch down point with headwind and more away with tailwind conditions.

The actual aircraft weight influences the point of descent and the deceleration point in a similar manner as the wind speed. Due to higher weight the flight path angle becomes steeper and the deceleration distance shorter and therefore both points have to be closer to the runway's threshold. Furthermore it is possible that fixed flight path angles during CDA-approaches are too steep for necessary deceleration if aircraft weight is low. Then an adaptation is required too.

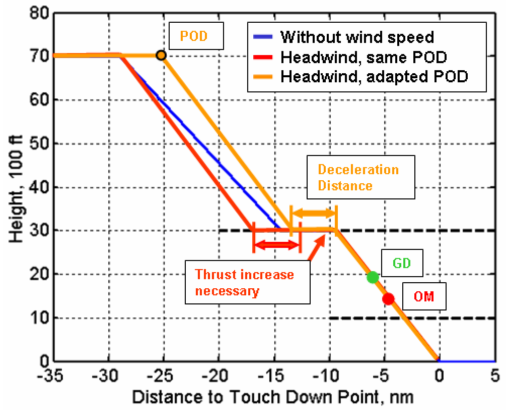

Fig. 21a. *OLDLP* with headwind conditions

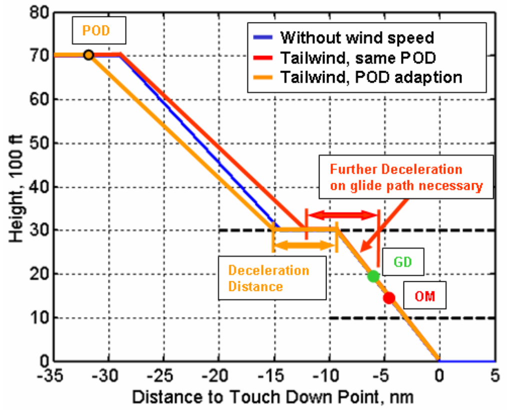

Fig. 21b. *OLDLP* with tailwind conditions

To satisfy procedure accuracy, the wind speed dependent PODs were given to the pilots in tables. Figure 22 shows one set of flown NAPs (each procedure was flown twice). All procedures were performed as planned (compare to Figure 20).

By means of 13 remote controlled noise measurement systems in the approach area (Figure 23), the noise impact was recorded. The results indicated an average noise reduction potential of 3 dB (Figure 24) and showed good agreement between measured and predicted approach noise levels [13].

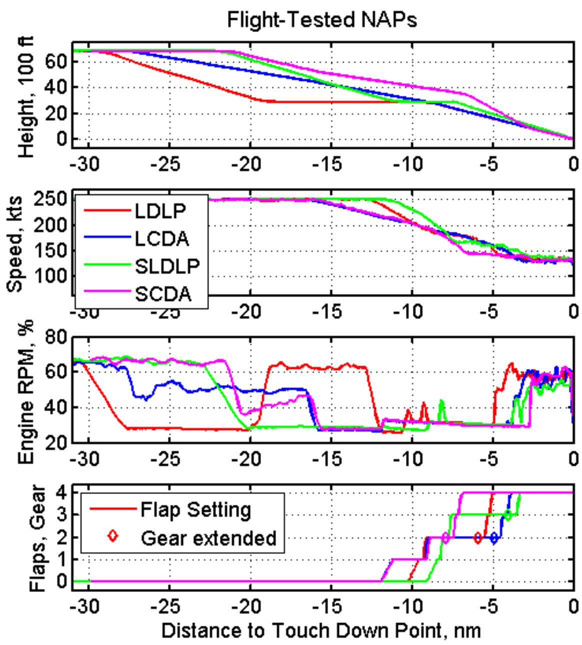

Fig. 22. Flight test results

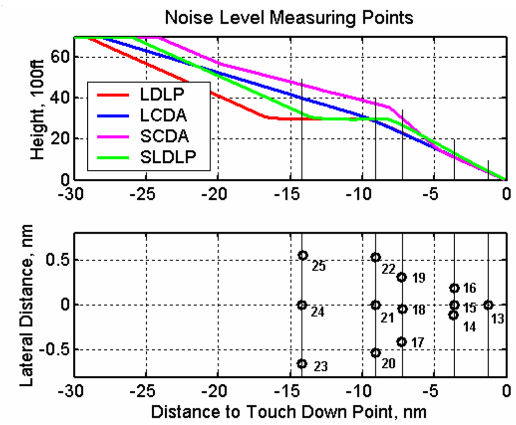

Fig. 23. Noise level measuring points

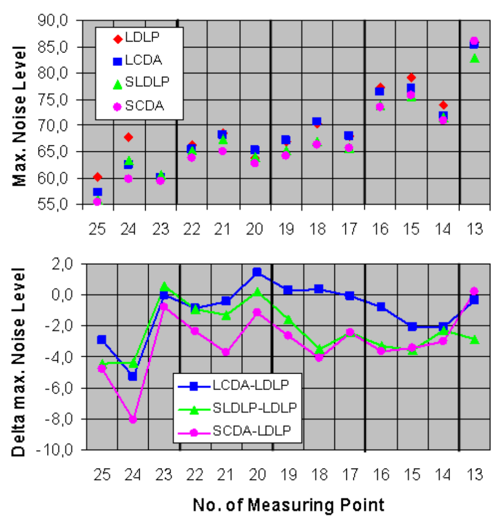

Fig. 24. Noise level measurement results

6 Summary and Conclusions

Noise abatement approach procedures were investigated systematically by fast time simulation with regard to noise levels below the flight path, contour areas, flight time and fuel consumption. The introduced procedures lead to a benefit in terms of noise reduction compared to the reference *LDLP* procedure. This benefit amounts to more than -10 dBA for the maximum noise level directly below the flight path and to more than -50% for the 60 dBA contour area in fast time simulations. But some of the procedures are either not short-term realizable, like the *SLDLP* (steep final descent until touch down), or are not economical, like the *ACDA*. The best trade-off for the given demands seems to be the *SCDA* which is indeed difficult to perform by the pilots.

To ensure safety and pilot acceptance the *SCDA*, and the *LDLP* as reference, were tested in Full Flight Simulation. Under the conditions investigated the overall performance in these cases was safety non-critical, but some pilots (14 of 44) rated subjectively the *SCDA* as less safe than the *LDLP*. They stated the need of more situational awareness and more assistance to perform an accurate procedure. All medical data indicated no differences between both procedures.

To validate procedure feasibility, noise reduction, and the results from noise calculation tool SIMUL, flight tests were performed. Four selected procedures were each flown twice with data recording on board and noise measurement on ground. The expected noise reduction could be verified and the pilots rated the procedures as feasible even under real world conditions. But this is true only for the single event and not for traffic scenarios. Especially the *SCDA* cannot be introduced in practice without more pilot assistance. Further work has to be done within this domain.

7 Acknowledgements

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