AUDIO INTERIOR FOR LIGHT AIRCRAFT

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OVERVIEW

This paper introduces the initial steps in developing a combined active noise- and audio system for a (very) light jet aircraft. An overview of the project is given including the current status. First results from the cabin noise assessment are shown, describing the measurement setup/equipment and first frequency spectra at various cabin positions. The measurement was done in a light jet of type Cessna Citation Bravo. Furthermore, a FE-model of the aircraft cavity mock-up is presented and verified in terms of eigenmode analysis and convergence region. A multichannel active noise controller based on a fast implementation of the Fx-LMS is being assessed for use in the current project in combination with an audio system.

1. INTRODUCTION

The purpose of most forms of Active Noise Control (ANC) is a general reduction of the sound pressure level or its equalization which is achieved by means of microphones as sensors and loudspeakers as counter-noise sources. This technique is based on the principle of superposition, creating zones of quiet where noise and counter-noise sound fields overlap and is usually employed in low frequency noise environments below 1 kHz. Passive noise reduction methods in this frequency range are often too bulky and too heavy for feasible use in small compartments. This is especially the case for vehicles such as light aircraft.
The current research project “Audio Interior for small Aircraft” (AIK) at the Mechatronics Department of the Helmut-Schmidt-University (HSU) is aimed at developing an audio-system for the cabin area of a small jet aircraft which, at the same time, should also function as an effective noise reduction system in order to enhance the cabin comfort as well as the audio quality. Noise in small jet aircraft is typically dominated by engine- and turbulence-induced noise, resulting in broadband noise excitation with turbine-specific peaks.
Main aspects of current research include the development of well suited algorithms for the combined ANC and audio approach as well as the implementation of a complete system and it’s verification with simulations and measurements. The system is to be integrated and tested in the interior of an acoustic mock-up, which is fabricated by the industrial project-partner “Innovint, Aircraft Interior GmbH”.
This paper is intended to define the position the current project holds in the field of active noise control. Furthermore, first concepts and results at the current stage will be presented.

2. THE AIK PROJECT

The “Audio Interior for small Aircraft” project may be divided into different specific phases, defining the required course and methodology to be followed throughout research. Amongst these, the most important are

- Mock-up: Conception, development and fabrication.
- Ascertaining typical cabin noise in (very) light jets and specification of acoustic demands (in terms of system components and algorithms).
- Development and fabrication of the cabin interior, integrating the audio/ANC system and determining the acoustic properties of the mock-up.
- Proficiency tests and experimental improvement of the system in the mock-up as well as optimization of sensor- and actuator positions and of actuator power requirements. Also, design and adaptation of control algorithms.

Knowledge of the noise spectrum in different flight-sequences, such as climb, cruise and descent, is required in order to characterize the sound field inside the cabin, to determine critical frequencies and to be able to create a primary sound field that is as realistic as possible. Furthermore, requirements towards the audio/ANC-equipment and algorithms may be assessed from parameters such as the maximum noise level and the Speech Transmission Index (STI).

The acoustic properties of the mock-up are to be measured and compared with the collected data. Changes in the cabin environment such as further cabin components or linings that introduce a variety of materials with different damping characteristics must be analyzed. To optimize the audio/ANC-system, resulting transfer paths from actuator positions to error sensors must be measured. Together with numerical analysis of optimal positioning, power requirements may then be optimized to achieve an efficient system in terms of power consumption as well as control profit.

Phases consisting of mock-up and interior design and fabrication are done in cooperation with the project partner. The mock-up itself is comparable in type (inner and outer dimensions) to other (very) light jets (VLJ’s) such as the Embraer Phenom 300 or the Cessna Citation Bravo, i.e. 4-7 seats (4 in club-arrangement, 2-3 in the front and back compartment). This will be further discussed in the following section when describing the cabin model.

3. PROJECT STATUS

At the current stage, the foundation for work in the actual mock-up is being set. This includes a measurement flight in a (very) light jet, first Finite-Element (FE) models of the mock-up cavity, experiments with multichannel control concepts and the evaluation of each. The mock-up itself has not yet been fully completed, requiring further work on the hull of the cockpit area and the general interior. A first version of the mock-up cabin will include very basic interior elements consisting of foams and wood. This simplifies the modification and optimization of sensor and actuator positions for preliminary measuring purposes i.e. transfer functions and real acoustic behaviour, before final integration of the components.

The following subsections briefly describe how these steps were accomplished and deliver an overview of first results.

3.1. Typical Cabin Noise Assessment

In order to determine the noise characteristics during different flight phases inside of a (V)LJ, measurements were done in a Cessna Citation Bravo. This jet type has a passenger compartment of approx. 4 m length and 1.46 m height, measured from the gangway floor to the ceiling. The cabin width was measured to be approx. 1.4 m. The engines are of type Pratt and Whitney PW 530A and are connected directly to the aft fuselage. All air conditioning was turned off during data acquisition. The measurements may be divided into three parts:

- Constant readout of signals from 5 microphones at fixed positions (s. Fig. 1) throughout the entire flight from takeoff to landing.
- Step-wise sound-field mapping with an array of 5 microphones at ear level of a seated passenger throughout the cabin area during the cruise state.
- Constant readout of 2 microphone signals at the ear positions of an artificial head.

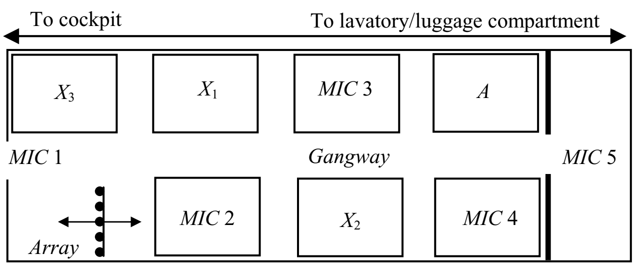


Fig. 1: Measurement configuration in the cabin area. Squares represent seats, *X* passengers, *MIC* microphones and *A* is the artificial head.

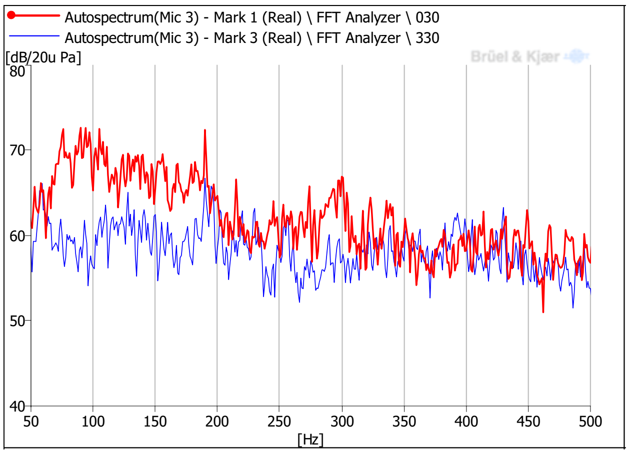
The microphones used in the fixed positions as well as in the array were of type Brüel & Kjaer 2671. 2 Brüel & Kjaer frontends type 3560B with 5 channels each were used for data acquisition. The artificial head was an HMS III Digital by Head Acoustics. The data was saved on 2 notebooks. During descent a charge accelerometer, Brüel & Kjaer Type 4374, was applied to the window covering next to passenger X_2. Each data channel was accordingly calibrated. As all components were battery-powered, no further power sources were required.

Microphones 2, 3 and 4 were attached to the seat headrest as shown in Fig. 2. The distance from microphone to headrest was 15 cm and 65 cm from microphone to the seat area, as required by DIN ISO 5129 [1].

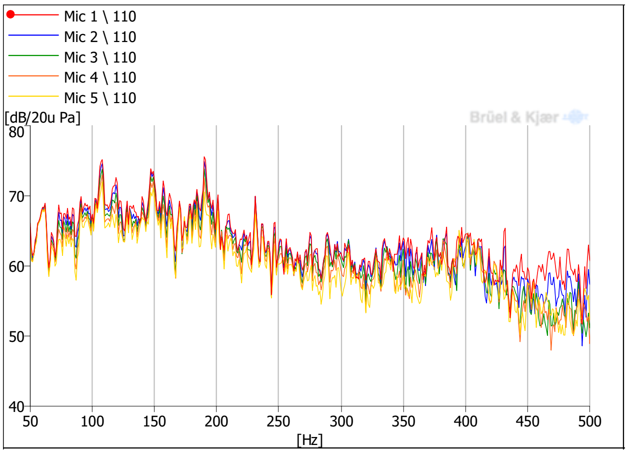
Fig. 2: Example of the microphone holder at position MIC 3. The artificial head HMS III can be seen on the seat behind it.

The sound-field mapping was done from back to front for each side. Data acquisition was done in equal intervals of 0.1 m at 1.18 m height (measured from the gangway floor). The microphones were aligned in a line array, starting 0.05 m from the cabin wall, firmly attached to a rod which was moved along the gangway. Data from the complete seat area was collected, excluding the lavatory/luggage compartment.

Although the mapping itself is still in evaluation, first results of the assessed data are shown in Fig. 3 a) and b). The frequency spectrum at 3 positions is shown for the left cabin side during cruise at 24000 ft with 268 KIAS (indicated air speed in knots).



a) Center array microphone at 0.3 m and 3.3 m from rear compartment divider.



b) All 5 array microphones at 1.1 m from rear compartment divider.

Fig. 3: Frequency spectrum plotted against the unweighted sound pressure at different locations of the left side cabin measured from the rear compartment divider in the ANC-relevant frequency range of 50 Hz – 500 Hz.

The results in Fig. 3 a) were taken from the center array microphone (located at the seat center) at instances, where the array was in the back (upper curve) and front of the cabin passenger area (lower curve). Sound pressure differences of up to 15 dB may be seen here when comparing the back and front positions during cruise. In Fig. 3 b) microphone 1 was closest to the fuselage, microphone 5 closest to the gangway. The spectral shapes of the curves are similar but a pressure difference between inner- and outermost microphone is detectable. At this position the difference is between 1 and 5 dB up to 440 Hz depending on the considered frequency. In total, the outer microphone delivers 91.4 dB, the inner 88.8 dB. When considering Fig. 3 b), dominant peaks between 100 Hz and 250 Hz are visible. However, further detailed analysis of the flight data is required to be able to completely determine and interpret the cabin sound field and globally effective modes. A generalization is not feasible on the basis of the preliminary results presented herein. It should also be noted that these results do not show the tonal penetration of engine vibrations as clearly as described in [2] for typical jet engine noise in aircraft.

3.2. Numerical Model of a Very Light Jet Cavity

The Finite Element Method (FEM) has become an important tool to solve acoustic problems during the past years. Numerical computation methods are used to deliver predictions of the acoustic properties for complex geometries as seen in aircraft cabins.

A goal of simulating room acoustics with an according model is determining transfer functions between error sensors and actuators as well as receiving an impression of the modal characteristics. The determined transfer functions may then be used to simulate active noise control systems in order to estimate performance bounds and also to optimize sensor and actuator positions. A numerical model of the aircraft cabin furthermore allows a prediction of acoustic behaviour when changes are applied to the cabin system such as the application of further interior structures and materials. Using technical drawings of the mock-up, a simplified cabin model geometry was created in COMSOL MULTIPHYSICS [3]. Simplifications were applied where no important changes to the acoustic properties could be determined (comparing the sound field for a certain eigenfrequency before and after simplification). Such analysis is preferable in a prototype stage in order to be able to quickly determine first results. The geometry of the model accounts for the internal structure including 4 passenger seats and 2 seats in the cockpit as well as the simplifications to avionics and seats. The seats were purposely modelled without legs, as these create high computational load when running calculations on the FE-model and do not significantly affect the sound field.

A first model was made with 71948 elements and 106064 degrees of freedom. An eigenvalue analysis was conducted using acoustically sound hard boundary conditions, thereby simulating the worst case scenario without damping. This analysis showed that 179 eigenmodes exist below 500 Hz. The first mode is found at approx. 36.3 Hz and the highest at 499.5 Hz. The latter is shown at passenger-head level in Fig. 4.

The reliability of the model was checked by increasing the number of elements and degrees of freedom to 203093 and 289115 respectively. Only a slight shift of the eigenmodes was determined (the highest mode shifted from 499.5 Hz to 499.2 Hz). Furthermore, using a damping factor of 1%, the relative shift of eigenfrequencies was determined to be 0.01%. The model converges for frequencies up to 500 Hz.

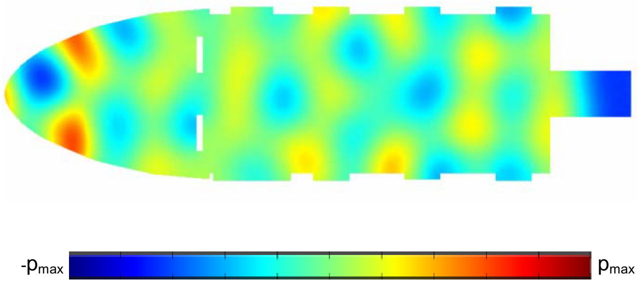


Fig. 4: Sound pressure distribution at the ear level of a sitting passenger for the eigenfrequency 499.5 Hz (top view).

3.3. Control Concepts

In order to drive the actuators of an active noise control system correctly, the control signal is calculated from the available error- and reference signals. Typically, in the field of active noise control, the error signal itself or a value generated from the measured error signal is to be minimized. This may be realized either by feedforward-, feedback- or hybrid control, the latter being the combination of the other two. The choice of a control concept is highly dependent on the type of sound field that is to be minimized and also on the choice if this minimization is to be achieved globally or locally.

First experiments are currently being done with a feedforward multichannel active noise control system in an arrangement with 6 error microphones, 6 actuators and one reference signal. The principle of feedforward control is shown in Fig. 5 where $x(t)$ is the reference signal, $y(t)$ is the control signal and $e(t)$ is the error signal. The adaptation algorithm block represents any kind of approach toward the adaptation problem and may include further filters or frequency domain transforms.

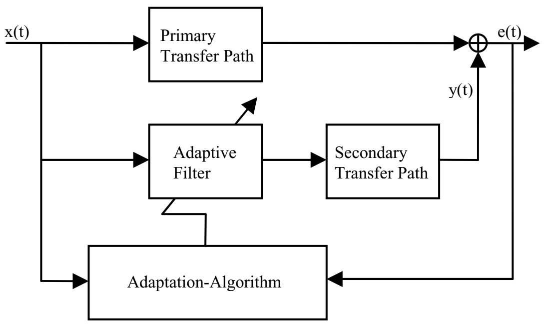


Fig. 5: General feedforward control algorithm structure.

The experimental system is set up in a typical pattern as would be found aboard a small jet aircraft using 6 seats with error microphones placed at approx. head level. The actuators are placed between the seats below seat level. The setup is comparable in dimensions to that of the previously described cabin for the measurement flight. Experiments are being conducted using a fast implementation of the standard Fx-LMS for control [4]. In this type of feedforward control, the reference signal x is filtered with an estimate (or model) of the secondary transfer path which includes the speaker system and the path between speaker and error microphone. The fast implementation of the control algorithm is especially effective when using a high amount of channels, as is shown in Tab. 1 in comparison to the standard implementation.

Ref. Sensors	Actuators	Error Sensors	Complexity MACs		Ratio
			Fx-LMS	FastFx-LMS	
8	4	4	45060	17520	39%
8	8	8	163848	35568	22%
8	16	16	622608	74736	12%

Tab. 1: Computational efficiency of the fast exact implementation of the Fx-LMS compared to the standard Fx-LMS for broadband noise. Control filter length: 256; Sec. path model length: 32.

For feedforward control in a (very) light jet, a main problem will be to determine appropriate reference signals that are well correlated with the noise present in the seat area. This is due to the fact that tonal noise peaks are not as dominant as in a propeller aircraft and that the broadband excitation is in part due to boundary layer noise [5].

The combination of active noise control with an audio system has been previously examined for non-headset active noise systems, e.g. in [6] and [7]. As shown in Fig. 6, the control principle is based on removing the musical interference in the measured error signal. This system may also be used to determine the secondary transfer paths between loudspeakers and error microphones in an "on-line" fashion, increasing the systems performance in case of varying transfer path characteristics. These may be caused, for example by moving passengers or objects that are placed in the area of control. In the case of a solely feedforward system with reference signals that are well correlated to the noise disturbance, compensation of musical interference is not necessarily required to ensure stability. This was verified in a number of systems including a 2x2 system with 1 reference signal for active noise reduction in daybeds.

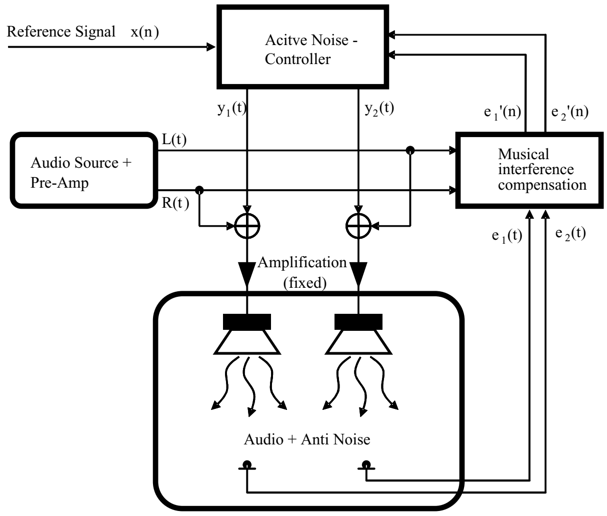


Fig. 6: General principle of compensating musical interference in an active noise control system [6].

4. CONCLUSION

Initial steps in developing a combined active noise- and audio system for a (very) light jet aircraft were introduced. An overview of the project was given including the current status. First results from a cabin noise assessment measurement in a light jet were shown, describing the frequency spectrum at various cabin positions. Furthermore, a FE-model of the mock-up cabin was created and analysis of the eigenmode-behaviour was done. A multichannel active noise controller with a fast implementation of the Fx-LMS is being assessed for use in the current project.

Upcoming research will be focussed on analysis of the acquired data from the measurement flight. The results from this analysis are fundamental for all further research, especially for the required control method and the optimal actuator and sensor positions. The latter must consider the restrictions and limitations defined by the aircraft cabin. Also, the FE-model is to be expanded with proper surface impedances. These have been determined for a variety of actual interior materials, including leather and other lining materials as well as carpets of different thicknesses. Measurements were done using an impedance tube (Kundt's Tube) for each surface sample [8].

5. ACKNOWLEDGEMENTS

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6. LITERATURE

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