Simulation of active low frequency noise control in closed spaces using the FDTD method

Dimitris Orlis
Department of Electrical & Computer Engineering, Aristotle University of Thessaloniki, Greece.
Marios Giouvanakis
Department of Electrical & Computer Engineering, Aristotle University of Thessaloniki, Greece.
Christos Sevastiadis
Department of Electrical & Computer Engineering, Aristotle University of Thessaloniki, Greece.
Georgios Papanikolaou
Department of Electrical & Computer Engineering, Aristotle University of Thessaloniki, Greece.

Summary
This paper presents the simulation of Active Noise Control (ANC) in a small enclosed workplace and modeling using the Finite Difference Time Domain (FDTD) method. The noise source is considered to be a rotating motor that is approximated by a sinusoid signal of a corresponding frequency. The control source is fed with the output of an adaptive feed-forward control configuration based on the FxLMS algorithm. Both noise and control signals are applied in the 3D model and the performance of the ANC system is evaluated. The numerical results show the quality of the noise control in the position of interest and the effect of ANC on other points in the room.

1. Introduction

Low frequency noise is difficult to be countered using traditional passive techniques and in certain cases, e.g. noisy workplace, it can be harmful to human health. In applications of active noise control (ANC) an acoustic field is created that interferes destructively with the noise field in the specified areas of interest. The successful application of an ANC system is not always possible and it is important to be able to estimate its applicability and effect before the actual implementation. Additionally, the effective application of ANC for an area might result in a noise increase in another area that was not predicted and should be known. All the above can be achieved by utilizing the means of computer simulation.
For this study, a model was created to simulate the propagation of low frequency acoustic waves in a closed room. The simulation model used was based in one of the established room acoustic simulation methods, the finite difference time domain (FDTD) [1][2]. The effect of an active noise control system was predicted by embedding it in the model.
Several control system configurations have been studied recently. Non-adaptive systems are implemented in cases where the noise does not significantly vary [3], while adaptive ones are used more often. Feed-back or feed-forward configurations have been proposed, each with its own advantages and limitations. Their difference lies mainly in the signal used for the control filter calculation [4].
In this study, an adaptive feed-forward control system was simulated, which uses the input from two virtual microphones located in the FDTD grid [5]. The FxLMS algorithm was used for the adaptation of the control filter. The impulse response of the path from the control source to the point of interest, i.e. secondary path, required in the algorithm was calculated in advance using the appropriate simulation model, though methods for calculating it online have been proposed [6][7].
Similar simulations of ANC systems have been presented recently in the literature, including multi-channel systems [8] and utilization of genetic algorithms in order to identify the optimal position for the control source [9]. An important advantage of the FDTD method is that it can be implemented using parallelized computing in GPUs resulting in very fast or real-time results, as has been proposed in recent literature [10].
The FDTD method for acoustics as used is described in part 2 and the adaptive feed-forward active noise control system is presented in part 3. In part 4 the specific problem and the simulated model details are presented with the results and conclusions discussed in part 5.

2. FDTD in acoustics

The FDTD method for acoustic waves is similar to the one for electromagnetic waves with acoustic pressure p and particle velocity v being the variables of interest. There are two equivalent variations of the method, the vectorial one where both pressure and velocity are used and corresponds to the initial formation of the algorithm by Yee for electromagnetic waves [11], and the scalar one where only the acoustic pressure is used. The latter is computationally more efficient while remaining as accurate as the former in the results obtained [12].

The numerical solution of the propagation equation requires the discretization of both time and space. The restrictions for the size of discretization arrive from the maximum frequency in the model, numerical stability criteria and the acceptable computational complexity. In the majority of implementations, the space is divided in cube (or square in 2D) cells of Δx edge. A good compromise between cost and accuracy is achieved for cell side equal to $\lambda_{min}/10$, with λ_{min} being the minimum wavelength for which the simulation should be accurate [13]. The temporal step, Δt, is such that the propagation speed in the computational grid matches the one in the physical medium. For a given Δx the time discretization step can be defined by the Courant stability factor [14], S, given by the equation

$$S = c\frac{\Delta t}{\Delta x} \tag{1}$$

The S factor depends on the scheme of the method used that determines which neighboring points are used in the calculation of the acoustic pressure in a certain node. For the node's future values (*n*+1) the past values (*n*) of the neighbors are used in combination with the two previous of the same node (*n*-1, *n*) to form the update equation. In the 3D case, the simplest scheme uses just the six neighboring points, two in each axis, (Standard Leap-Frog), while the most accurate uses all twenty six (Interpolated Wideband) [15].

Regarding the boundary conditions, the reflection of the acoustic wave from the boundary walls is approximated with the model of the locally reacting surface (LRS), in which the particle velocity in front of the wall depends only on the acoustic pressure at the same spot and is independent from the pressure on the neighboring nodes [16]. This property is transferred into the scalar formation of the FDTD method. Some of the neighboring nodes of a boundary node are not available from the grid's calculation; hence the update equation is modified to compensate for the unknown ghost nodes. The frequency dependence of the boundary condition is embedded in the modified equation [17].

Finally, the acoustic source is implemented in the model so that the physical excitation is simulated accurately. Three excitation techniques have been proposed and can be used in both the vectorial and scalar formation. The simplest case is that of the hard source, where the source value is assigned to a specific source node that is excluded from the update equation. This exclusion inserts an error that is compensated with the soft source technique in which the value of the excitation is added to the result of the update equation. A consequence of the summation is mismatch between the desired excitation and the assigned value. The transparent source technique uses an estimation of this error through the impulse response on the source node to compensate for the difference [17].

3. Adaptive feed-forward ANC using the FxLMS algorithm

A feed-forward active noise control system with a single control source requires two input signals from microphones or other similar sensors. One is called the error signal which is picked from the area of interest and the second is a reference signal. It is proved that the coherence of the reference signal with the noise source limits the resulting error, hence the system's performance [19].

The block diagram of the simulated system is presented in Figure 1. The microphones are utilized by storing the value of the acoustic pressure on the specified nodes so that it can be used in the processing. The control filter coefficients, *w*(*n*), are calculated by the LMS algorithm and the output of this filter, *y*(*n*), is used as the control source signal. To compensate for the disturbance caused by the propagation from the control source to the point of interest the reference signal, *x*(*n*), is filtered with an estimation of the impulse response of this specific path [20]. This estimation has been calculated in advance by using the identical model while placing an impulse source at the location of the control source and measuring the response where the error microphone is located. This impulse response was stored and loaded in the actual simulations that followed.

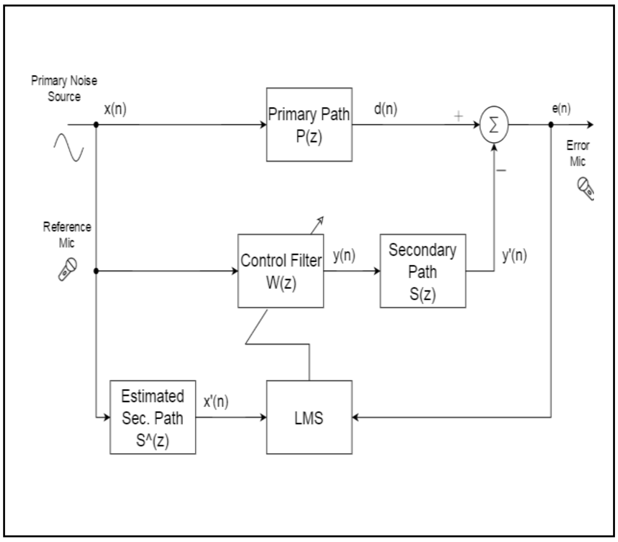

Figure 1. Block diagram of a single-channel feed-forward ANC system implementing the FxLMS algorithm as used.

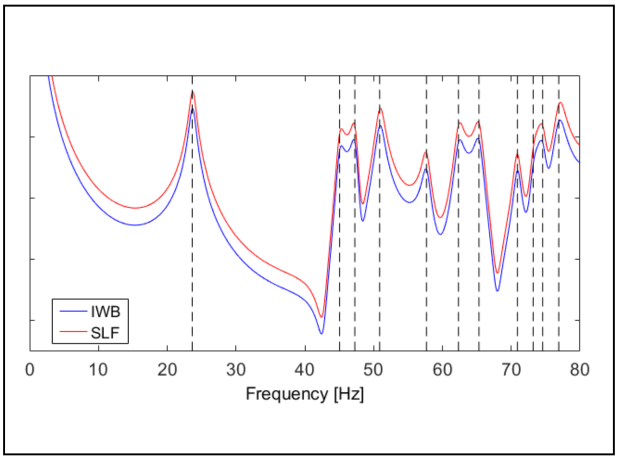

Figure 2. Room's modes (dashed black) and estimation with FDTD models using the Interpolated Wideband (blue) and Standard Leapfrog (red) schemes.

The two most important factors of this ANC system are the adaptation step μ, and the length of the control filter, L. The length must be large enough to accurately simulate the response of the physical system. The maximum stable step value can be expressed in closed form as a function of properties of the reference signal, the filter length L, and of the impulse response of the path from the control source to the point of interest (secondary path) [21, 22]. The filter coefficients are calculated for each discrete time step by equation 2. The $x'(n)$ is the result of the filtering of the reference signal with the secondary path impulse response.

$$w(n+1) = w(n) + \mu e(n) x'(n) \qquad (2)$$

4. ANC Simulation

An orthogonal room of 7.3 m length, 3.8 m width and 3 m height, was simulated. Discretization step of $\lambda/10$ was used, which results in cubic grid with approximately 12 cm edge length for the maximum frequency of 300 Hz that was assumed sufficient for the low frequency range. The behavior of the rigid bounding surfaces was implemented as frequency-independent. The interpolated wideband scheme was implemented, with the Courant stability factor equal to 1. This scheme is compared to the simplest, standard leapfrog, in calculating the room's modes up to 80 Hz in Figure 2. It is noticed that both schemes are accurate in this low frequency range.

The temporal discretization step, Δt, is calculated by Equation 1 to be approximately 0.35 ms. A period of 20,000 steps, or 7 seconds, was simulated. A sinusoidal signal of 100 Hz mixed with 20 dB lower Gaussian noise was used as the source signal. Hard source implementation was used for all sources. An example of the noise propagation in the 3D model is presented in Figure 3 with two snapshots.

The L and μ parameters of the control system were selected equal to 600 and 0.05 respectively. The impulse response from the control source to the error microphone (secondary path) was calculated in advance using a sole Dirac source in the position of the control source in the actual room. The active control was initiated approximately 1.3 s after the beginning of the simulation.

The ANC application is focused on 100 Hz and the overall effect on a 1 m^2 area around the locations of interest is investigated. The effect of the system depends on the control source location relative to the room's modes. The control source should be placed on a location where the mode of the driving frequency is sufficiently excited in order for it to have a significant effect [12]. Additionally, the reference signal should also be picked from a similar location.

Based on the above, six different cases were created for the combinations of three control sources locations (A, B, C) and two areas of interest (X1, X2), varying between minimum and maximum excitation of the room at 100 Hz from a steady noise source. The arrangement in the room and excitation of the noise source at 1.2 m height is presented in Figure 4. It is expected that the best result will be achieved by controlling the X1 area from either the A or C control sources, since both are located in well-excited points.

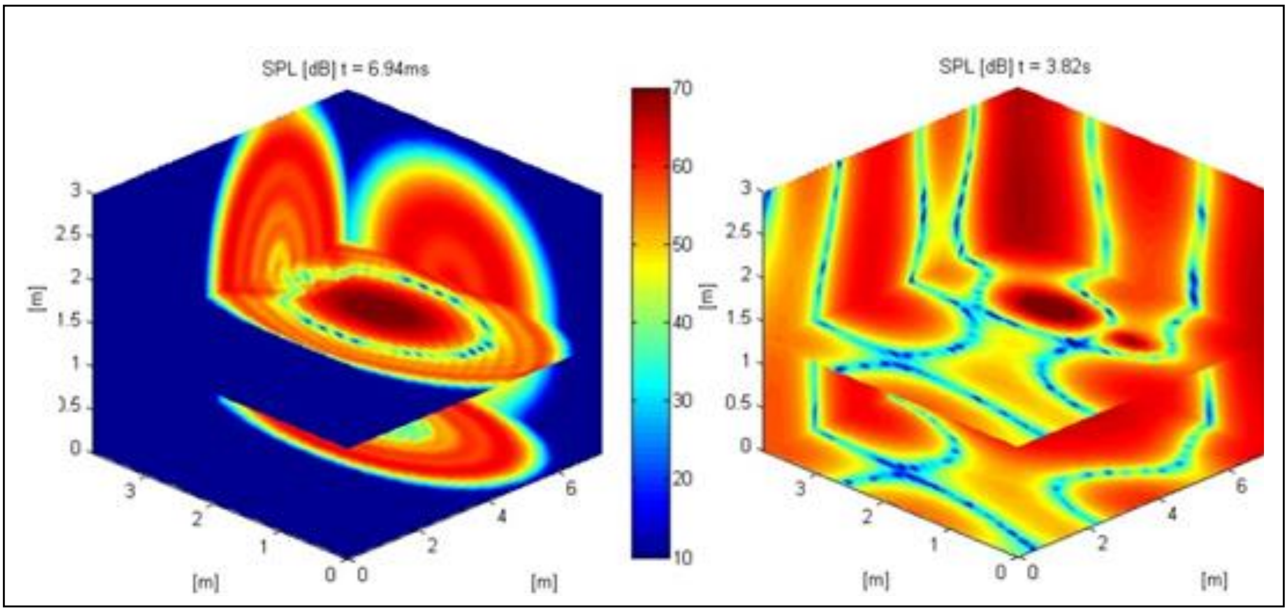

Figure 3. Snapshots of four slices in the simulated model at 6.94 ms (left) and 3.82 s (right).

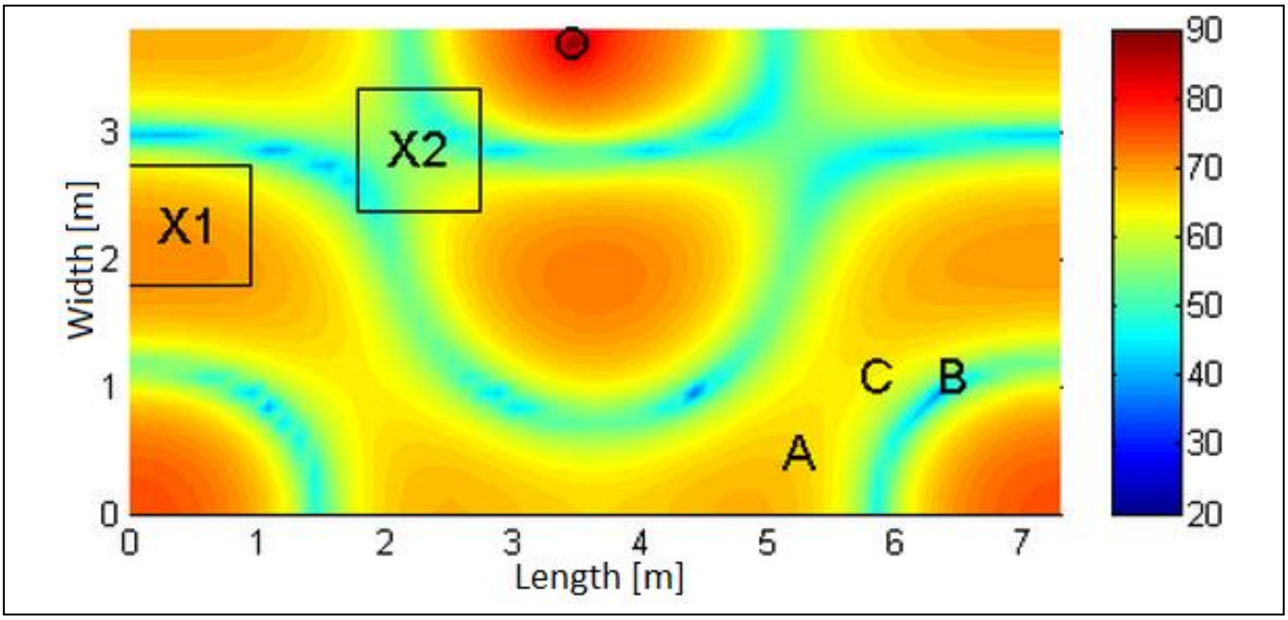

Figure 4. Room excitation (SPL dB) at 1.2 m height from a 100 Hz noise source (circle) and ANC system locations.

5. Simulation results and discussion

The sound pressure level at the areas of interest for each control scenario is presented in Figure 5. As shown in Figure 5, a decrease of a few dB after the initiation of the active noise control system at location A is observed (lighter colors), validating the applicability of the control configuration as described earlier. The difference resulting from the control source position is also noticed, with the B position not being able to sufficiently excite the room in order to cancel the noise in any of the control areas. The best result is achieved by the control source at C position. The level of the virtual microphone at the X1 location of interest is presented in Figure 6, where an attenuation of more than 12 dB is observed in less than 10 s after the application of the ANC to the C position.

One of the advantages of such a simulation is the ability to estimate the effect of the active control system to the whole room. Hence, a possible negative effect, i.e. increase of noise level on some areas, can be identified without the need of additional simulations. The focus of the 1 m^2 area can be further narrowed or expanded in the plane or in the third dimension. The available memory is the major limiting factor in the size of the area and the duration that can be stored to be presented in the post processing stage.

Before proceeding to the actual implementation of the physical control system it is important to consider the details of the simulation and the assumptions made in the simulations above. Both noise and control sources are certainly not omnidirectional point sources and their dimensions should be considered in a more accurate model. The reflections and diffraction of such a volume source must also be added in the model, along with its directivity pattern. Additionally, the boundary conditions on the majority of surfaces is frequency-dependent, even in the relatively small frequency range simulated in this work, and the difference among the ceiling, floor and side walls should be incorporated. Finally, compensating for the influence of any hardware used in the actual configuration would further improve the accuracy of the simulation.

Regarding future work, the above suggestions should be considered. The implementation and simulation of a multichannel system is also suggested in the quest of a more broadband control. Finally, the results from a detailed and accurate simulation can be validated through comparison with experimental measurements in situ.

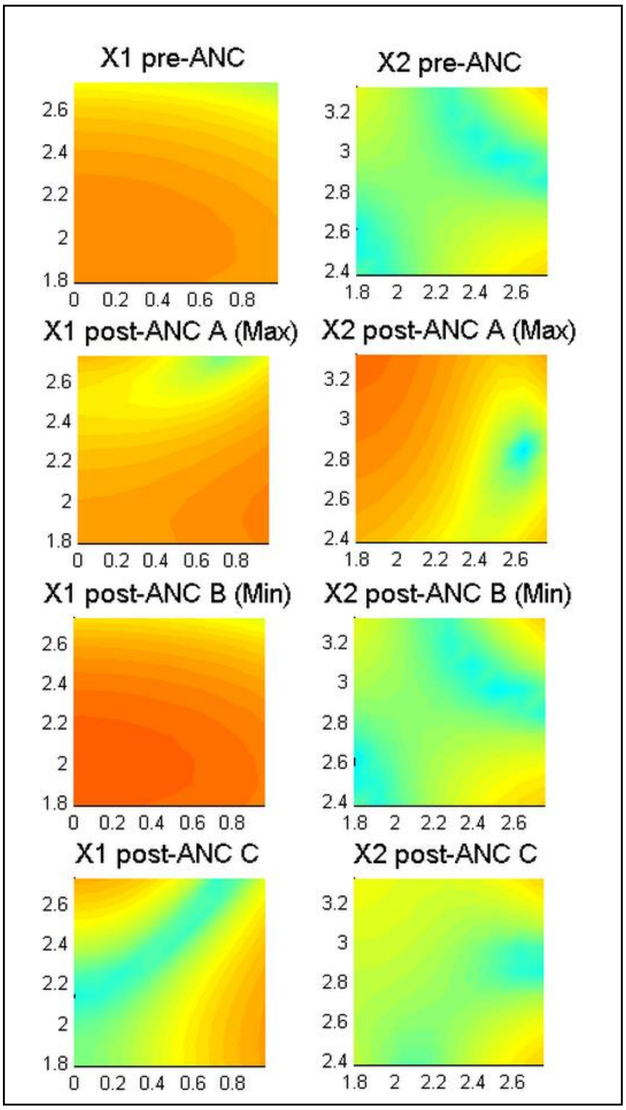

Figure 5. Simulation results in areas of interest for different control scenarios, as described in Figure 4.

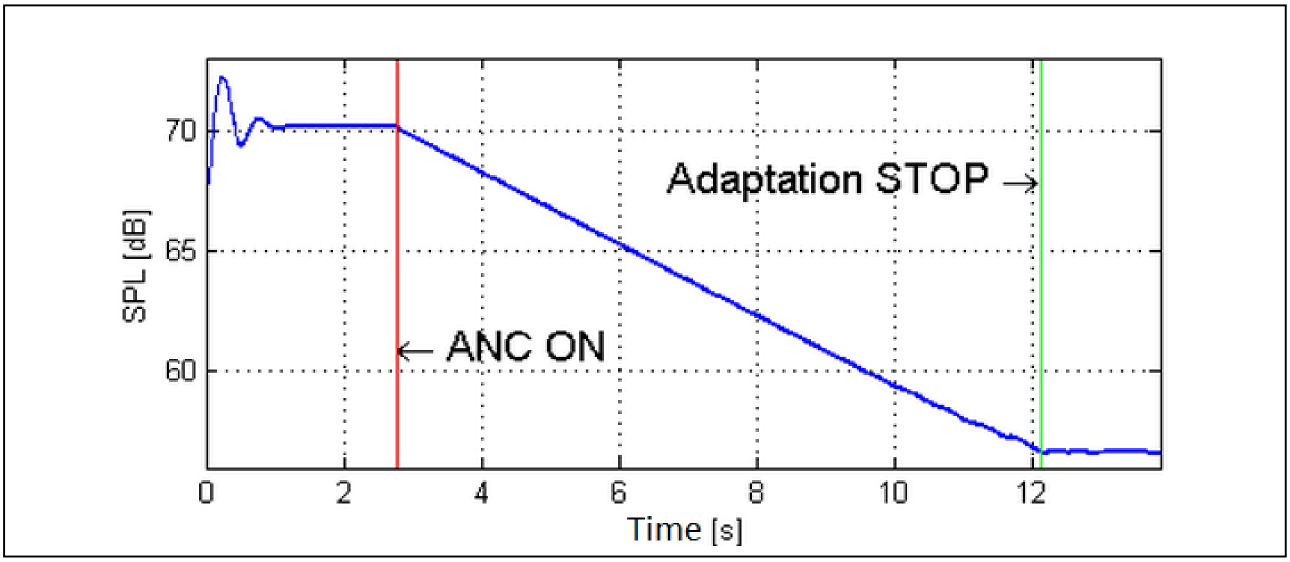

Figure 6. Virtual microphone in X1 location (C).

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