Evaluation of robust position optimization of loudspeakers and microphones for an adaptive active noise control system

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ABSTRACT

The aim of active noise control systems in aircraft cabins is the noise reduction in a monitoring region, where the head of a sitting or a standing person is located. The achievable noise reduction strongly depends on the positions of loudspeakers and microphones. This work investigates the effect of perturbations in the acoustic path in the frequency range below 300 Hz of a single-aisle fuselage mock-up. A genetic algorithm is used to find an optimal robust configuration of loudspeakers and microphones from a pre-defined superset, in which the mean sound pressure at all monitoring microphones is minimized. The positions of loudspeakers and error microphones in the lining as well as a frequency-selective weighting parameter are free parameters of the nonlinear optimization problem. Measuring results obtained in an experimental test environment show good performance of the robust configuration at three targeted tones, compared to a nominal configuration created with an undisturbed acoustic path. The robust optimization enhances the overall noise reduction at the monitoring microphones and reduces the variability due to perturbations.

Keywords: Active Noise Control, Optimization, Transducer position
I-INCE Classification of Subjects Number: 38.2

1. INTRODUCTION

Propeller engines, such as counter rotating open rotors, generate narrow band – almost tonal – low frequency noise ($f < 300$ Hz). In order to guarantee passenger comfort, the expected noise level inside the aircraft cabin has to be reduced down to an acceptable value. This can be achieved with Active Noise Control (ANC) treatments, as reported in (1). The locations of loudspeakers and microphones are of major importance for the achievable noise reduction. The present paper follows the results presented by Foht et al. (2) and describes a robust design inside a wooden fuselage mock-up (Figure 1) with a subsequent experimental validation.

Figure 1 – Wooden fuselage mock-up © HSU/UniBwH

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2. PROBLEM DESCRIPTION

The multichannel ANC system achieves noise reduction at its pre-defined superset in the lining of the fuselage mock-up (Figure 2) with available positions of 90 loudspeakers and 663 error microphones.

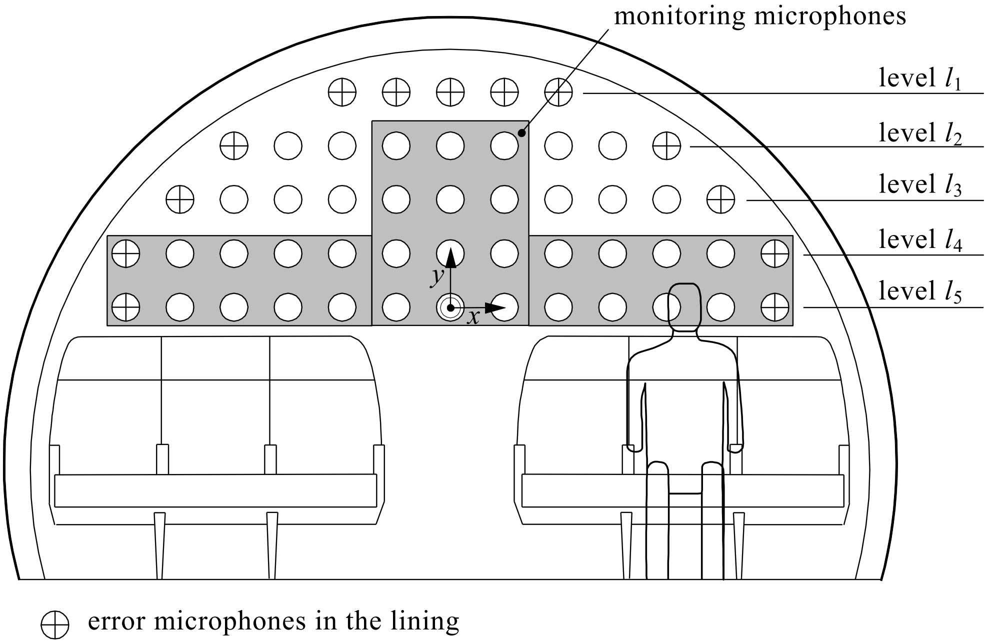

Figure 2 – Microphones positions in the cabin mock-up

The objective should be the reduction of noise at the monitoring microphones, where the head of a standing or sitting person is located. Suitable positions of loudspeakers and error microphones have to be found. Because of the high number of possible combinations of loudspeakers and microphones, this problem is solved by position optimization with a genetic algorithm. Further, the configuration of loudspeakers and microphones should be robust against changes during the flight like a shift of frequency or an altered directivity of the primary noise source. This can be achieved with a robust optimization with pre-measured disturbance signals and plant responses.

3. ANC MEASUREMENT ENVIRONMENT

Figure 3 shows the measurement environment of the wooden aircraft cabin mock-up, with a total length of 15 m and a diameter of 4 m. It is furnished with seats and is positioned asymmetrically in a laboratory hall. The rectangular hall segment with dimensions of 18 m × 10 m is bounded by an acoustically hard brick wall and three perforated sheet metal walls with a height of 2.5 m. The floor is made of wood block paving and concrete. The primary noise (from engine) is reproduced at one side by loudspeakers (PL) outside the cabin at the rear end. Inside the cabin mock-up, secondary loudspeakers (SL) are mounted in the lining and at the rear wall. Foam wedges are placed in the front to suppress reflections in the longitudinal direction. An automatic measurement system, equipped with 51 equidistant spaced microphones, distributed among five levels (l_1, l_2, l_3, l_4, l_5), measures the sound pressure at 51 positions in z-direction for three frequencies ($f_1 < f_2 < f_3$) between 100 Hz and 300 Hz. The distance between each adjacent microphone in x-y-direction and the positioning increments of the measurement system in z-direction is 0.25 m, up to the end of the rear section. That leads to 2601 microphone positions in total.

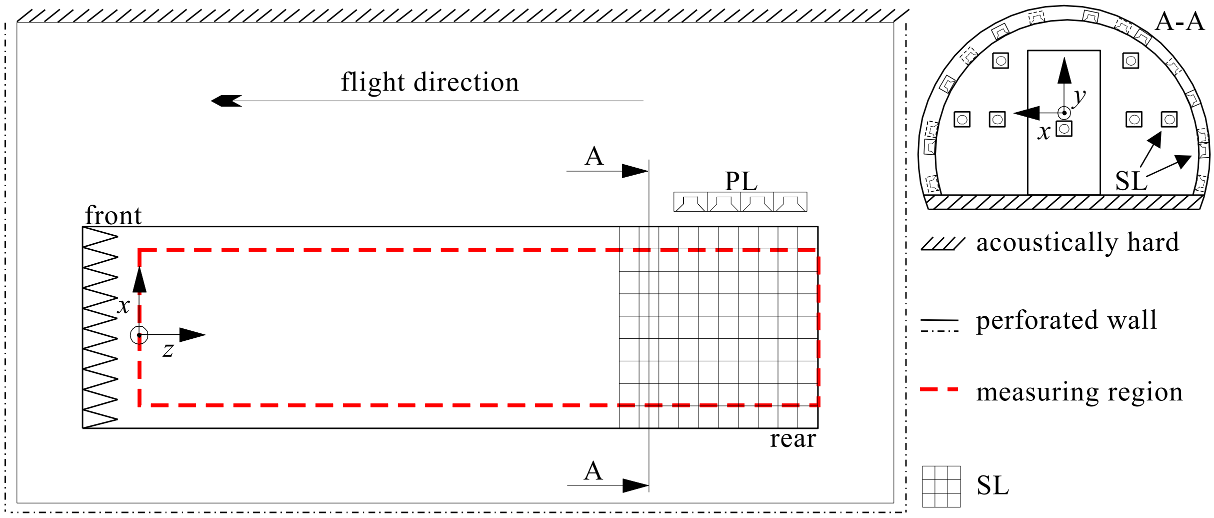

Figure 3 – Test environment

Four plant response measurements are taken for different scenarios, which are listed in Table 1. The nominal state is defined as the measured data set of the complex disturbance signal vector **d** at all microphones and the plant responses **G** between all microphones and all secondary loudspeakers with nominal frequencies (f_1, f_2, f_3) and without a change of directivity of the primary source. All disturbance vectors and matrices of plant responses contain the entries measured at the error microphones ($\mathbf{d}_e$, $\mathbf{G}_e$) and at the monitoring microphones ($\mathbf{d}_m$, $\mathbf{G}_m$). The measured data sets also contain the responses of the used analogue-to-digital converters, digital-to-analogue converters, reconstruction filters, antialiasing filters, preamplifiers and audio amplifiers.

Table 1 – Scenarios of the nominal and of the changed disturbances and plant responses

Scenario 1	Nominal state
Scenario 2	Frequency shift: $(f_1, f_2, f_3) + 4$ Hz
Scenario 3	Frequency shift: $(f_1, f_2, f_3) - 4$ Hz
Scenario 4	10° change of directivity of the primary source in flight direction

4. GENETIC POSITION OPTIMIZATION

A genetic search algorithm selects positions of N_{ls} loudspeakers and N_{mic} microphones by a scalar fitness value resulting from the residual noise vector

$$\underset{N_{ls},\, N_{mic},\, \beta}{\text{minimize}}\ 10\log_{10}\|\mathbf{e}_m\|_2^2 \tag{1}$$

to maximize the lowest noise reduction at the monitoring microphones for all measured data sets. The residual noise $\mathbf{e}_m$ at the monitoring microphones is calculated by

$$\mathbf{e}_m = \mathbf{d}_m + \mathbf{G}_m \mathbf{u}_{opt} \tag{2}$$

The optimal control actuation $\mathbf{u}_{opt}$ results from the derivative of the cost function

$$J = (1-\beta)\mathbf{e}_e^H \mathbf{e}_e + \beta \mathbf{u}^H \mathbf{u} \tag{3}$$

with weighted sum of modulus squared error signals $\mathbf{e}_e$ and actuation signals $\mathbf{u}$

$$\mathbf{u}_{opt} = -\left[\mathbf{G}_e^H(\mathbf{I}-\beta\mathbf{I})\mathbf{G}_e + \beta\mathbf{I}\right]^{-1}\mathbf{G}_e^H(\mathbf{I}-\beta\mathbf{I})\mathbf{d}_e \tag{4}$$

where β is a weighting parameter and H denotes the Hermitian transpose. This expression is reported in (3, 4). Free parameters are the positions of all loudspeakers and the positions of all error microphones as well as the frequency-selective weighting parameter β which has a value range of $0.06 \le \beta \le 0.96$. The constraints of the optimization are the maximum number of loudspeakers ($N_{ls,max} = 90$) and the maximum number of microphones ($N_{mic,max} = 60$) as well as the maximum allowed actuation voltage for each loudspeaker u_{max}, in order to avoid nonlinear effects

$$N_{ls} \le N_{ls,max},\ N_{mic} \le N_{mic,max},\ u_{opt} \le u_{max} \tag{5}$$

The noise reduction ΔL is calculated with

$$\Delta L = 10\log_{10}\left(\mathbf{d}_{\mathrm{m}}^{\mathrm{H}}\mathbf{d}_{\mathrm{m}} / \mathbf{e}_{\mathrm{m}}^{\mathrm{H}}\mathbf{e}_{\mathrm{m}}\right) \tag{6}$$

5. ANC CONTROLLER FOR EVALUATION

The used controller is a multiple input multiple output (MIMO) feed-forward filtered reference least mean square (FxLMS) algorithm in the frequency domain for multi-tonal noise with a frequency- selective weighting parameter β. It minimizes the cost function (3) with the resulting update equation

$$\mathbf{u}(n+1) = \left(\mathbf{I} - 2\mu\beta\mathbf{I}\right)\mathbf{u}(n) - 2\mu\mathbf{G}_{\mathrm{e}}^{\mathrm{H}}\left(\mathbf{I} - \beta\mathbf{I}\right)\mathbf{e}_{\mathrm{e}}(n) \tag{7}$$

where μ is the convergence factor. The reference signal vector $\mathbf{x}$ is obtained from an internally generated primary noise signal and is filtered by an estimated plant response, for each scenario separately.

6. NOMINAL AND ROBUST OPTIMIZED CONFIGURATION

Figure 4 and Figure 5 show the two evaluated configurations of loudspeakers and microphones which results from the genetic optimization based on the nominal data set (nominal configuration) and on datasets of all scenarios (robust configuration). Both configurations exhibit a microphone-loudspeaker ratio of approximately two. This is the same ratio as used in (1).

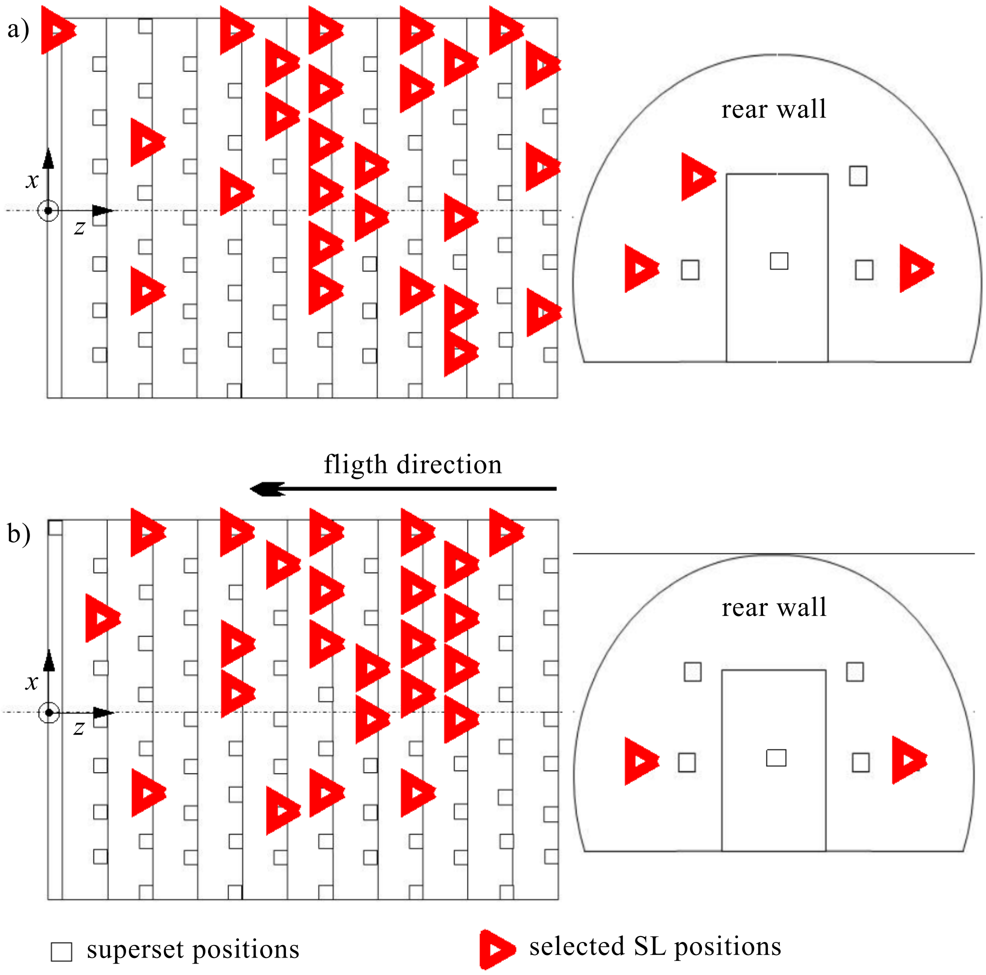

Figure 4 – Selected secondary loudspeaker positions with genetic optimization for a) the nominal configuration (N_{ls}=29) and b) the robust configuration (N_{ls}=26)

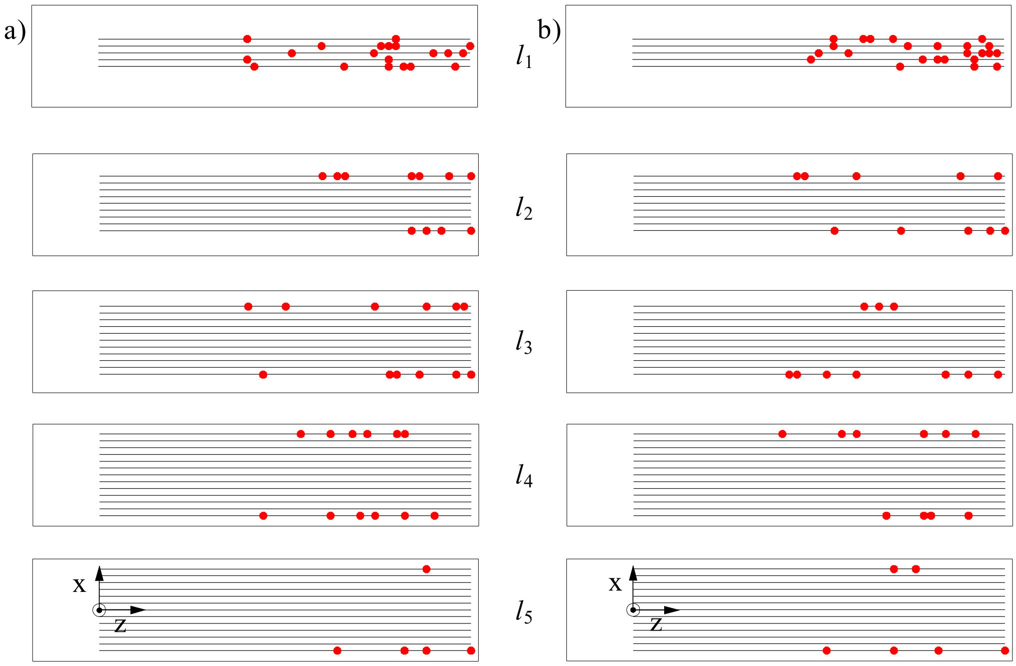

Figure 5 – Selected microphone positions with genetic optimization in the 5 levels from superset for a) the nominal configuration (N_{mic}=60) and b) the robust configuration (N_{mic}=60)

7. PREDICTED AND MEASURED NOISE REDUCTION

The absolute difference between the predicted and the measured noise reduction for the robust configuration at the monitoring microphones for all scenarios is shown in Table 2.

Table 2 – Difference between predicted and measured noise reduction ΔL [dB]

	f_1	f_2	f_3
Scenario 1	1.3	1.6	0.2
Scenario 2	0.3	0.7	1.5
Scenario 3	1.5	0.4	0.3
Scenario 4	0.7	1.1	0.8

The distribution of noise reduction for the nominal state with the robust configuration for the frequency f_1 in the 5 horizontal levels is illustrated in Figure 6. The noise reduction is detectable in the rear part of the cabin, wherein the front part exhibits blue zones which indicates local noise increase.

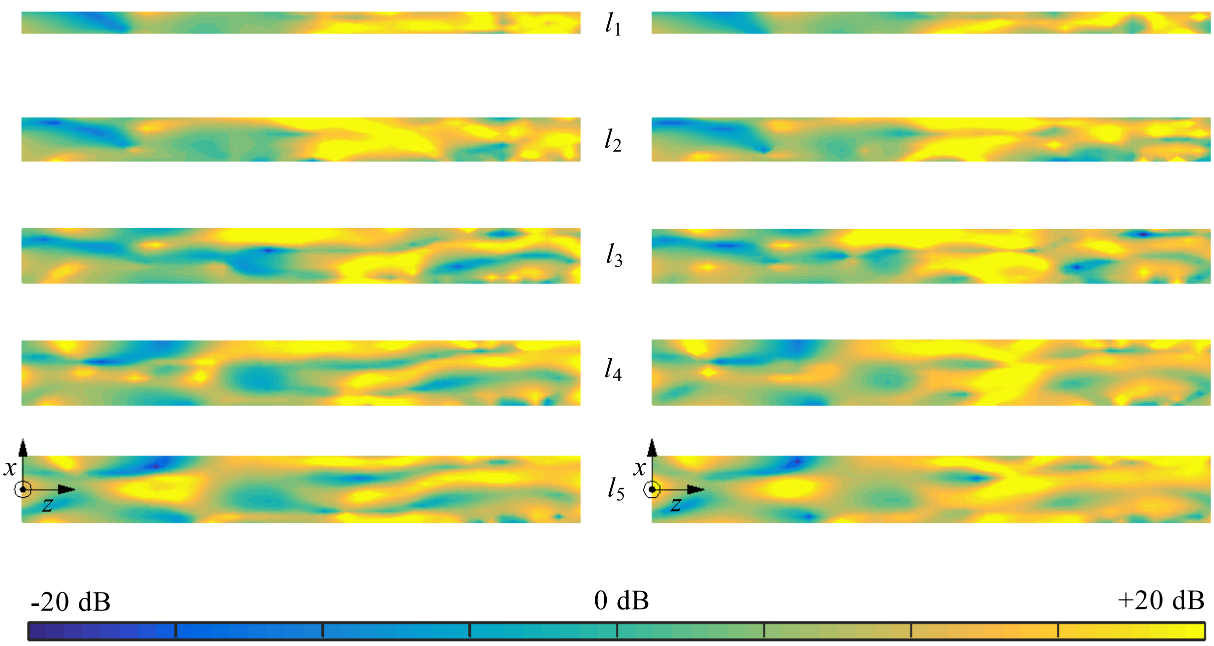

Figure 6 – Distributed noise reduction ΔL, measured (left) and predicted (right)

To verify the performance of the robust configuration, the measured noise reduction for all scenarios for the nominal and the robust configuration is compared in Table 3. The average noise reduction for f_2 and f_3 enhances with robust design, while for f_1 it is reduced. The variability of ΔL is reduced with the robust configuration, compared to the nominal configuration.

Table 3 – Measured noise reduction ΔL with the nominal and the robust configuration [dB]

	Nominal configuration			Robust configuration		
	f_1 (β=0.6)	f_2 (β=0.06)	f_3 (β=0.36)	f_1 (β=0.18)	f_2 (β=0.06)	f_3 (β=0.48)
Scenario 1	11.4	7.8	1.9	9.2	8.6	2.5
Scenario 2	11.6	6.1	-0.5	10.1	9.6	1.2
Scenario 3	8.2	3.9	1.0	11.3	8.2	1.9
Scenario 4	10.3	9.5	-1.0	9.7	8.5	0.4

8. SUMMARY

A genetic algorithm is applied to select positions of loudspeakers and microphones in a wooden aircraft cabin mock-up as well as a frequency-selective weighting parameter. Pre-measured data sets of disturbance signals and plant responses for different flight scenarios are implemented in the positioning optimization step. The robust configuration of loudspeakers and microphones reduces the variability and enhances the overall noise reduction in comparison with the configuration based on the nominal data set.

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