IMPROVED ENERGY MANAGEMENT DURING ARRIVAL FOR LOWER NOISE EMISSIONS

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Abstract

Analysis of operational flight data has shown that energy management during approach is a challenging task for pilots. This is detrimental for both fuel consumption and noise emission. The difficulty is increased when shortcuts result in an over-energy scenario. To alleviate the situation, a novel functionality was developed which improves aircraft energy management during descent and approach. It includes cues shown in the Primary Flight Display and the Navigation Display of an exemplary single-aisle aircraft. Noise benefits of the functionality were evaluated during piloted real-time simulation trials. Using the functionality, noise emissions during descent and approach can be decreased in the area within 10 NM from the threshold.

Keywords

Continuous Descent Operations; energy management; aircraft noise; pilot support systems; human-machine interface

NOMENCLATURE

Symbols

L_{AE}	A-weighted sound exposure level	dB(A)
V_{FE}	Maximum flap extension airspeed	kts

Abbreviations

ATC	Air Traffic Control
CCO	Continuous Climb Operations
CDO	Continuous Descent Operations
DTG	Distance To Go
EFB	Electronic Flight Bag
FMS	Flight Management System
GIS	Geographic Information System
HMI	Human-Machine Interface
LNAS	Low Noise Augmentation System
ND	Navigation Display
NM	Nautical Mile
PFD	Primary Flight Display
RTS	Real-Time Simulation
RWY	Runway
SESAR	Single European Sky ATM Research
TMA	Terminal Manoeuvring Area
VDEV	Vertical Deviation

1. INTRODUCTION

Noise emission and fuel consumption are important factors to consider for more environmentally friendly aviation. In the DYNCAT project (“Dynamic Configuration Adjustment in the Terminal Manoeuvring Area”) funded by the SESAR Joint Undertaking, many flights were analysed in this regard. During descent and approach, flights often produce more noise and consume more fuel than they could or should [1]. Thus, flights are not as energy-efficient as they can be. A key factor for non-optimal energy efficiency during this phase is the pilots’ lack of information about the difference between the current and the optimal energy state of the aircraft.

The situation can be improved by providing information and cues to the pilots. These cues support the pilots in changing aircraft configuration at the ideal points for an optimal energy management.

This paper presents the noise impact of an assistance system designed to increase the pilots’ energy state awareness and support them in the energy management task. With improved energy management and configuration change cues, it is possible to fly energy-efficient approaches without increasing the workload.

The proposed system is based on the previously developed and tested Low Noise Augmentation System (LNAS) [2]. While LNAS is an Electronic Flight Bag (EFB) application, DYNCAT is a further evolution of the system and integrated into the Flight Management System (FMS) and its displays.

Several previous works considered Continuous Descent Arrivals, mostly the generation of such routes. However, many of those did not consider how these trajectories can be flown the most efficiently.

To assist pilots in flying these trajectories, an assistance or support system is required. Such systems were developed and evaluated as part of the "Time and Energy Managed Operations (TEMO)" concept as well [3]. However, these systems implemented profiles with segments flown using non-idle thrust. Other similar projects included level-flight segments as well [4].

The following section describes the task of energy management during approach and the associated challenges for the pilots. In addition, the factors contributing to aircraft noise, especially during arrival, are explained. Section 3 presents an exemplary assistance/support function for pilots and its benefits. The results are then discussed, followed by a summary and an outlook in the final section.

2. THE CHALLENGE OF ENERGY MANAGEMENT DURING ARRIVAL

Ideally, arrivals are flown using "minimum engine thrust, ideally in a low drag configuration" [5]. This procedure is known as Continuous Descent Operations (CDO). Thus, one of the pilots' tasks during descent and approach is to fly energy-efficiently. The goal of this procedure is to conduct the flight with low noise as well as low fuel consumption at the same time. However, pilots often lack information to do so.

In this phase of flight, energy has to be dissipated. The total energy consists of a kinetic part, due to airspeed, and a potential part, due to altitude. Both airspeed as well as altitude have to be decreased during descent and approach. Insufficient energy dissipation can be a reason for an unstable approach, which should result in a missed approach/go-around.

A challenging aspect of total energy dissipation is the aerodynamic efficiency of modern aircraft. In a clean configuration, it might be difficult to decrease airspeed sufficiently while descending due to the high lift-to-drag ratio.

During descent, an over-energy situation can arise in which the aircraft has a surplus of energy. This situation might occur when Air Traffic Control (ATC) gives the clearance for a shortcut, with the resulting route being shorter than the planned one, as depicted in Figure 1. In this case, additional drag is required and can be obtained using the speed brakes, flaps and slats, and/or the landing gear. The point at which these devices are used, however, is at the discretion of the pilots. Because the length of the eventual lateral route and weather influences are uncertain, the use of speed brakes by the pilot could be delayed compared to the optimum case.

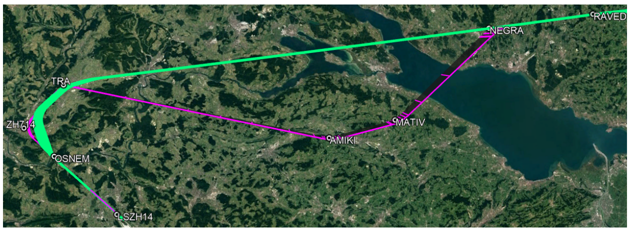

**FIG 1. Radar vectoring shortcut during approach to LSZH, RWY 14 [6].
Magenta: planned route, green: shortcut.
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2.1. Aircraft noise emission and noise exposure on the ground

The main noise sources of an airplane are the engines and the airframe. The airframe noise primarily depends on the indicated airspeed and aircraft configuration, with the airflow around flaps/slats, speed brakes and landing gears as main contributing components. Typically, higher airspeeds result in increased noise emission levels. The airframe noise becomes particularly important during descent and approach, when the engines are at comparably low thrust [7]. Nevertheless, even in this phase of flight, engine noise might account for a significant proportion of the total noise emission or may even be the dominant noise source if thrust is increased. The engine noise is almost exclusively depending on the thrust setting, variables such as airspeed or air density have only second-order effects.

The most important factor of the sound propagation and thus the aircraft noise exposure on the ground is the distance between source and receiver due to the geometric spreading of the sound energy. Hence, flight altitude is the most important factor apart from the sound source itself. Shielding effects, e.g. by elevated terrain such as hills, only occur in greater lateral distance to the flight trajectory, where the sound exposure levels are generally lower.

2.2. Energy management considerations

Energy management considerations regarding noise are motivated twofold: On the one hand, lower speeds reduce the noise radiation at the source; on the other hand, a higher flight altitude increases geometric spreading and atmospheric absorption and therefore reduces the noise exposure on the ground. If necessary, it is favourable to dissipate energy by using flaps/slats and/or speed brakes with higher drag at higher altitudes, where the noise impact on the ground is still low. Landing gears could also be used to dissipate excess energy. However, they have the disadvantage that, once extended, they are not supposed to be retracted again except in case of a go-around. Therefore, if too much energy is dissipated by their use, thrust might have to be increased, which has an unnecessarily negative effect on noise emission. In this case, the use of speed brakes is preferable. Consequently, landing gears should be extended as late as possible.

The challenge with speed brakes consists in the estimation of the required amount of their use. Using the speed brakes for too long, thus dissipating too much energy, leads to the same problem as too early deployed landing gear - thrust has to be increased prematurely, resulting in increased noise emission and fuel consumption. Using them too little does not dissipate enough energy, requiring the speed brakes to be used again later, or earlier deployment of flaps and/or landing gears, thus also increasing noise.

Consequently, the following strategy for low-noise approaches can be deduced:

- Thrust: preferably in idle
- Configuration: minimal and early use of speed brakes and late deployment of landing gear
- Energy management: reduce speed first, then altitude

While this strategy reduces the noise impact of the approach, early speed reduction increases the total flight time during approach. Therefore, the opposite strategy increases noise, but decreases fuel consumption, when flown in idle as well.

For idle approaches, flights with higher airspeeds save fuel by decreasing the total flight time. However, they lead to increased noise emission as described above. Therefore, a compromise between lower noise emission and fuel consumption reduction has to be made during all approaches. A schematic Pareto-optimum curve for the trade-off is depicted in Figure 2. In this figure, each blue dot represents the assessment of an entire approach regarding the factors noise emission and fuel consumption. The black line represents a Pareto-front, along which one criterion can only be improved at the cost of impairing the other. Suboptimal solutions, shown here above and to the right of the Pareto-front, should be avoided. Due to the difficulties in achieving an energy-optimised flight profile mentioned above, most approaches emit more noise as well as consume more fuel than necessary. Thus, they do not reach a Pareto-optimal solution. Clearly, the energy management can be improved.

All these considerations are relevant for and until reaching the Final Approach Fix/Point. At this point, the aircraft follows the landing glide path at an approach speed which is pre-defined for each aircraft model. The landing is carried out only if the aircraft is in a stable configuration. This is the case if all required high-lift devices are set up as prescribed and the airspeed matches the final approach speed without acceleration or deceleration. Since this procedure is standardised for all aircraft types, no optimisations are possible in this phase within the framework of DYNCAT.

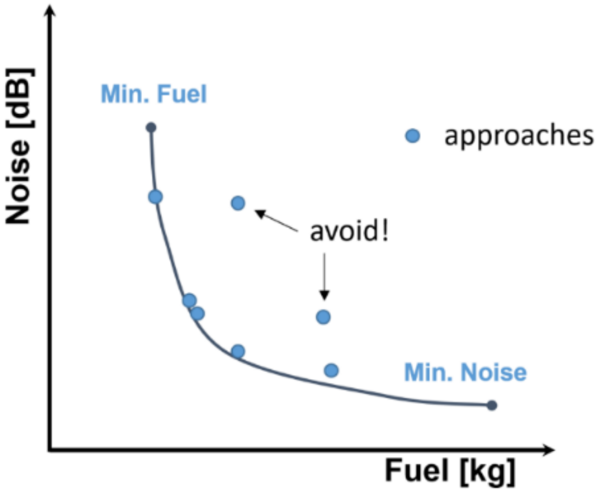

FIG 2. **Pareto-optimum curve and trade-off between fuel consumption and noise emission (schematic).**
Non-Pareto-optimal approaches should be avoided.

3. IMPROVING THE SITUATION - OVER-ENERGY SCENARIOS

3.1. Supporting pilots in the energy management task

In the DYNCAT project, a system for increasing energy state awareness and thus improving energy management was prototyped. A novel Human-Machine Interface (HMI) functionality displays cues according to the previously calculated optimum profile. All the cues are constantly updated to reflect the current aircraft energy state and possible deviations from the optimised profile. For the calculation, a Distance To Go (DTG) information is required. This information can currently be received once from ATC via radio communications during arrival, e.g. using the phraseology "you are approximately 55 track miles from touchdown". The obtained DTG is then manually entered into the FMS when using the DYNCAT function.

In the Navigation Display (ND), several cues are shown along the calculated trajectory, as depicted in Figure 3. Those cues indicate optimal configuration set points for flaps/slats, landing gear and FMS mode switches. The symbols for the exemplarily used Airbus A320 family are listed in Table 1.

The maximum airspeed at which flaps should be extended is V_{FE} and differs for each flap setting. The DYNCAT function includes a safety margin of 5 kts, so the cues for flap configuration changes are indicated at the respective $V_{\mathrm{FE}} - 5$ kts or below.

Depending on the exact margin to the $V_{\mathrm{FE}} - 5$ kts threshold, the cues are displayed in different colour schemes. When the flap extension is calculated below this value, the cues are displayed with a green symbol on black ground. This means that there is a margin to dissipate more energy. When all excess energy can be dissipated, but the flaps have to be extended at their $V_{\text{FE}} - 5$ kts, the symbol changes to a black symbol on green ground. When the flap configuration points are calculated at their $V_{\text{FE}} - 5$ kts and there is still excess energy, not enough energy can be dissipated using high-lift system and landing gear alone. In this case, the cues change to black on amber ground.

TAB 1. DYNCAT symbology

Symbol	Indication
↘ ↘ ↘	Vertical speed mode (V/S)
D D D	**D**eceleration
1 1 1	Flaps/Slats Configuration **1**
2 2 2	Flaps/Slats Configuration **2**
F F F	**F**inal Configuration: Landing Gear, Flaps/Slats Configuration 3, Flaps Full

The corresponding configuration change should be initiated when the aircraft symbol is directly on top of the cue on the ND.

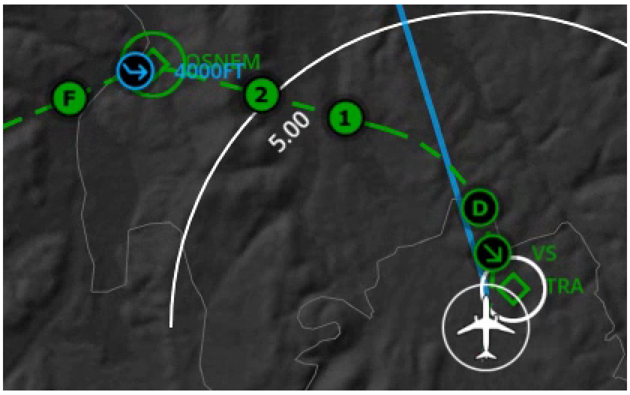

FIG 3. Configuration set points (black/green circles) displayed in the Navigation Display.

Another indication to the pilots, which increases their situational awareness, is the display of an optimum altitude along the glide path. The indication consists of a magenta dot displayed in the altitude tape, as depicted in Figure 4. It represents an optimised vertical profile which is calculated by the FMS based on the aircraft's total energy state. When the optimum is further away from the current altitude than can be displayed, the vertical deviation (VDEV) is indicated in magenta in hundreds of feet as well. Using the VDEV indication, the pilots' awareness of the relation between the aircraft's current and its ideal energy status is increased.

Furthermore, the FMS determines an optimised DTG based on the current energy state of the aircraft. This is based on a balanced trade-off between noise emission and fuel consumption along the Pareto-front described above. For over-energy situations, the DTG intended by the air traffic controller is shorter than the optimised DTG, i.e. energy has to be dissipated faster. The margin between both values is indicated in the bottom right of the ND. Before any controller-intended DTG was entered, the margin uses the flight plan trajectory distance instead of the DTG.

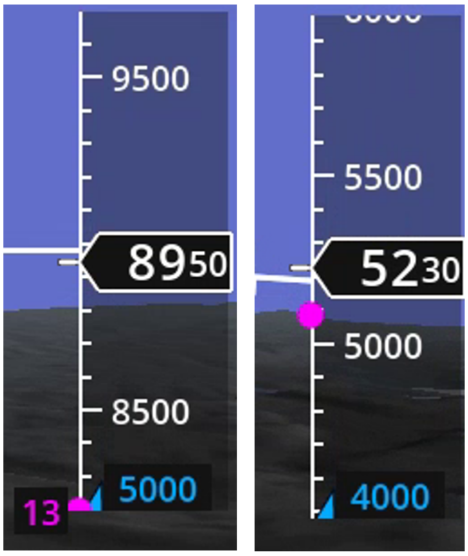

FIG 4. Optimal altitude (magenta dot) and VDEV indication in the Primary Flight Display.
Left: VDEV of 1300 ft, Right: VDEV about 100 ft.

Another aspect of the DYNCAT functionality is that the need to dissipate more energy using speed brakes can be anticipated early on during the approach, as it is the case for over-energy scenarios. In this case, more total energy has to be dissipated and an "EXTEND SPD BRK" message appears in the PFD. Once enough excess energy has been dissipated, another message appears indicating that the speed brakes should be retracted.

3.2. Influence on noise impact

To quantify the benefits of the DYNCAT functionality, a series of pilot-in-the-loop real-time simulations was conducted. The simulations consisted of a typical over-energy scenario during descent and approach to Zurich Airport (LSZH), Runway 14, as depicted in Figure 1.

Twelve active and experienced airline pilots participated in the trials. For each pilot, two reference flights (REF) were conducted and recorded without the use of the DYNCAT functionality. These two flights were based on the same lateral trajectory in an over-energy scenario, but with two slightly different instruction sets from ATC. Afterwards, the same two flights were simulated and flown using the cues of the DYNCAT system.

To assess the influence of the DYNCAT system on the flights carried out in the test series in terms of noise, they were simulated using the sonAIR aircraft noise

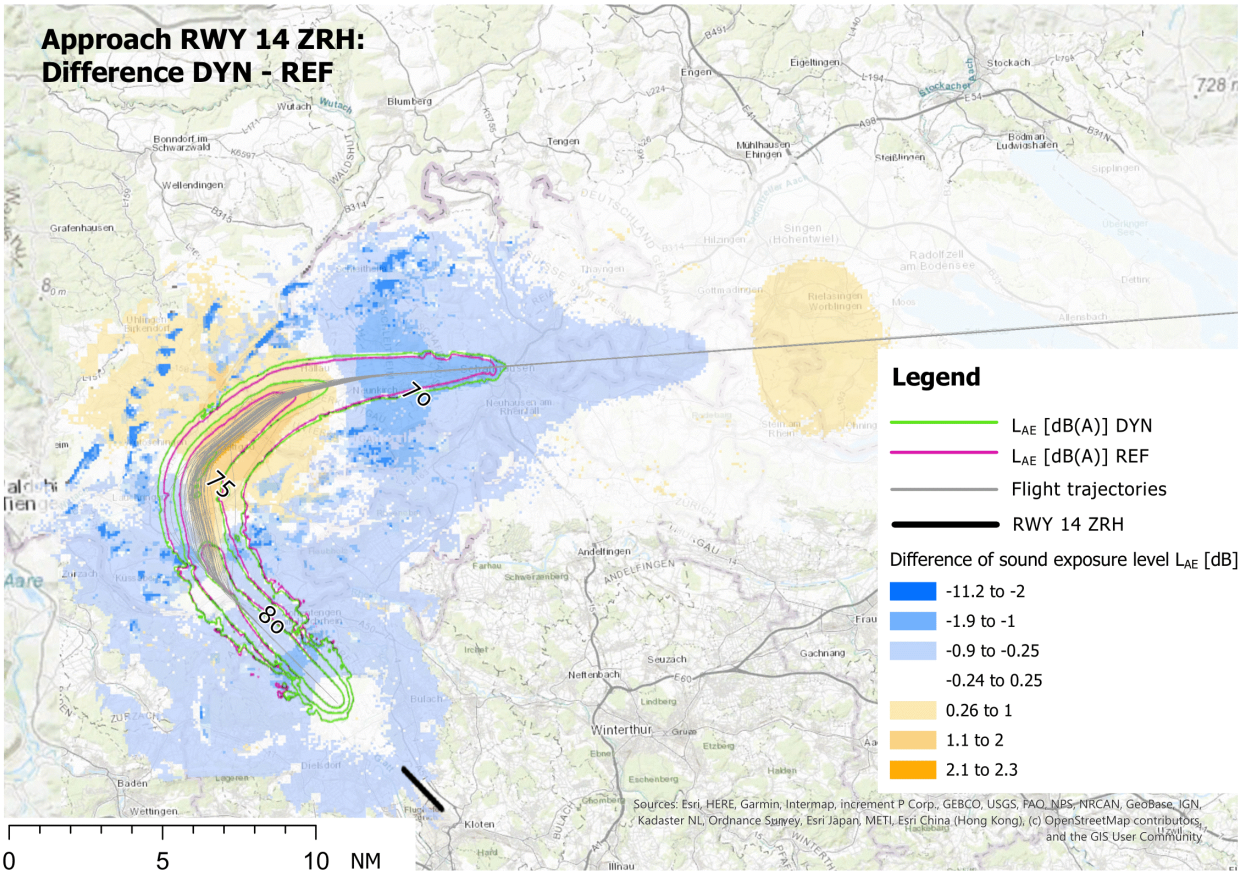

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FIG 5. Differential plots (DYN-REF) and averaged noise contours of sound exposure level of all trial flights.

calculation model [8,9]. sonAIR consists of two different parts:

1) A MATLAB implementation to calculate time histories of the noise level at specific receiver locations
2) A Geographic Information System (GIS) implementation to calculate noise exposure on ground over large areas to generate noise maps, differential plots, noise contours, etc.

Figure 5 shows the difference between the averaged flights conducted with the DYNCAT system (DYN) and the averaged reference (REF) flights as calculated using sonAIR to show the effect of the DYNCAT functionality on noise exposure. Two smaller areas in orange can be seen, where higher levels result when DYNCAT is active, and a large area in blue, where DYNCAT leads to lower exposure levels. Importantly, during the last approximately 10 NM of the flight, where the noise exposure is generally highest, DYNCAT has a beneficial effect on noise exposure. The noise increase in the orange coloured area is explained by the increased airspeed of the DYNCAT flights. In this area, the system has specified a higher airspeed to reduce fuel consumption by spending less time. This indicates a trade-off between noise reduction and fuel savings as mentioned above. Thus, flights using DYNCAT may become noisier in certain areas, but only to shift focus on fuel savings by maintaining the Pareto-optimum as depicted in Figure 2. Moreover, the noise increase in this case occurs in an area that is less problematic from a noise point of view due to the higher flight altitude. Closer to the runway, flights using the DYNCAT system are quieter. This is due to several positive effects. At approximately the same flight altitude, the average thrust setting could be reduced over long sections. In terms of configuration, the use of speed brakes is almost completely avoided in this area. Furthermore, the landing gears are generally extended later and the flaps are used more uniformly. With simultaneous fuel savings, a better energy and configuration management was thus achieved over all flights with the use of DYNCAT.

Shielding effects only occur in greater lateral distance to the flight trajectory, where the sound exposure levels are generally low. This can be seen best in the areas to the northwest of the flight path, where several dark blue spots are found.

During debriefing, the pilots confirmed the helpfulness of the system and that their workload was not increased by it.

4. DISCUSSION

A novel functionality for an improved energy management during approach was developed. The developed functionality was perceived well by professional pilots who participated in the simulator-based evaluation of the system. The pilots confirmed their increased awareness of the energy state when the DYNCAT system was used.

For the trials, an over-energy scenario was used in which the use of speed brakes was necessary. This is not always the case in real operations, but increases the difficulty of energy management. Using the system, an improvement was measurable regarding both noise emission as well as fuel consumption. Especially in the critical area within 10 NM of the threshold, the perceived aircraft noise can be reduced. The sonAIR software used for the simulation could previously be validated for the area where DYNCAT's effects are largest [10]. Thus, the DYNCAT functionality is expected to help flying Pareto-optimal approaches regarding noise and fuel.

All pilots participating in the RTS trials were interested in the challenge of energy management. They might have brought more knowledge about the task as well. Thus, they could have flown the REF cases more energy-efficiently than other pilots and decreased the noise differences obtained using the DYNCAT system compared to average flights.

5. CONCLUSION

5.1. Summary

Energy management during descent and approach is a challenge for pilots because of lacking information. Especially in scenarios with shortcuts cleared for pilots by ATC, a surplus of energy must be dissipated, which increases the difficulty. A new FMS/HMI functionality which supports pilots in the energy management task has been prototyped and evaluated. When flying using the functionality, pilots can configure the aircraft according to the current energy status. One result of the improved energy management is an improved noise profile on the ground.

The effects on noise of an assistance system such as DYNCAT were evaluated using piloted real-time simulation trials. Flights with and without the novel functionality were recorded and used for a subsequent noise simulation. For these simulations, noise emission as well as propagation were considered. These simulated noise levels were then compared.

The comparison of noise levels of reference flights and flights using the system shows an improvement of noise levels in multiple areas in the Terminal Manoeuvring Area. Especially in the most sensitive area within 10 NM to the runway threshold, a noise reduction by up to 2 dB was achieved.

The simulated results should give a good indication of possible improvements for noise emission and exposure as well as fuel consumption.

5.2. Outlook

The findings of this paper are also interesting in view of other solutions for decreased environmental impact, such as increased glide path angles. A steeper approach makes energy dissipation with the minimal use of speed brakes even more challenging [11]. As other projects have shown, there are margins to the envelope in which those approaches can be performed. An assistance system such as the presented one can certainly support achieving energy-efficient flights at a higher glide slope angle.

Other aircraft types use other designations for high-lift system configurations. For adaptation of the system to those types, the symbology will have to be updated.

ACKNOWLEDGEMENTS

The DYNCAT SESAR 2020 Exploratory Research project has received funding from the SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 893568.

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