
Concepts of Active Noise Reduction Employed in High Noise Level Aircraft Cockpits

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During the past two decades, reducing exposure to high level noise in aircraft cockpits by methods of active noise control (ANC) has aroused the interest of researchers. Also, some commercial applications were initiated by leading manufacturers. For this purpose, fundamentally different approaches were used. While active noise compensation reduces the noise level by generating an interfering antinnoise, structural vibration control aims to limit sound emittance through active damping of the aircraft structure vibrations. These approaches are linked with very different financial and technical boundary conditions, which implied distinct degrees of success. The ANC approaches used in cockpit noise reduction will be summarised, and their success- or failure-reasons will be analysed. Thereafter, the focus will be set on the industrially more successful way of protecting pilots from high noise levels, which is the use of active headsets. The development and the current state of commercial products will be presented, and the requirements of future trends will be derived. These requirements consist in extending the band width of noise reduction and making the control adaptive to changing conditions. Finally, the development of a prototype of a new generation of ANC headsets is presented. The prototype combines standard feedback with adaptive feedforward control techniques, and processes the control algorithms by an integrated DSP platform.

1 Passive versus Active Noise Reduction

To distinct passive from active noise reduction, we advance a definition based on the information flow in a noise reducing system. A system based on an open loop reaction mechanism to reduce sound energy is considered to be passive. Sound proofing and non-actuated resonator plates are examples of passive noise reduction devices. These are used for example to absorb sound

energy in anechoic rooms to produce free-field conditions. We define an active noise reduction device as an autonomous decision support based system with a closed loop reaction mechanism. Generally, these systems are reducing sound pressure level by means of actuators. In this paper we will focus on the reduction of the exposure of pilots and passengers to high level noise inside the interior space of aircrafts. This has been primary achieved by means of passive sound proofing. But during the past two decades, active approaches of noise reduction increasingly emerged, mainly in research projects and at a lower degree in industrial applications. The motivation of active noise reduction is related to the fact that passive sound proofing requires the use of bulky materials to effectively reduce low frequency noise. This comes obviously into conflict with the critical constraint of reducing the weight of aircrafts. Especially in the frequency range up to 100 Hz, active noise reduction could achieve considerably superior results at a lower weight load. We classify the concepts of active noise reduction employed in high noise level aircraft cockpits in three general categories:

- Active noise cancellation
- Active structural/acoustic control (also called structural vibration control)
- Active noise control in aviation headsets

Our classification is based on scientific and technical criteria and boundary conditions. Although it exists a great number of research publications related to active noise reduction, practical applications are still limited [Han04]. In order to procure a view about the applicability of active noise reduction in the aerospace industry, in this contribution a focus will be set on the reporting of industrial applications and application oriented research activities.

2 Active Noise Cancellation

Active noise cancellation is the reduction of sound wave level through generation of a phase delayed wave - generally called antinoise.

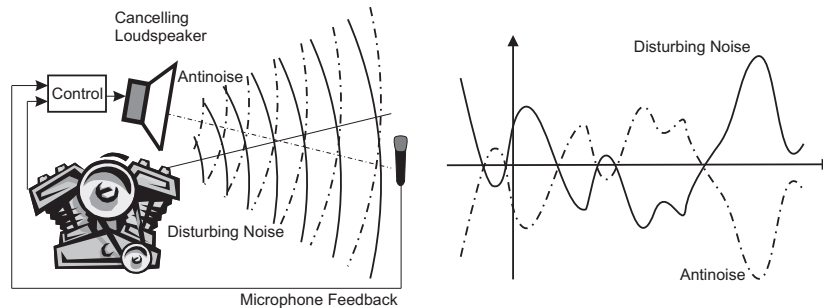


Fig. 1. Active noise cancellation

The superposition of the primary disturbing noise and the generated antinoise modifies the sound field characteristics and at some areas of the space, destructive interference leads to a cancellation of the disturbance. Fig. 1 shows a realisation of active noise cancellation. This approach generally needs the feedback information of a so called "error microphone" to generate a controlled antinoise. In some applications the generation of antinoise is additionally based on a reference signal of the disturbance source. This is not necessarily a microphone signal, it could be for example a tachometer information of an engine. The actuators used in active noise cancellation are generally loudspeakers. Active noise cancellation is usually called active noise control, which is not exactly the same, since active noise control is a more general notion including for example controlled sound field design which may not pursue any aim of noise reduction.

Among the tasks of the Advanced Subsonic Technology (AST) program initiated by the National Aeronautics and Space Administration (NASA) between 1992 and 2000, active noise cancellation was incorporated as a potential promising technology to be used in the reduction of fan noise level.

Fig. 2 shows the "active noise control fan" constructed by the NASA, which is a low-speed fan specifically designed for active noise control testing. The system aimed to reduce fan noise level in both the inlet and the aft ducts via controlled loudspeakers.

A second example of a leading application oriented research activity related to active noise cancellation is given by a cooperation work conducted by a consortium constituted by the German Aerospace Center (Deutsches Zentrum fuer Luft- und Raumfahrt - DLR), the European Aeronautic Defence and Space Company (EADS) and Germany's leading aircraft engine manufacturer MTU aero engines. This work was incorporated as a sub-project of the research cluster Turbotech II from 1996 till 2000.

The constructed prototype within this project is shown in Fig. 3. The active noise cancellation system incorporates 32 microphones and 32 loudspeakers. According to the German Aerospace Center in its final report [Eng00], the project was completed with "great success", as far as the prototype inves-

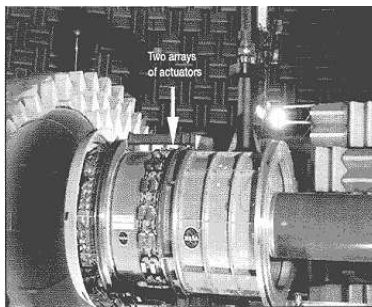


Fig. 2. NASA prototype for active noise cancellation of fan noise

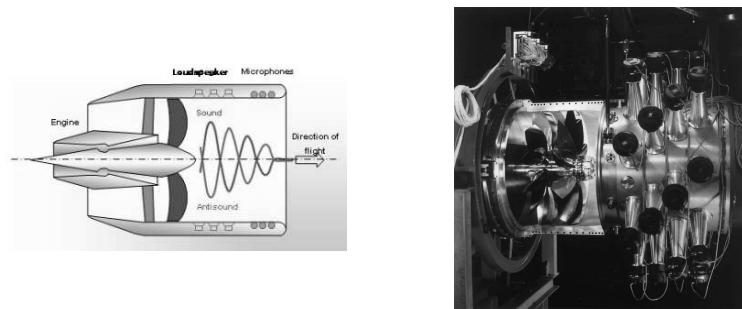


Fig. 3. DLR / EADS / MTU Active noise cancellation of engine sound

tigation is concerned. Currently, the German Aerospace Center is informing that works on active noise cancellation are being carried out in cooperation with the aircraft engine manufacturers MTU, SNECMA and Rolls-Royce to achieve an industrial realisation.

From the first mentioned project of the NASA a widely deviant appreciation of the industrial applicability of active noise cancellation is reported. In its evaluation of the prospects of active noise cancellation technology [Gol05], the NASA mentioned that active noise cancellation was never successfully demonstrated in a relevant environment by the end of the AST program. This program element was dropped when the AST program was terminated by the year 2000 and the work did not continue under the successor program effort.

These widely deviant appreciations of the prospects of active noise cancellation in the given examples is symptomatic for the widely variegated presentiments among the researcher and manufacturer communities towards the technology during the last years. In the nineties the majority of leading researchers in the field of active noise cancellation like P.A. Nelson and S.J. Elliott in 1993 [Nel93], S.M. Kuo and D.R. Morgan in 1996 [Kuo96] and L.J. Eriksson in 1997 [Eri97] prophesied a great success for the technology in this current decade. Only one leading researcher, C.H. Hansen, warned from too much "unfounded optimism in statements made in the media about the potential applications of the technology", as he wrote in 1997 in [Han97]. Considering the current expansion of industrial applications, Hansen is right after all. In 2004 he reexamined the situation and stipulated that the unrestrained, unfounded and, as he accused, sometimes insincere optimism of the nineties resulted in the current scepticism of manufacturers towards the active noise cancellation technology [Han04].

One of the more popular reasons for the narrowness of industrial applications was and still be the elevated costs related to the hardware requirements related to the technology. We confirm this reason but consider that it is light-headed and counterproductive to restrict the discussion to this constraint. Actually, the optimism of the nineties was widely based on the consideration,

that the main constraint to the expansion of the technology is the high signal processing effort, and that in some years the decrease of the costs of digital devices and the increase of their capacity will necessarily engender a breakthrough of the active noise cancellation technology. As it could be noticed, during the last fifteen years a tremendous change occurred in the costs and capacity of digital devices but this did not have a notable effect on the applicability of the active noise cancellation technology in real environments. During our research activity in the field of active noise cancellation we identified some other reasons which could explain the current situation:

- Complexity of the task of controlling a three-dimensional sound field.
- Signal processing and control engineering communities have a lack of knowledge of the physical limitations of noise control in real acoustical environments due to principles of room acoustics and special characteristics of acoustical sensors and actuators.
- Active noise cancellation is often realised by control engineers with methods of adaptive signal processing to solve a complex acoustical problem. Since only few researchers are well qualified in all these fields, there is an imperative need for a well functioning multidisciplinary team with specialists from the involved fields of control engineering, signal processing and acoustics.
- Too much academic research without any ambition of application and a unbalanced ratio of fundamental research to application oriented research.
- No possibility for volume production since each new environment requires a new custom-made solution.
- Existence of competing and promising technologies like active structural/acoustic control.

Thus, it becomes difficult to advance an expectation of the potentials of active noise cancellation for the future, particularly because there exist few examples of successfully functioning systems in real "common" environments. As far as aircraft cabins are concerned, in the past there was a unique example of successful industrial application of active noise cancellation. In 1994 the concern Ultra Electronics developed the system "UltraQuiet" as a retrofitting device for a Saab 2000 aircraft. Fig. 4 shows the components of the noise cancellation system "UltraQuiet". The first introduced "UltraQuiet" system was a tonal active noise cancellation system for quieting cabins of turboprop and rear engine jet aircrafts. In the following years this system was integrated to other turboprop aircrafts as a standard equipment like the Q-Series Dash 8 (since 1996) of Bombardier Aerospace, the Saab 240 (1996), and the Beech King Air 350. In 2004 Ultra Electronics reported that it has over 700 active noise cancellation systems in operation [Gor04]. The amount of systems integrated as standard fit attests the success of this realisation. From the technical point of view the success could be explained with the reason that the noise reduction task was achieved by tonal noise cancellation, which means that the system generates only harmonic waves. It consists in the generation of a



Fig. 4. Components of the Ultra electronics system of active noise cancellation "UltraQuiet"

harmonic wave based on a reference signal (generally a tachometer signal) and the adaptation of only two parameters: The amplitude and the phase delay. This method is extensively simpler than broadband noise cancellation and provides very good results in a spatially confined sound field with a considerably dominant low frequency harmonic, which is the case for the mentioned aircrafts. Our expectation for the future of active noise cancellation in aircrafts is that it has rather prospects of being used in niche markets, where the control task is simplified like the example stated above, than in general global noise reduction tasks. As an alternative noise reduction solution it could be primarily used as retrofitting in specific environments, where for example no transformation of the construction through passive or active vibration control devices is allowed. The use of loudspeakers which are already existing or which could be easily integrated in the interior space of an enclosure presents an advantage with respect to a potential use as a retrofitting solution. A second advantage of the active noise cancellation is the Ability to design sound fields. Active noise control could focus on a certain point of the space in which the sound level is reduced or the spectrum is selectively changed with a minimum of effort.

3 Active Structural/Acoustic Control (ASAC)

Active Structural/Acoustic Control (ASAC) aims to reduce sound level through vibration reduction of sound emitting structures. This technology already exists as standard equipment in some automotive applications; it is now being developed by the same concerns which formerly did not succeed to realise reliable active noise cancellation systems. As far as industrial applications and application oriented research activities are concerned, also in the aerospace industry we noticed in the last years a trend to give up research on active noise cancellation for the benefit of active structural/acoustic control. This could be deduced from the increasing active structural/acoustic control approaches

investigated by application oriented researchers and leading manufacturers in the last years. Within the same NASA AST program mentioned in section 2 diverse research activities related to active structural/acoustic control were carried on from 1992 to 2000. To reduce the sound emittance of engines, active rotor blades with embedded piezoelectric actuators to control the magnitude of blade vibrations were developed. In this regard, the HCC (Higher Harmonic Control) strategy aimed to realise an active blade pitch through excitation of the swashplate by dynamic actuators while the IBC (Individual Blade Control) technique fulfilled an active blade root pitch through replacement of the pitch-links with high-frequency actuators. In 1997 within a research project of the Massachusetts Institute of Technology, individual blade control for the purpose of reducing rotor vibrations and noise was realised by an active flexible blade. Active fiber composites were used to induce shear stresses and hence a twisting moment along the blade. For the reduction of helicopter interior noise the concerns DaimlerChrysler Aeroacoustics and Eurocopter presented in 1999 a new approach of active vibration isolation realised on a BK117 helicopter. They identified that the structure-born noise path via the gearbox struts is dominant, and stipulated that it should be sufficient to control the structure-born noise by applying additional control forces to the strut. They constructed the prototype of smart gearbox struts shown in Fig. 5 where the control forces were induced through piezoceramic shells. The reached results were reported in [Mai99].

These were examples of realisations preventing vibrations to arise from the source. Other approaches of active structural/acoustic control aim to inhibit the transmission of the vibrations through the structure of the aircraft. To reduce the interior noise the NASA in cooperation with Raytheon-Beech Aircraft used in the year 1999 in a prototype construction shown in Fig. 6 21 inertial force actuators and 32 microphones mounted directly to the aircraft frame of a Raytheon-Beech 1900D. The reached results were reported in [Cab01]. The actuators produce controlled inertial forces to counter excitation forces arising from the vibrating source. As an alternative to inertial force actuators, within the AST program the NASA investigated the structure

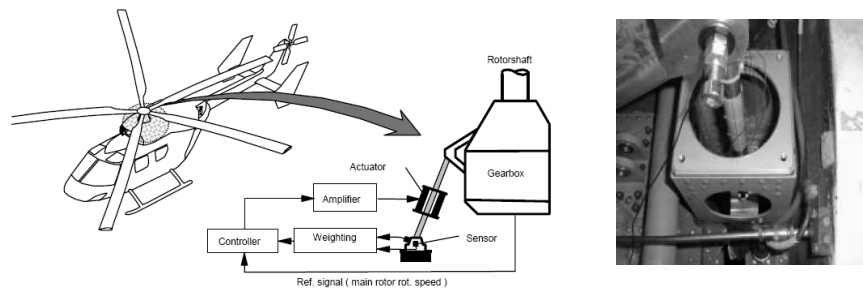


Fig. 5. DaimlerChrysler Aeroacoustics & Eurocopter smart gear struts

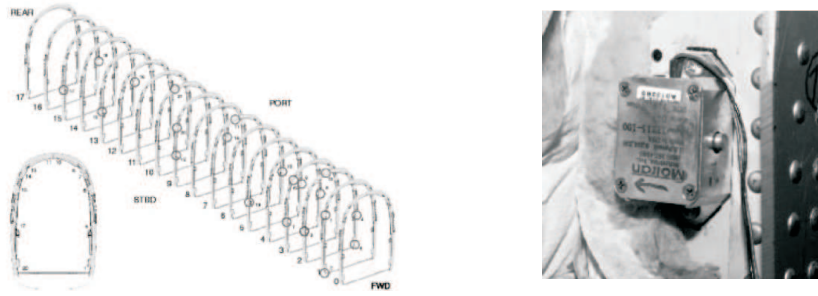


Fig. 6. NASA & Raytheon-Beech aircraft ASAC system with 21 inertial force actuators mounted to the aircraft frame

vibration reduction by means of Piezoceramic actuators bonded to the outer surface of the trim panel [Ste96]. In a similar approach the EADS Corporate Research Center France published in 2002 its results of using piezoelectric actuators to control vibrating plates and thus take influence on sound transmission in aircraft interior [Pet02].

The trend we noticed of giving up the active noise cancellation technology for the benefit of the active structural/acoustic control technology is confirmed with the revealing example of the further development of the only existing commercial active noise cancellation system for the reduction of aircraft interior noise, "UltraQuiet". Its developing concern, "Ultra Electronics", introduced Active Tuned Vibration Attenuators (ATVAs) that were mounted to brackets fitted to the aircraft fuselage as actuators in replacement of loudspeakers. The active tuned vibration attenuators of the "UltraQuiet" system undertook the same task as the NASA inertial force actuators mentioned above of damping structure vibrations and hence reduce sound emittance. Microphones were further on used as sensors. Through controlled excitation of the ATVAs the vibrations of the aircraft structure and hence the emitted sound were reduced.

Ultra Electronics, in cooperation with Bombardier Aerospace, reported in 2002 about the realisation of the above described system comprising 42 ATVAs and 84 sensors, of which 80 are microphones [Hin02]. Ultra Electronics stated in this publication three reasons for its choice to use active structural/acoustic control instead of active noise cancellation. Firstly, there are significantly more potential locations to install ATVAs than loudspeakers. This results in a "finer resolution" of potential actuator locations, which allows better spatial matching of the actuators relative to the sound field within the aircraft. Secondly, for a production system installing the ATVAs onto the fuselage is much simpler than installing loudspeakers through the trim. Thirdly, unlike active noise cancellation, active structural/acoustic control allows both noise and vibration control. Similar reasons are given by publications of other manufacturers and research organisations like in [Mai99], [Cab01], and [Pet02].

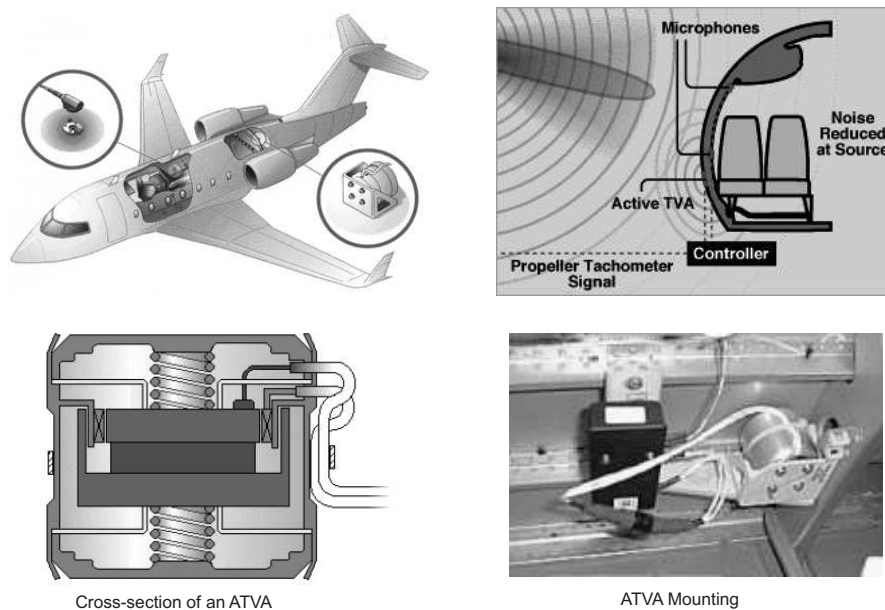


Fig. 7. Ultra Electronics' ASAC system with active tuned vibration attenuators (ATVA)

We extend the reasons for the use of active structural/acoustic control instead of active noise cancellation by the fact that active structural/acoustic control intervenes in the sound generation process at an early stage, effecting directly the the primary sound source. The control of a vibrating plate is simpler than the control of a three-dimensional sound field, since complex effects of room acoustics like interferences and near-field/far-field characteristics are not to be taken into account. Also, the effect of plant time delay of acoustical transfer paths, which is from the point of view of controllability unfavourable, does not exist.

In the mentioned publication [Hin02] from the year 2002, the manufacturers Ultra Electronics and Bombardier Aerospace announced that they had 53 Q400 aircrafts in service throughout the world, all with the active structural/acoustic control system installed. Currently, Bombardier Aerospace integrated this active structural/acoustic system as standard equipment of the Q-Series of Bombardier's Dash 8 in replacement of the former active noise cancellation system.

4 Active Aviation Headsets

This approach is in fact an active noise cancellation solution, but due to very different technical and practical boundary conditions it will be treated apart.

Since ten years, active aviation headsets have been representing the unique widespread and successful commercial application of active noise cancellation. In fact it is a noise cancellation task in a very confined space where there is no need for global noise cancellation with multiple sensors and actuators. The following facts explain how the noise cancellation control task in headsets is simplified.

- Each ear cup of an active aviation headset is a Single Input / Single Output system, as shown in Fig. 8.
- The vicinity of the sensing microphone to the ear reduces the general three-dimensional sound field control task to a noise reduction problem at a unique point of space.
- The proximity of the actuator to the sensing microphone reduces the time delay of the Control response.
- The almost unchanging conditions within the ear cup lead to a relatively unchanging plant compared to a general active noise cancellation task in a room with changing reflection characteristics through potential geometrical rearrangements.

These favourable technical boundary conditions related to the ear cup enclosure made an industrial application possible at a very early stage of the research in the field of active noise cancellation. Additionally, from a cost-effectiveness point of view, an active aviation headset is designed for use in any environment, and hence enables a volume production while an active noise cancellation system for a room is a custom-made solution for each different environment. The problem of custom-made production was noticed by C.H. Hansen who tried itself to implement active noise cancellation solutions for rooms [Han04]. He insisted that a breakout of the active noise cancellation in rooms could only be reached if the researchers try to develop less specific and more generic solutions which could be implemented and adapted by less specialised staff. Already at the end of the eighties, the first commercial successful active aviation headsets were manufactured independently by Bose and

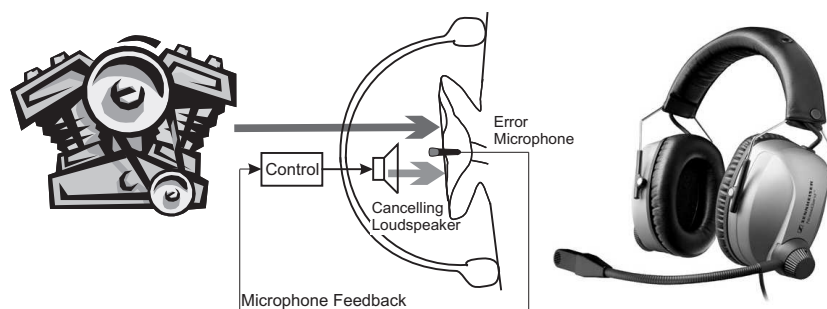


Fig. 8. Active aviation headset, theory and commercial application: ANC Headset HMEC450 of Sennheiser

Sennheiser . From that time on, many manufacturers like David Clark, Peltor, Telex etc. are developing and successfully bringing to market active aviation headsets.

5 An Aviation Communication Headset Prototype with Digital Adaptive Noise Reduction

Commercial active aviation headsets have been based on non-adaptive, analogue, and mainly feedback control techniques. However, during the last two decades the digital signal processing has been increasingly used by researchers in the domain of active noise control. The trend of ever-growing performance of processors simultaneously to the reduction of their size and costs has made possible the use of adaptive algorithms in practical applications. Particularly adaptive digital feedforward control techniques are considered to be realistic and promising approaches to be implemented in commercial active aviation headsets. Numerous works describe different active noise controller structures and optimisation algorithms by use of either feedback or feedforward strategies. Especially in active headsets, the simultaneous use of both control strategies could be of great benefit [Kuo96].

In the following, a new prototype of an active noise cancellation headset is presented. This work was achieved in cooperation with the concern *Sennheiser electronic*. The noise cancellation strategy uses an adaptive feedforward control technique. The advantage of adaptive feedforward active noise control is the ability to control high frequencies and to focus on the reduction of the dominant frequency band of the disturbance. However, the implementation of digital adaptive algorithms is linked to high expenses. In a commercial appli-



Fig. 9. Testing a new prototype of active aviation headset in a Dornier DO228-212

cation these expenses should be kept within a realistic limit. A promising issue was to confer a part of the cancelling task to a non-adaptive feedback controller, in order to save calculating and memory resources. This was achieved by a combination strategy of feedback and adaptive feedforward control, in which the adaptive feedforward component is intended to cancel high frequencies and to focus on specific dominant noise, while the feedback component is designed to cancel low frequency noise. More detailed informations related to the control strategy were provided by the authors in former publications [Fou07],[Wol07].

The realised prototype, which processes the control strategy by an integrated fixed-point DSP platform, was tested in the interior of a *Dornier DO228-212* turbo-prop aircraft, as shown in Fig. 9. During the flight, the sound pressure level averaged 105 dB SPL.

Fig. 10 presents the results of the active noise reduction of the developed new headset prototype in comparison with a current commercial ANC headset. In the relevant frequency range of the disturbance of the turbo-prop aircraft (up to 1 kHz) the prototype outperforms the commercial headset in terms of noise reduction at an average of 15 dB. Especially within the dominant frequency band of the noise disturbance between 80 and 150 Hz the new prototype was able to outperform the commercial headset by 20 dB to reach a total active noise reduction of more than 30 dB. The adaptive digital control techniques offer a great improvement potential to the performance of active noise reduction aviation headsets. Nevertheless, the perspectives of commercial success in the future will depend on the ability to implement these techniques at a reasonable expense-benefit ratio. This includes the acceptance of a minor loss of performance for the benefit of a considerable save of realisation costs. Some issues could be given by the realisation of hybrid

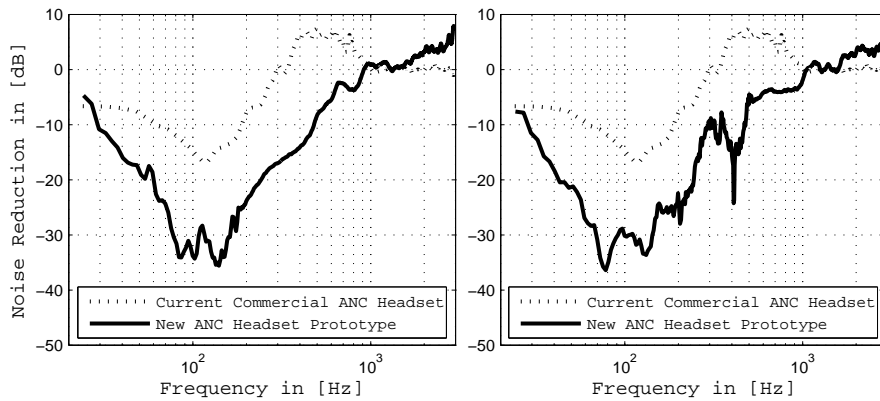


Fig. 10. Active noise reduction of a new prototype of ANC headset for the left and the right ear cup

analogue/digital control schemes or the development of fast algorithms to be implemented on low cost digital platforms.

6 Conclusions

This contribution provided an overview of active approaches used for the protection of passengers and pilots from high level noise in aircraft cockpits. Three approaches were presented: Active noise cancellation, active structural/acoustic control and active aviation headsets. These approaches are linked to different technical and financial boundary conditions, which implied distinct degrees of success. Related to each technique, some examples of applications of leading aerospace manufacturers and research organisations were given and their success- or failure-reasons were analysed. Finally, a prototype of a new generation of aviation headsets was presented.

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