Implementation of Active Noise Control on an Embedded System

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Abstract: Propeller-driven passenger aircraft are becoming increasingly popular due to their fuel efficiency and low operating costs. However, propeller noise is a major discomfort factor for passengers and crew members. Active noise control (ANC) is a promising technology for reducing propeller noise in aircraft cabins. The joint project CATECO (Cabin Acoustics at the hearT of ECO-responsibility) aims to develop a model-based acoustics aircraft design to evaluate new, climate-neutral aircraft and cabin concepts. As a part of the project CATECO works, this research paper presents the design and implementation of a small, lightweight, and reliable ANC system for propeller-driven passenger aircraft, implemented on an embedded system based on a microcontroller, and it is able to achieve significant noise reductions in real-time. The ANC system uses a feedforward control algorithm to cancel out low-frequency propeller noise, which is developed using MATLAB® and Simulink®. The research paper presents the results of experimental test setup of the ANC on embedded system in a real aircraft cabin demonstrator located at Hamburg University of Applied Sciences.

Keywords: active noise control, embedded systems, real-time noise reduction, microcontroller, propeller-driven aircraft, propeller-noise, cabin noise, aircraft cabin, passenger comfort

Introduction

In recent years, propeller-driven passenger aircraft have gained significant traction within the aviation industry due to their perceived advantages in fuel efficiency and operational cost-effectiveness [1]. However, alongside their economic appeal, propeller-driven aircraft pose a major challenge for the cabin acoustics, as high tonal noise in the low frequency range are expected in the cabin. Prolonged exposure to high levels of noise during flight can lead to increased stress, fatigue, discomfort, and overall dissatisfaction with the flight experience for passengers as well as crew members.

To address the challenge of reducing low-frequency noise through passive means, a considerable increase in mass would be necessary. However, Active Noise Control (ANC) technology offers an achievable technical solution to the issue of propeller noise in aircraft cabins [2]. This approach offers several advantages, including the ability to maintain aircraft weight at manageable levels, thus helping to maintain optimal fuel efficiency and operational performance. Moreover, ANC systems have the capability to track and adapt to varying sound fields, allowing for efficient reduction of noise levels across different flight conditions and environments. This adaptability is particularly crucial in aircraft settings where noise levels can fluctuate during take-off, cruising, and landing phases.

The introduction of ANC technology in commercial aircraft, starting with the SAAB 340 and its successor, the SAAB 2000, demonstrates the industry's recognition of the importance of addressing cabin noise for enhancing passenger comfort. By implementing ANC systems, aircraft manufacturers can greatly improve the overall flight experience for passengers by reducing cabin noise levels, which typically hover around 80 dBA. However, integrating ANC systems with other cabin functions can be challenging due to their high level of complexity. It is essential to note that while ANC offers effective noise reduction, it may not completely eliminate all noise problems. Combining ANC with passive techniques can often yield the best results, providing comprehensive noise mitigation across a broad spectrum of frequencies and environmental conditions. Therefore, a holistic approach that integrates both passive and active noise control methods is often recommended to achieve optimal cabin comfort and noise reduction in aircraft.

In line with this, the joint project CATECO (Cabin Acoustics at the hearT of ECO-responsibility) aims to research a model-based acoustic aircraft design to evaluate new, climate-neutral aircraft and cabin concepts. Building upon insights from previous studies [3][4], this paper focuses on the design and implementation of a small, lightweight, and reliable ANC system on an embedded system based on a microcontroller platform capable of effectively reducing propeller noise in real-time, thereby enhancing passenger comfort and satisfaction during flight.

Cabin Noise in Propeller Aircraft

Propeller aircraft have two main exterior noise sources: the fuselage boundary layer, and the propellers [4]. The boundary layer noise is random broadband with mainly high-frequency characteristics. Such noise is currently reduced using passive insulation techniques. The dominant noise source in propeller aircraft is propeller noise [4]. This noise results from the periodic changes in the pressure on the fuselage caused by the propeller blades passing by. Propeller noise consists of several low frequency tonal components associated with the propeller Blade Passaging Frequency (BPF) and its harmonics. Figure-1 shows the typical cabin noise spectrum measured in an ATR72-600 propeller aircraft. During take-off, propeller engines rotate at a higher revolution per minute (RPM) than during cruise flight, resulting in a high first BPF with a significant number of harmonics and a high sound pressure level (SPL) experienced within the cabin as compared to cruise flight condition. The most interesting frequency range for ANC is approximately 50–500 Hz, where dominant low frequency tonal noise components observed during take-off and cruise flight.

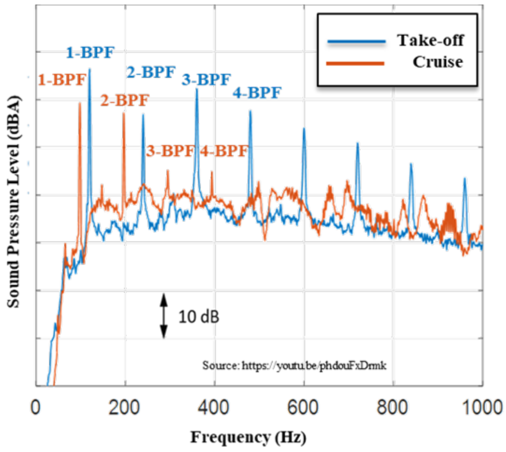


Figure-1: Typical cabin noise spectrum measured in an ATR72-600 propeller aircraft [3].

Narrowband Feedforward ANC Model

Figure-2 shows a basic block diagram of single channel narrowband feedforward ANC model using 1-microphone and 1-loudspeaker for reducing periodic acoustic noise in a propeller aircraft cabin. Here, tachometer or speedometer signal is used as a non-acoustic sensor signal to generate synchronized reference signal internally by ANC system at BPF. This approach offers the following advantages [5]: 1. Avoids unwanted acoustic feedback from the cancelling loudspeaker on the reference microphone. 2. Avoid nonlinearities and aging issues with the reference microphone. 3. Using an internal reference signal enables independent control of each harmonic.

Adaptive Feedforward Controller and Frequency Domain Filtered-X Least Mean Square Algorithm (FDFxLMS)

The ANC system can be constructed using N loudspeakers and M error microphones. Figure-3 shows the block diagram of the adaptive feedforward control system. In this block diagram, a single mono frequency tonal noise source is assumed, and the angular frequency ω of the disturbance is known from the noise source via the reference signal. Here, x is the reference signal, $\mathbf{d}$ is the complex noise field, $\mathbf{e}$ is the complex sound pressure measured at error microphones, $\mathbf{u}$ is the complex destructive interference control signal for the loudspeakers, and $\mathbf{G}$ is the complex transmission control matrix of the ANC system.

The adaptive feedforward control for tonal noise can be implemented using the FDFxLMS algorithm, and the iteration equation for active control using N loudspeakers and M error microphones in the frequency domain [3] is given as follows:

$$\mathbf{u}(n+1) = (\mathbf{I} - 2\mu\gamma\mathbf{I}) \cdot \mathbf{u}(n) - 2\mu\mathbf{G}^{\mathrm{H}} \cdot \mathbf{e}(n) \qquad [\mathrm{V}] \quad (1)$$

In equation (1), $\mathbf{u} = [u_1, u_2, \dots u_N]^{\mathrm{T}}$ is the complex column vector of the control signals for the N loudspeakers, $\mathbf{e} = [e_1, e_2, \dots e_M]^{\mathrm{T}}$ is the complex column vector of the error signals of the M error microphones, $\mathbf{G}$ is the complex transmission control matrix of the size $N \times M$, $\mathbf{G}^{\mathrm{H}}$ is the complex conjugate transpose of the $\mathbf{G}$ matrix, γ is the leakage factor, $\mathbf{I}$ is the identity matrix of the size $N \times M$, μ is the fixed step-size of the algorithm, and n is the time-step of the algorithm.

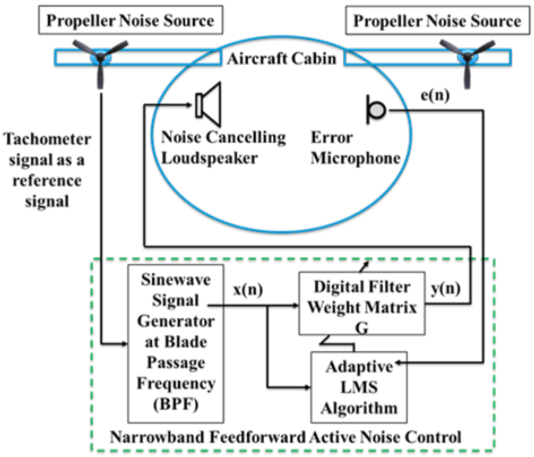


Figure-2: Shows an equivalent representation of the narrowband single-channel feedforward ANC model within the context of a propeller aircraft scenario.

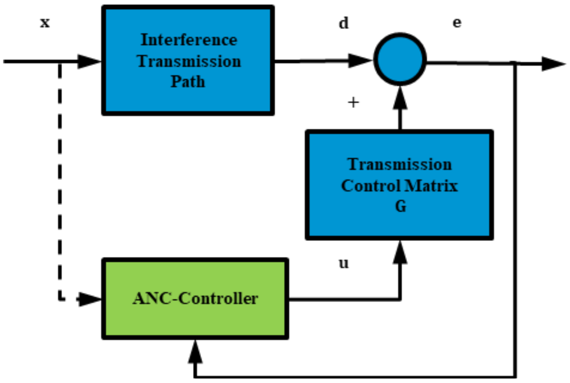


Figure-3: The block diagram of the adaptive feedforward control system [3].

ANC Implementation on Embedded System

ANC Hardware Implementation

Figure-4, the yellow dashed line rectangular box shows the ST Microelectronics (STM) STM32F7 discovery board (STM32F746G-DISCO), which was chosen as an embedded system. The STM32F746G-DISCO board is equipped with STM32F746NGH6 ARM® 32-bit Cortex®-M7 core-based microcontroller, clock frequency up to 216 MHz, 1 Megabyte (MB) of flash memory and 340 KB of Random Access Memory (RAM), three 12-bit Analog to Digital Converters (ADCs), two 12-bit Digital to Analog Converters (DACs), two Serial Audio Interfaces (SAIs), thirteen 16-bit timers, two 32-bit timers, two watchdogs timers, and one SysTick timer, in Ball Grid Array (BGA) 216 package. The on-board peripherals and hardware features, such as integrated ST-LINK/V2-1 debugger and programmer for the STM32 MCU, 10/100-Megabit (Mb) Ethernet, microSD™ card, SAI audio codec, stereo input and output over 3.5 mm audio-in and audio-out jacks, two Micro-Electro-Mechanical Systems (MEMS) digital microphones, and stereo speaker outputs, supports the development and testing of initial audio applications, including ANC algorithms.

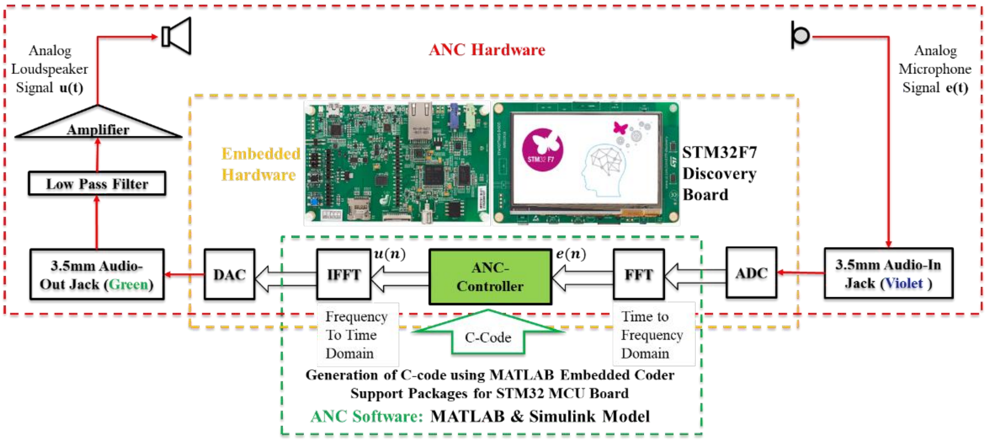


Figure-4: Hardware and Software implementation of single channel ANC with STM32F7 Discovery Board.

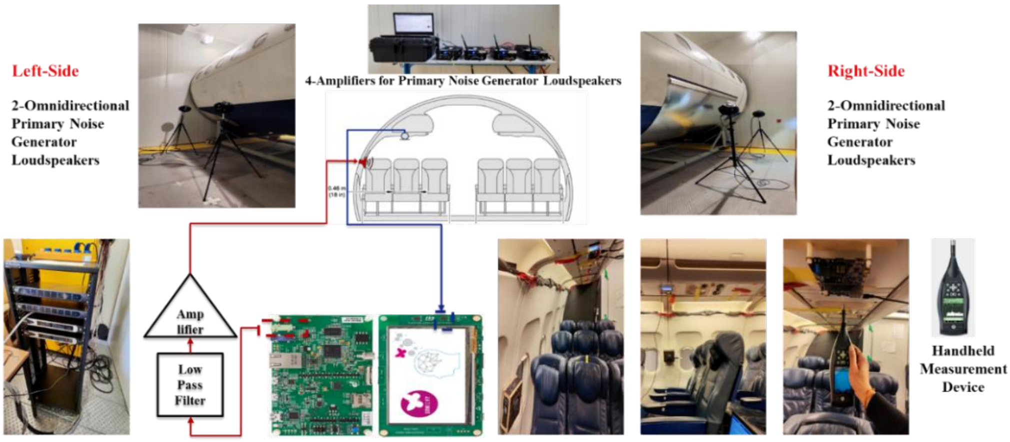


Figure-5: Experimental test setup of the single channel ANC with STM32F7 discovery board in an AIRBUS A320 aircraft cabin demonstrator located at Hamburg University of Applied Sciences (cabin cross-section sourse: AIRBUS A320, Aircraft Characteristics - Airport And Maintenance Planning Manual, Revision No. 39 - Dec 01/20).

Figure-4, the red dashed line rectangular box shows the single-channel ANC hardware implementation with STM32F746G-DISCO. The on-board single MEMS microphone (IMP34DT05) served as the error microphone, while a GBS-low profile woofer (GBS-85N25PR07-04, 4 Ohm, 12 Watt) was utilized as the secondary noise cancelling loudspeaker in the setup. The control signal for the loudspeaker underwent initial filtration through a low-pass filter (the t.racks 8x8 Matrix) followed by amplification using a power amplifier (Sirus I-Amp 8.150).

ANC Software Implementation

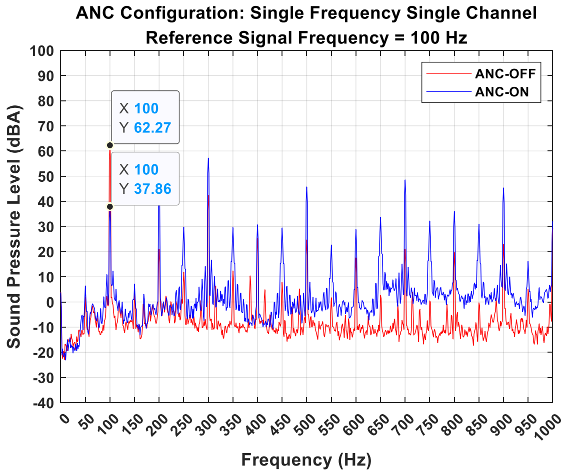
Figure-4, the green dashed line rectangular box shows the ANC software implementation, which uses the adaptive feedforward control algorithm for noise cancellation and was developed using MATLAB® and Simulink®. The model-based design of the FDFxLMS ANC algorithm for single frequency tonal noise was realized using Simulink blocks known as ANC-Model, and the ANC-Model's parameters were formalized in MATLAB scripts. The ANC-Model was mainly divided in 3 subsystems: 1. frequency to time domain conversation using fast Fourier transform (FFT), 2. ANC-Controller, 3. time to frequency domain conversation using inverse discrete Fourier transform (IFFT). To generate optimized C-code of the ANC-Model, the Embedded Coder support packages for STM32F746G-DISCO were successfully installed with MATLAB and Simulink.

ANC Test Setup

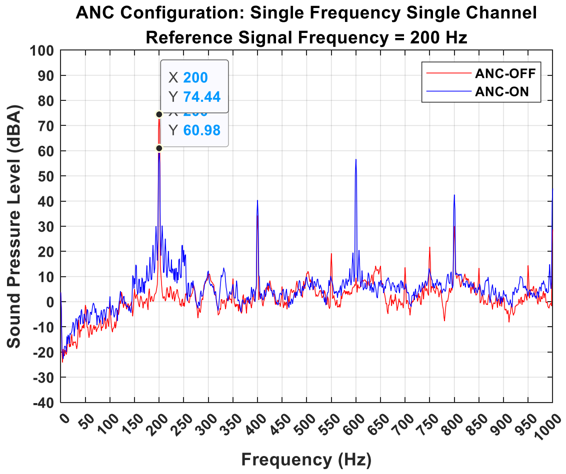
Figure 5 shows the complete experimental test setup of the single channel ANC with STM32F7 Discovery Board (STM32F746G-DISCO) in an Airbus A320 aircraft cabin demonstrator located at Hamburg University of Applied Sciences. The 4-omnidirectional loudspeakers were positioned outside the cabin to generate primary noise for the ANC test setup, in contrast to real propeller engines. The STM32F746G-DISCO was mounted above the middle seat head position. The on-board single microphone served as an error microphone and the secondary loudspeaker was mounted on the sidewall panel at the head position. During the ANC test, the handheld analyser (Brüel & Kjær, Hand-held Analyzer Type 2270) was utilized as the standard measuring instrument, and all measurements were taken at the microphone position for both ANC-ON and ANC-OFF conditions, as seen in Figure 5.

ANC Test Results

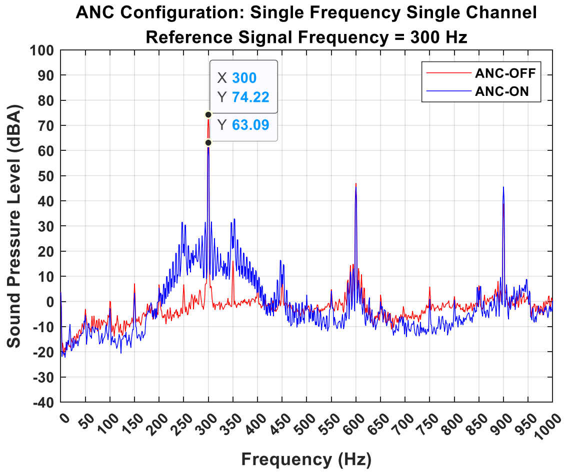
ANC experiments were conducted with a single frequency, single-channel configuration for the primary noise at 100 Hz, 200 Hz, and 300 Hz. Figure-6 shows the results of the plots (a), (b), and (c) corresponding to the experiments performed for the primary noise frequencies of 100 Hz, 200 Hz, and 300 Hz, respectively. Table 1 shows the tonal noise reduction obtained at each primary noise frequency.



(a) primary noise at 100 Hz



(b) primary noise at 200 Hz



(c) primary noise at 300 Hz

Figure-6: ANC test results for the primary noise (a) at 100 Hz; (b) at 200 Hz; and (c) at 300 Hz.

Table-1: The tonal noise reduction at primary noise frequency.

Primary Noise Frequency	ANC-OFF (dBA)	ANC-ON (dBA)	Noise Reduction (dBA)
100 Hz	62.27	37.86	24.41
200 Hz	74.44	60.98	13.46
300 Hz	74.22	63.09	11.13

Conclusion and Future Work

In this study, we have presented the design and implementation of an ANC system tailored for propeller-driven passenger aircraft, utilizing an embedded system based on a microcontroller platform. Through experimental tests conducted in a real aircraft cabin demonstrator, we have shown significant noise reductions, as summarized in Table 1, at primary frequencies of 100 Hz, 200 Hz, and 300 Hz with single frequency single channel ANC configuration with 1-microphone and 1-loudspeaker. This lightweight and reliable ANC solution offers a practical approach for enhancing passenger comfort and satisfaction during flight, without adding significant weight or material complexity to the propeller aircraft.

Further optimization of ANC algorithms and system parameters to enhance noise reduction across a broader frequency spectrum, including consideration of single frequency with higher harmonics and multifrequency with higher harmonics. Exploration of 2-channel ANC implementation with embedded systems and testing to improve noise reduction capabilities. Furthermore, investigating the integration of ANC with other cabin functions and systems could lead to comprehensive solutions for optimizing passenger comfort and cabin acoustics in propeller-driven aircraft.

Acknowledgements

The research discussed in this paper was conducted within the framework of the project CATECO, which is funded by the Green Aviation Technology funding program of the Hamburgische Investitions- und Förderbank. The project is a collaborative effort involving partners from the Hochschule für Angewandte Wissenschaften Hamburg, AIRBUS Operations GmbH, and the German Aerospace Center (DLR) Institute of System Architectures in Aeronautics.

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