Integrated simulation of active noise cancellation using a computational fluid dynamics approach

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Abstract

An attempt has been made in this paper to simulate active noise control (ANC) in a three dimensional space using computational fluid dynamics and pressure acoustics. We have considered a rectangular box, with primary and secondary sources at the two opposite sides of the box. A model of ANC has been developed, which considers a cardboard surface and air as the fluid. A control algorithm, which interacts with the fluid dynamic model has also been developed, which tries to achieve active noise control. The proposed approach can be used as an initial feasibility study to predict acoustic pressure field inside the control space.

Keywords: Computational fluid dynamics, active noise control

1 INTRODUCTION

Noise control strategies may be broadly classified into passive noise control (PNC) and active noise control (ANC). ANC has been reported to be effective for low frequency noise mitigation when compared to PNC[1]. The basic principle of ANC is destructive interference of sound. In a feed-forward ANC system, a primary microphone is used to measure the reference signal, a loudspeaker is used to produce the necessary control sound and an error microphone is used to sense the residual noise. The loudspeaker is controlled by an adaptive controller, which is usually an adaptive filter. The most widely used controller is an adaptive finite impulse response (FIR) filter, the weights of which are updated using a filtered-x least mean square algorithm (FxLMS)[2].

The effectiveness of an FxLMS algorithm based ANC system is dependent on appropriate modeling of the secondary path, which is the electro-acoustic path from the loudspeaker to the error microphone[3]. When ANC is implemented in a 3D space, multiple loudspeakers and microphones are necessary, making the implementation a multi-channel ANC[4], also requiring different algorithms to achieve the same[5],[6]. For implementing ANC in a new environment, the first step is a modeling of the secondary paths, which is followed by appropriate placement of the loudspeakers and microphones. A suitable algorithm is then implemented to achieve ANC[7].

In an endeavour to design a mechanism to visualize noise cancellation in an arbitrary space, before attempting any physical implementation, this paper proposes a fluid dynamic modeling scheme. The arbitrary space in which the noise cancellation is envisioned is modeled by using a finite elements method. Further, the loudspeakers necessary for achieving ANC are introduced in this model as surface perturbations. The microphones are considered as acoustic pressure probes. In addition, the control algorithm is implemented in a MATLAB environment, with a real time interface achieved using MATLAB Livelink^{TM}. The proposed approach is also envisioned to help in determining optimal positions of loudspeakers and microphones in a given ANC system implementation. Other similar approaches include methods based on finite difference time domain approach [8], wave field synthesis [9] and finite element method [10].

A real time implementation of ANC in a rectangular cardboard box has also been carried out and the expected sound levels during the noise cancellation process has been visualized using the proposed fluid dynamic approach. This method can serve as an initial feasibility study to predict acoustic pressure field inside the control space. The rest of the paper is organized as follows: The geometry, governing equations and the modelling strategy followed in this paper is introduced in Section 2. The simulations results obtained through the proposed method are also presented in this section. Section 3 deals with the experimental setup as well as a discussion on the experimental results and the concluding remarks are drawn in Section 4.

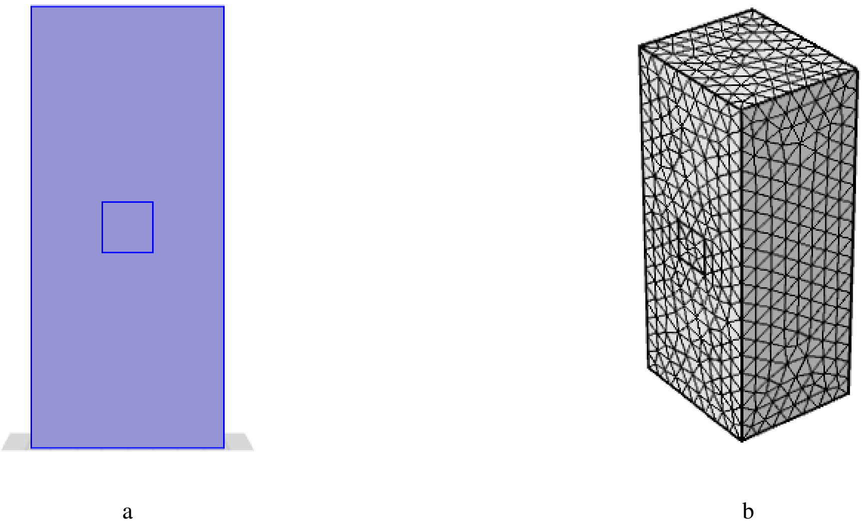


Figure 1. a. The geometry b. Meshing

2 GEOMETRY, GOVERNING EQUATIONS AND MODELING

An attempt has been made to create a simulation mechanism to understand noise cancellation at various locations in an arbitrary three dimensional space. We have used COMSOL multiphysics to achieve this task. The geometry, which includes an air column inside a rectangular box, was developed in the software using COMSOL geometry interface. Two separate rectangular sub-geometry are made, to simulate the primary and control speakers, on opposite faces of the rectangular box. Meshing is another crucial step in the numerical simulation wherein the geometry is subdivided into smaller cells and the equations of motion are solved. Here a fine meshing is performed using a free tetrahedral mesh with minimum element size of 0.01 m and a maximum of 0.1 m. The mesh size has been considered to be less than one-sixth of the minimum wavelength involved in this exercise. As the maximum frequency used in this study is 200 Hz, we have used a maximum element size of 0.1 m, which is less than one sixth of the minimum wavelength $\lambda = c/f = 343/200$, where c is the speed of sound in air and f is the frequency of interest. It may be noted that we have used uniform meshing in this study. The geometry and the meshing used is shown in Figure 1. The medium has been assumed as stationary, with no flow into or out of the system. The Neumann boundary conditions has been taken for the surfaces of the rectangular box, which is defined as

$$\frac{\partial P'}{\partial n} = 0, \tag{1}$$

where P' is the acoustic pressure at the boundary and n is the normal vector to the surface. In COMSOL environment, this boundary condition is also referred to as the sound hard boundary condition. A pressure boundary condition is applied to primary speaker. The pressure condition can replicate a speaker diaphragm generating a time dependent harmonic pressure signal, which is explicitly defined using a field function. The control speaker is also given a pressure boundary condition wherein the pressure values are updated for each time step of the simulation through the *Livelink*^{TM} feature for MATLAB provided with COMSOL software.

In this study, we have assumed the air column within in the rectangular box to be stationary. Thus we use a pressure acoustics physics model, which solves the 3D acoustic wave equation to analyze this system. The sound produced by the primary or the secondary speakers can be considered as small perturbations. This allows us to make a linear approximation approach also referred to as the classical acoustic approach. The 3D acoustic

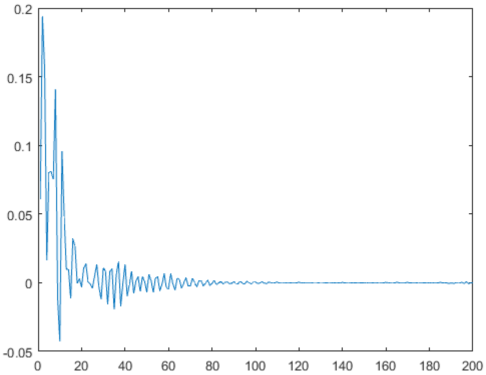


Figure 2. The impulse response for the secondary path in simulation

wave equation which we have tried to implement in this study is given by

$$\nabla^2 P' = \frac{1}{c^2}\frac{\partial^2 P'}{\partial t^2}, \tag{2}$$

which has been obtained from the momentum equation, mass conservation equation and the state equation given by

$$-\nabla \cdot P' = \rho_0 \frac{\partial \mathbf{u}}{\partial t}, \tag{3}$$

$$\frac{\partial \rho'}{\partial t} = -\rho_0 \nabla \cdot \mathbf{u}, \tag{4}$$

and

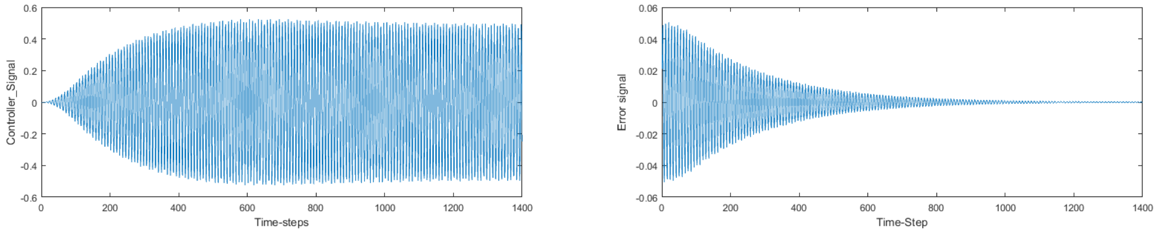
$$\frac{dP_t}{d\rho_t} = c^2 \tag{5}$$

respectively. In the above mentioned relations, P' is the acoustic pressure, $P_t = (P' + P_0)$ is the total pressure, c is the speed of sound, ρ_0 is the fluid density, $\rho' = (\rho_t - \rho_0)$ is the change in density and *bmu* is the fluid particle velocity. The acoustic wave model used in COMSOL Multiphysics also takes a similar form and is defined as follows:

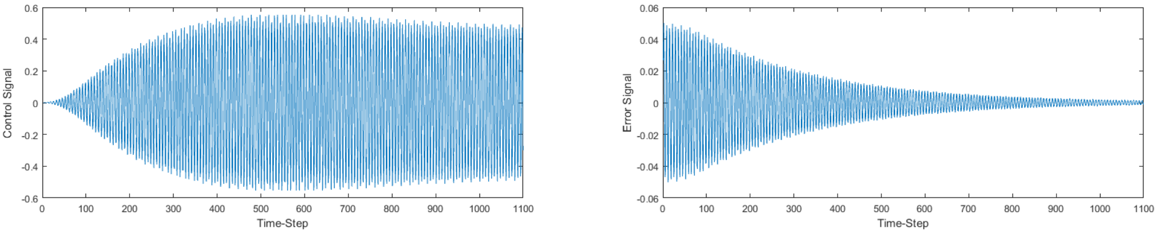
$$\frac{1}{\rho c^2}\frac{\partial^2 p_\mathrm{t}}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho}\left(\nabla p_\mathrm{t} - \mathbf{q}_\mathrm{d}\right)\right) = Q_\mathrm{m}, \tag{6}$$

where p_t is the acoustic pressure, ρ is the specific mass $\mathbf{q}_\mathrm{d}$ dipole source and Q_m is the monopole source [11]. A multi-frontal massively parallel sparse parallel solver (MUMPS) has been used to solve the system of linear equations in the simulation. A time dependent study has been performed to understand how sound propagates in the medium with time. The pressure wavefront of the primary loudspeaker travels at a speed of 343 m/s (as the domain has been selected as air) and reaches the error microphone (which is placed at the geometric centre point of the cardboard box model), which is at a distance of 0.375 m from the primary loudspeaker in $343(m/s)/0.375(m) = 0.00109(s)$. Thus to accurately capture the sound field at the error microphone, we have used a time stepping of 0.001 s in this study.

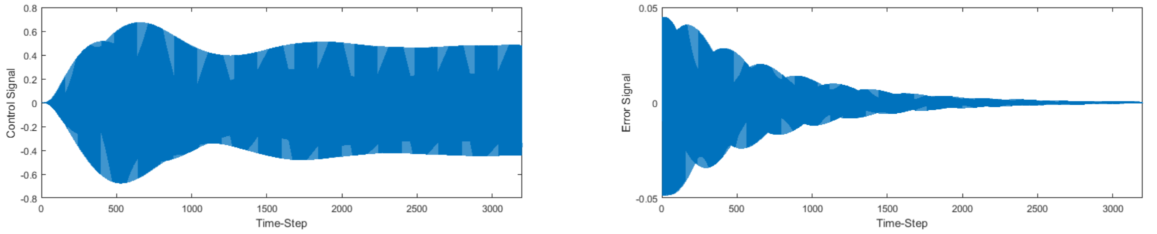
The first step in the proposed integrated simulation task is a secondary path modeling. A band limited white noise was generated in MATLAB and was used to drive the primary loudspeaker model. The response at the error microphone for this input was captured in the COMSOL model. The input signal as well as the error microphone response were used to estimate the secondary path model using an offline implementation of the LMS algorithm. The impulse response of the secondary path obtained is shown in Figure 2. This secondary



a. 115 Hz, $\mu = 0.1$ b. 115 Hz



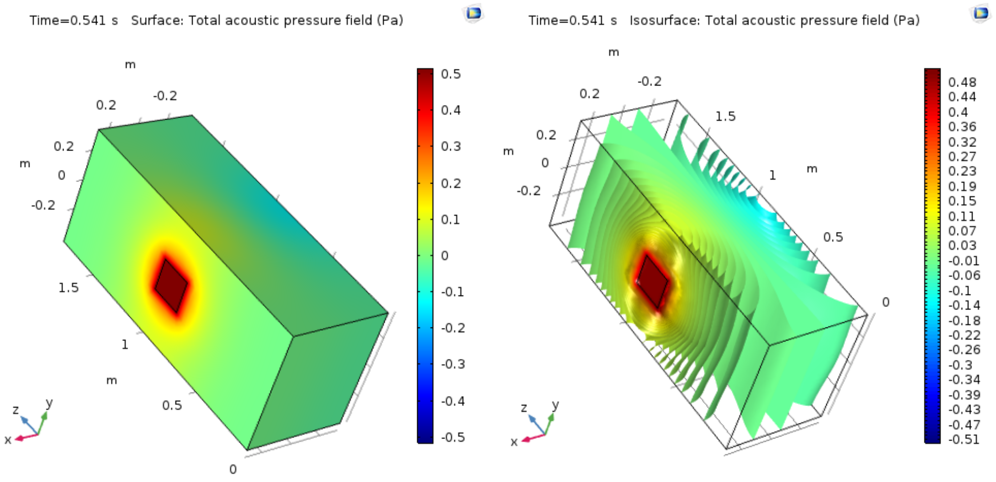
c. 150 Hz, $\mu = 0.1$ d. 150 Hz



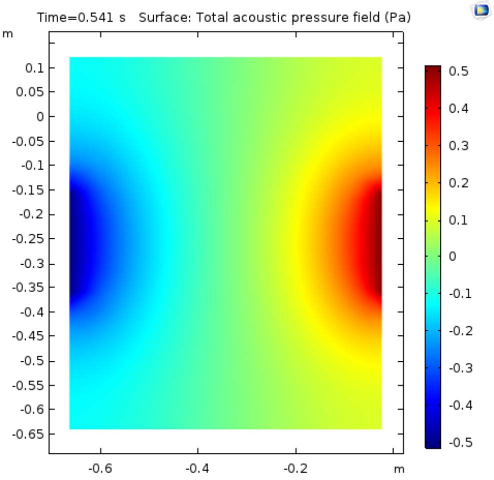
e. 200 Hz, $\mu = 0.01$ f. 200 Hz

Figure 3. Control speaker signal (a, c, e) and corresponding error signals (b, d, f) for 115 Hz, 150 Hz and 200 Hz

path impulse response was used in the FxLMS algorithm to control the sound field in the COMSOL model, by driving the control loudspeaker using MATLAB $LiveLink^{TM}$. The three noise cancellation scenarios considered in the experimental study were repeated using the proposed COMSOL model. The control signal applied for the three cases and the corresponding error signals are shown in Figure 3. We can also observe a close match between the noise cancellation results obtained using simulation as well as experimental study. Figure 4 shows the pressure surface plots and iso-surfaces for the simulation run at 115 Hz. It shows how pressure levels inside the domain varies with the control speaker. Thus the proposed approach acts as a good visualization tool for understanding noise cancellation in 3D environment. This can also help in checking feasibility of noise cancellation before attempting any real time implementation for any arbitrary sound column, which could be modeled in a COMSOL platform.



a. Surface plot b. Iso-surfaces



c. Vertical slice plot

Figure 4. Simulation results (Using COMSOL 5.2a) for pressure fields at 115 Hz,$\mu = 0.1$

With the modern day developments in computational fluid dynamics and computational acoustics, we will be able to easily predict the noise propagation in any space and also the noise generation patterns from various types of flow phenomenon, by coupling the acoustic wave equations with the Navier-Stokes equation. With increasing resources for computation and technology computational acoustics coupled with computational fluid dynamics is expected to become a great product design and problem solving tool [12].

3 EXPERIMENTAL SETUP AND RESULTS

The experimental setup considered in this paper consists of a rectangular corrugated cardboard box of size $175 \times 65 \times 75$ cm, with the two smaller inner walls covered with polystyrene sheets of 100 mm thickness. Two Presonus Eris E5 studio monitors are then placed at two sides of the larger surface of the box by cutting two holes of size 32×15 cm, with the loudspeaker diaphragm facing the inside of the box. The first loudspeaker acts as the primary noise source and the second loudspeaker is the control loudspeaker. The setup described

Figure 5. Experimental setup showing the control speaker

above is shown in Figure 5. An attempt has been made to implement feedback ANC in the box, with an error microphone (Behringer C2 microphone) placed at the geometric centre of the box. A Behringer U-Phoria UMC404HD audio interface has been used to connect the speakers and the microphone with the adaptive controller, which has been implemented on a Simulink platform in a 64 bit Windows 10 PC, with 2.2 GHz Intel Core i7 processor with 6 GB RAM.

The first task in a feedback ANC implementation is the estimation of the secondary path transfer function. A band-limited white noise in the band 10-500 Hz was played through the control speaker and was measured using the error microphone. These signals were used to estimate the secondary path transfer function and we have used LMS algorithm for this task. The impulse response of the estimated secondary path is shown in Figure 6. An FxLMS algorithm was implemented to achieve noise cancellation. We have considered three cases of single tone noise control, with the primary disturbances of 115 Hz, 150 Hz and 200 Hz. These frequencies are so chosen so as not to exceed the cut on frequency for the box model. This avoids inclusion of multiple modes inside the domain [13]. The error signal, measured at the error microphone for the three cases and the convergence characteristics are shown in Figure 7. A significant noise reduction can be observed from the convergence characteristics. The reduction is sound level in terms of sound pressure level was also measured using a sound level meter. The sound levels for the three cases, before and after noise cancellation is shown in Table 1.

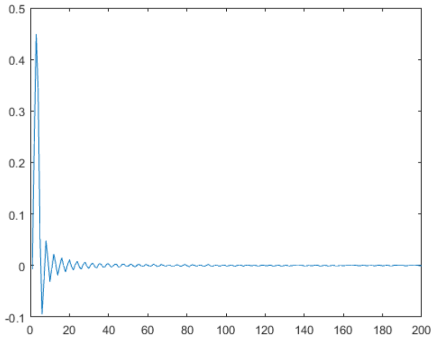
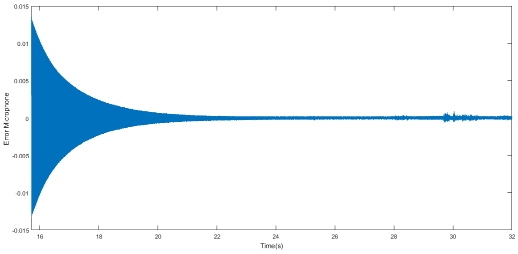
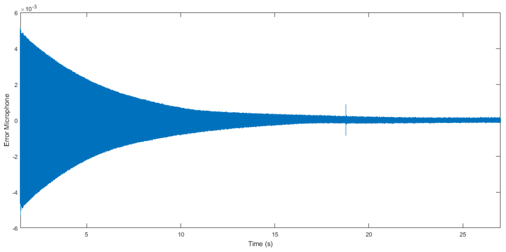


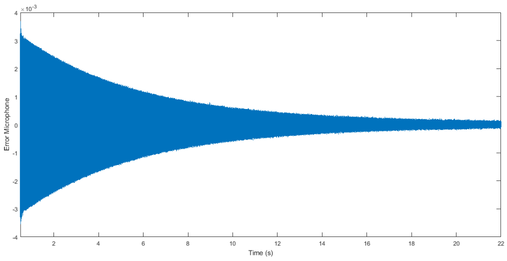
Figure 6. Impulse response of the secondary path in experiment



a. 115 Hz



b. 150 Hz



c. 200 Hz

Figure 7. Measured Error Mic values from Experiment.

Table 1. Reduction in Sound Pressure level (dB)

Frequency [Hz]	Without ANC (dB)	With ANC (dB)
115	86.6	71.2
150	83.2	68.6
200	85.4	73.4

The results obtained from the experiment and the simulation does follow the same trend, but the reduction in sound pressure levels at the measured point is higher in the simulation than in the experimental setup. This may be accounted to the fact that the default boundary conditions in COMSOL are for ideal cases. By implementing an impedance boundary condition at domain surface and applying perfectly matching layers (PML) to simulate infinite boundaries may offer comparable and physically accurate results.

4 CONCLUSION

This paper develops a computational fluid dynamic scheme for analyzing ANC systems. This has been achieved by considering a stationary air column as the fluid and implementing loudspeakers as surface perturbations where pressure values are updated using pressure field functions. In the control speaker, this pressure variation is governed by a FxLMS algorithm. The proposed approach acts as an effective visualization tool for noise cancellation within an arbitrary space without the need for a physical implementation. The simulation study was followed by an experimental study, wherein ANC was implemented in a 3D space of properties similar to the one used in the simulation.

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