

Simultaneous Online Modeling of the Secondary Path and Neutralization of the Feedback Path in an Active Noise Control System

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Summary

This paper proposes a new method for modeling the secondary path and neutralizing the feedback path for a feedforward single channel active noise control (ANC) system in a duct, during its online operation. Using auxiliary white noise with fixed variance for this purpose is the most widely used method but in the final stage the noise adds up to the residual error and reduces the performance of the ANC system. In the proposed method a gain scheduling strategy is used to control the variance of the injected white noise. The variance is in turn controlled by the convergence of the feedback path neutralization filter and the secondary path modeling filter. Instead of the traditional Least Mean Squares (LMS) algorithm, the Normalized Least Mean Squares (NLMS) algorithm is used in the proposed method. This ensures the robustness of the system in practical situations, where the power of the signal can vary anytime. The algorithm is tested in a MATLAB/Simulink environment. Custom Simulink blocks like F_x_NLMS block were designed using Level-2 S-Functions from Simulink. Simulations show that the proposed method ensures reduced steady state error at the error microphone and provides an excellent steady state performance even if power of input noise is varied.

PACS no. 43.50.+y, 43.60.+d

1. Introduction

A block diagram of a single channel feedforward active noise control (ANC) system in a duct environment with fixed secondary path modeling and feedback path modeling and neutralization filter (FBPMN) is shown in Fig. 1. Here $P(z)$ is the transfer function of the primary path from reference microphone to error microphone, $F(z)$ is the feedback path transfer function from anti-noise loudspeaker to reference microphone and $S(z)$ is the secondary path transfer function from anti-noise loudspeaker to error microphone. The primary noise $r(n)$ passes through the primary path and generates the primary noise $d(n)$ at the error microphone, $y_s(n)$ is the anti-noise signal to cancel $d(n)$, $y_f(n)$ is the feedback signal which leads to a corrupted reference signal $c(n)$ at the reference microphone and $e(n)$ is the residual error signal picked up by the error microphone. $F'(z)$ is the FBPMN filter and $W(z)$ is the ANC filter. For proper application of the ANC filter it is necessary that the reference signal is processed by the model $S'(z)$ of the secondary path $S(z)$. The algorithm used for this purpose is known as filtered-X Least

Mean Squares (F_x_LMS) algorithm. Due to its ease of implementation and robustness it is the most widely used algorithm for ANC systems [1]. The ANC filter $W(z)$ produces the anti-noise signal $y(n)$. This is introduced in the system through the anti-noise loudspeaker and travels downstream through the system and through the secondary path to generate $y_s(n)$ that adds up with $d(n)$ and produces the residual error $e(n)$. The F_x_LMS algorithm is fairly robust in removing the secondary path effect but the performance depends on the perfect modeling of the secondary path. This can be done offline but for real life applications an online modeling of the secondary path is necessary. There are two approaches for online modeling of the secondary path. The first one introduces random noise to the system and uses system identification. The second approach models the secondary path from the output of the ANC filter. The comparison of the two approaches can be found in [2]. The anti-noise signal also travels upstream through the duct and adds up with the noise picked up by the reference microphone. This corruption of the reference noise is known as the feedback path problem. In the literature many approaches have been reported to solve the feedback path problem. Again adaptive filtering

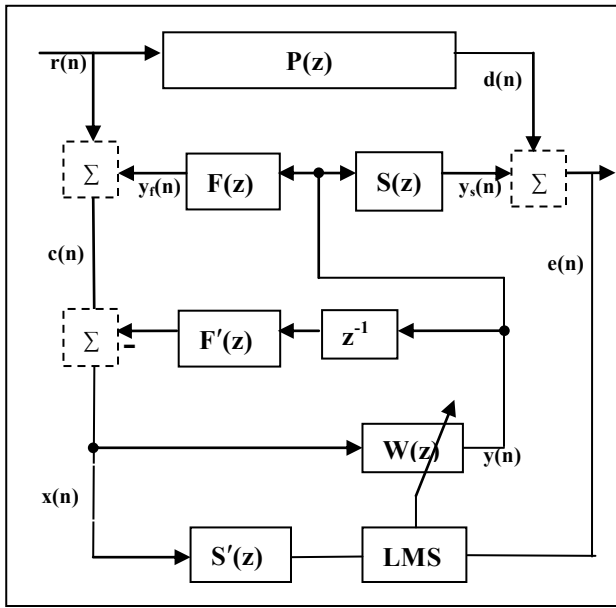


Figure 1. Block Diagram of an ANC System

provides the best performance with lower computation and implementation complexity [3]. As shown in Fig.1 using a fixed FBPMN filter for feedback path neutralization is the simplest solution which can be obtained offline. But in real life the feedback path can be time-variant which leads to the need for an adaptive FBPMN filter that can neutralize the feedback path online. The existing online FBPMN method uses additive auxiliary noise which leads to the increase of residual error [4].

In this work an adaptive FBPMN filter is used for feedback path neutralization with a gain control strategy for controlling the effect of additive auxiliary white noise. The feedback path neutralization method is a simple modification of the method suggested in [4]. The secondary path model presents a secondary path modeling based on the gain scheduling strategy also proposed in [4]. The whole simulation was done using MATLAB and Simulink. As all the necessary blocks were not available in Simulink Library, some custom blocks were created using Level-2 MATLAB S-Functions. The main purpose of this work was to create a set of general Simulink blocks which could be also used later to investigate different ANC algorithms, for example the ANC system in [5] will be investigated.

2. Proposed Method

The proposed method comprises a whole ANC system with simultaneous online solution to the

feedback and the secondary path problems. For the ease of explanation the proposed method is explained in three parts. First part is the feedback path neutralization, second part is the secondary path modeling, and third part is the whole ANC system combining the first two parts with the ANC filter. A Simulink diagram of the ANC system will also be provided to show the simulation model used in this work.

2.1. Feedback Path Neutralization

A block diagram of the proposed method is shown in Fig. 2. White noise with variable variance is used to obtain the model of the feedback path online. The variable variance is obtained by the gain control block. The ANC filter $W(z)$ is designed as an FIR filter and its output is given as

$$y(n) = \mathbf{w}^T(n) \cdot \mathbf{x}_w(n) \quad (1)$$

where $\mathbf{w}(n)$ is the tap-weight vector iteration at n , $\mathbf{x}_w(n)$ is the reference signal vector of $W(z)$. The weights of $W(z)$ are updated using the NLMS algorithm by

$$\mathbf{w}(n+1) = \mathbf{w}(n) - \mu_w(n) \cdot e(n) \cdot \mathbf{x}'(n) \quad (2)$$

where, $\mu_w(n)$ is the step size parameter and $\mathbf{x}'(n)$ is the filtered reference signal vector. $x(n)$ is filtered through $S'(z)$ to compute $x'(n)$. The residual error signal $e(n)$ is given by

$$e(n) = d(n) + y_s(n) + v_s(n) \quad (3)$$

where $v_s(n)$ is the contribution of the additive auxiliary white Gaussian noise (WGN) $v(n)$ at the error microphone after traveling through the secondary path. This signal is generated internally in the system and introduced to the system by the anti-noise loudspeaker in addition with ANC filter output $y(n)$. The output of the anti-noise loudspeaker is given by

$$y_{total}(n) = y(n) + v(n) \quad (4)$$

This anti-noise signal does not only travel downstream through the secondary path $S(z)$ to cancel $d(n)$ but also travels upstream through feedback path $F(z)$ to create a corrupted reference signal $c(n)$ that is picked up by the reference microphone and given as

$$c(n) = r(n) + y_f(n) + v_f(n) \quad (5)$$

The output of the FBPMN filter $F'(z)$ is subtracted from $c(n)$ to compute the reference signal $x(n)$ for ANC filter $W(z)$ as

$$\begin{aligned} x(n) &= c(n) - y_f'(n) - v_f'(n) \\ &= r(n) + y_f(n) + v_f(n) \\ &\quad - y_f'(n) - v_f'(n) \end{aligned} \quad (6)$$

The signal $x(n)$ also acts as the desired response for the Adaptive Noise Cancellation Filter $H(z)$ which is used to adapt the FBPMN filter faster.

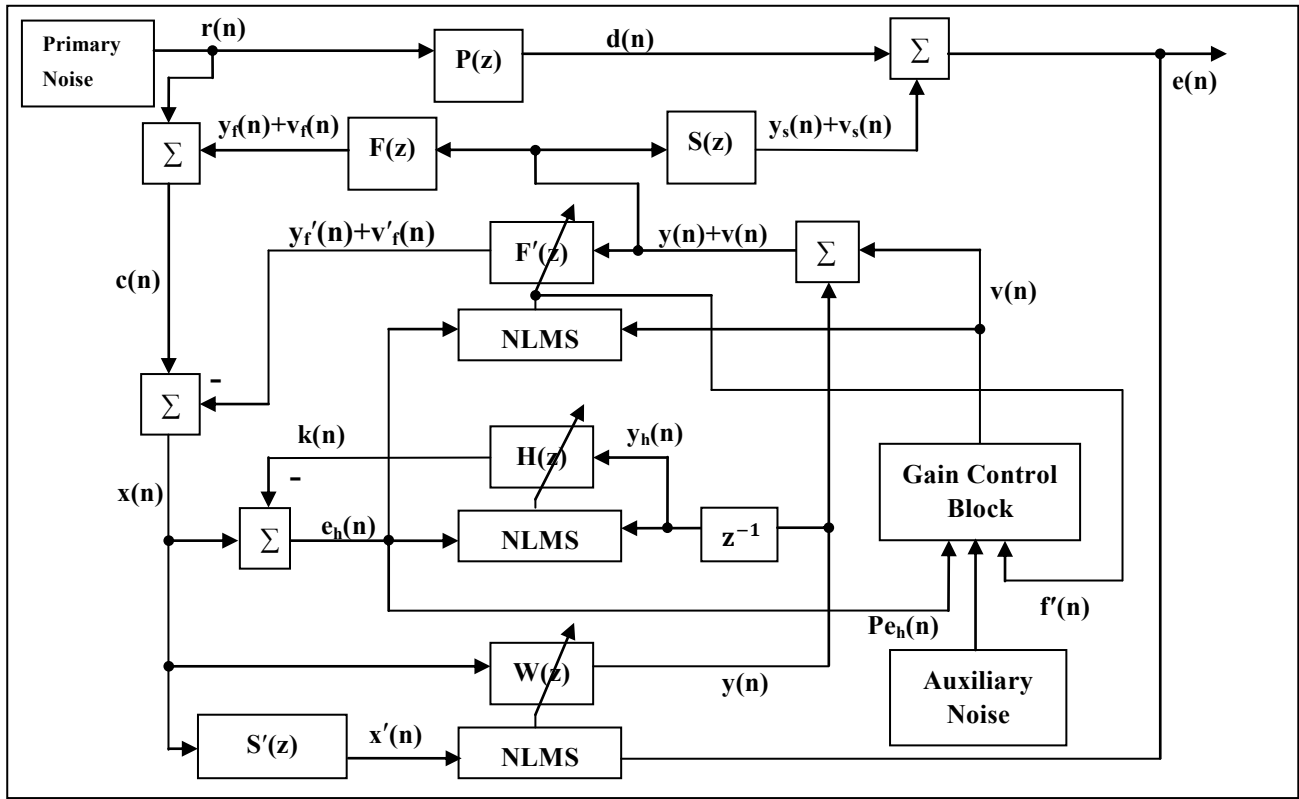


Figure 2. Proposed Feedback Path Neutralization Model

The detailed mathematical computation of the gain control block can be found in [4].

$H(z)$ is updated using the NLMS algorithm as

$$\mathbf{h}(n+1) = \mathbf{h}(n) + \mu_h(n) \cdot e_h(n) \cdot \mathbf{y}_h(n) \quad (7)$$

where $\mathbf{h}(n)$ is the tap weight vector iteration at n , $\mu_h(n)$ is the step size parameter, $\mathbf{y}_h(n)$ is the input signal vector, and $e_h(n)$ is the error signal to $H(z)$

$$e_h(n) = r(n) + y_f(n) + v_f(n) - y_f'(n) - v_f'(n) - k(n) \quad (8)$$

where $k(n)$ is the output of $H(z)$ given as

$$k(n) = \mathbf{h}^T(n) \cdot \mathbf{y}_h(n) \quad (9)$$

$e_h(n)$ is also used as an error signal to FBPMN filter $F'(z)$. But the term $r(n) + y_f(n) - y_f'(n)$ in $x(n)$ acts as disturbance to the adaptation of $F'(z)$. The task of the filter $H(z)$ is to remove the disturbance term from $x(n)$. Assuming that $H(z)$ converges leading to $k(n) = r(n) + y_f(n) - y_f'(n)$ then $e_h(n) = v_f(n) - v_f'(n)$. Using $e_h(n)$, $F'(z)$ is adapted using NLMS algorithm as follows

$$\mathbf{f}'(n+1) = \mathbf{f}'(n) + \mu_f(n) \cdot e_h(n) \cdot \mathbf{v}(n) \quad (10)$$

$\mu_f(n)$ is the step size parameter, and $\mathbf{v}(n)$ is the input signal vector of $F'(z)$. As stated earlier the variance of the auxiliary white noise is controlled by a gain control block and it is computed as

$$v(n) = G(n) \cdot v_b(n) \quad (11)$$

where $v_b(n)$ is a zero mean unit variance WGN and $G(n) = \alpha G(n-1) +$

$$\gamma \sqrt{P_{eh}(n-1) / \|\mathbf{f}'(n)\|^2} \quad (12)$$

2.2. Secondary Path Modeling

The block diagram of proposed secondary path modeling is shown in Figure 3. The proposed method is a simple upgrade of Eriksson's method as proposed in [6] for a duct environment with addition of a gain control block to control the variance of WGN.

As it can be seen from the block diagram, the system consists of two adaptive filters: F_x NLMS based ANC filter $W(z)$ and NLMS algorithm based secondary path modeling filter $S'(z)$. Additive White Gaussian Noise with variable variance (same as with feedback path neutralization) is used to model the secondary path. The residual error $e(n)$ to the error microphone is given as

$$e(n) = d(n) + y_s(n) - v_s(n) \quad (13)$$

where $v_s(n)$ is the contribution of WGN after travelling through the secondary path. The secondary path modeling filter $S'(z)$ has an input $v(n)$ and output $v_s'(n)$. $S'(z)$ is updated using the NLMS algorithm as

$$\mathbf{s}'(n+1) = \mathbf{s}'(n) + \mu_s(n) \cdot e_s(n) \cdot \mathbf{v}(n) \quad (14)$$

Here $\mu_s(n)$ is the step size parameter, $\mathbf{v}(n)$ is the additive white Gaussian noise and $e_s(n)$ is the error signal to NLMS filter given as

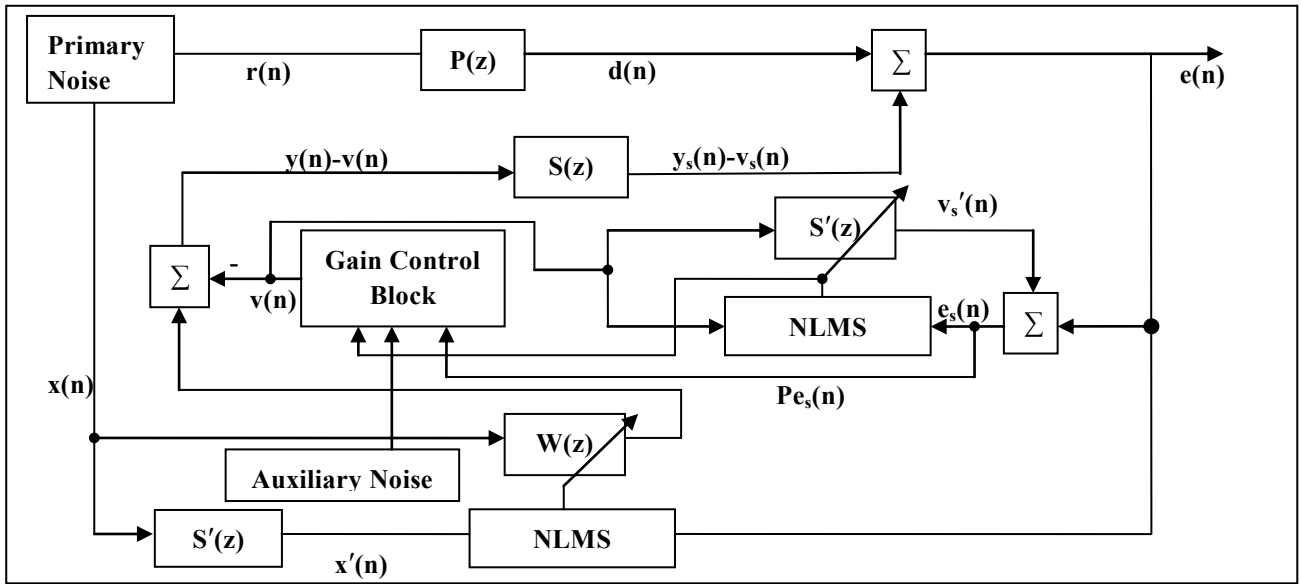


Figure 3. Proposed Secondary Path Model

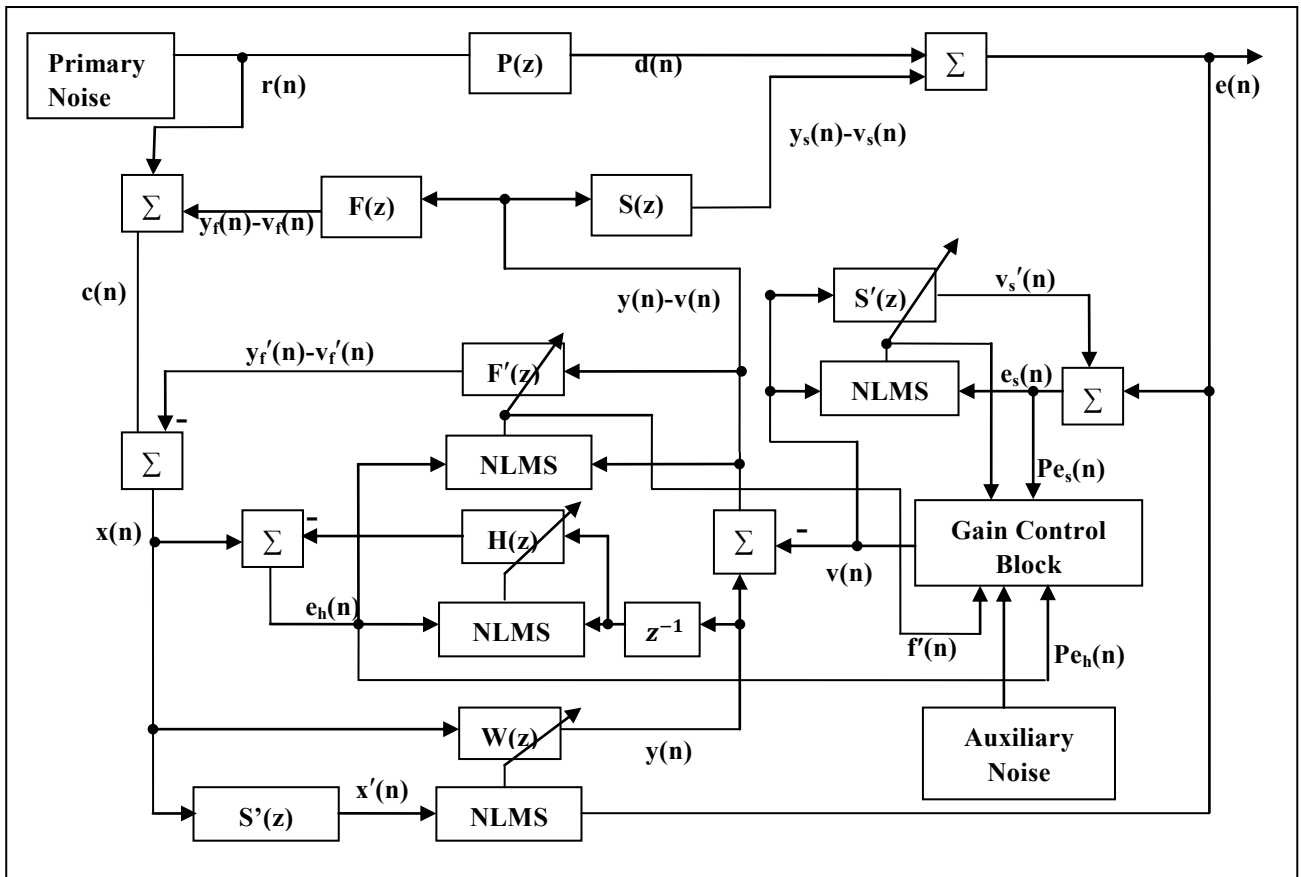


Figure 4. Proposed ANC System

$$e_s(n) = e(n) + v_s'(n) \\ = d(n) + y_s(n) - v_s(n) + v_s'(n) \quad (15)$$

Assuming that $S'(z)$ converges $d(n) = -y_s(n)$ and $-v_s(n) + v_s'(n) = 0$ there is no effect of the secondary path. Variance of the additive white noise is controlled by a gain control block as

$$v(n) = G(n) \cdot v_b(n) \quad (16)$$

where $v_b(n)$ is a zero mean unit variance white Gaussian noise and $G(n)$ is computed as

$$G(n) = \alpha G(n-1) + \frac{\gamma \sqrt{Pe_s(n-1)} / \|s'(n)\|^2}{\gamma \sqrt{Pe_s(n-1)} / \|s'(n)\|^2} \quad (17)$$

The detailed mathematical analysis of the gain control block can be found in [4].

2.3. Proposed ANC System

The block diagram of the proposed ANC system is shown in Figure 4. The system provides simultaneous online solution to feedback and secondary path problem.

3. Implementation Method

The implementation method description will be divided in two parts. In the first section the creation method for custom blocks and in the second section the whole implementation of the ANC system will be explained.

3.1. Custom Blocks

Simulink provides the user to create blocks on his own with custom configuration. Starting from the number of input/output ports and the relation between the input and output ports all can be configured. The custom blocks are created through the S-functions from Simulink. There are two sets of S-functions, Level-1 S-functions and Level-2 S-functions. Level-1 S-functions can be written in C/C++/Fortran, on the other hand Level-2 S-functions are written in MATLAB Language

template comes with the basic functions and setups necessary for the creation of custom blocks. Not all the functions of the template are necessary. Functions can be chosen depending on the block functionality. The important functions are input and output port configuration, D-Works that work as the memory spaces and the output function where the whole relation between the input and output is basically defined. In the template a brief description of all the functions is available. Details of the S-functions can be found in MATLAB docs. The working principle of Fx_NLMS block can be found in details in [1]. As described in [1] to make an Fx_LMS three input ports, one output port and three D-Work blocks were necessary. The input ports were reference signal $x(n)$, error signal $e(n)$ and filtered reference signal $x'(n)$. Output port gives the filter output $y(n)$. The D-Work blocks were reference signal, filter weights and filtered reference signal. In the output function block of S-function template the algorithm of Fx_NLMS has been written. The other parameters inside the Fx_NLMS block were modified as necessary. The other custom blocks were created following the same guideline and their respective algorithms.

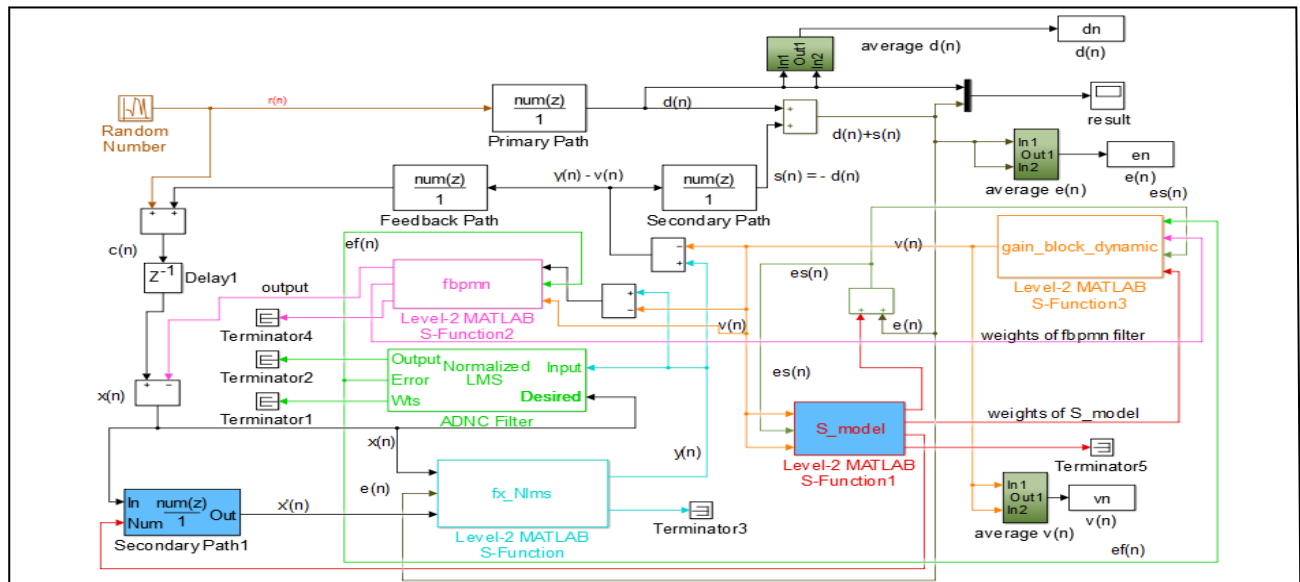


Figure 5. ANC System in Simulink

In this work Level-2 S-functions were used. As a general method of custom block creation the method of creating an Fx_NLMS block will be discussed here as it is the most widely used block in any ANC system.

To start building the custom block, the template available from Simulink library was used. The

3.2. ANC System Implementation

For the ANC system implementation $P(z)$, $S(z)$ and $F(z)$ were created using FIR filters. Fx_NLMS, FBPMN, S-Model, Gain Control Block were created as custom blocks. To obtain the results and convert them in decibels (dB), another custom block was used and the plotting of the results was done interactively using MATLAB plotting tools.

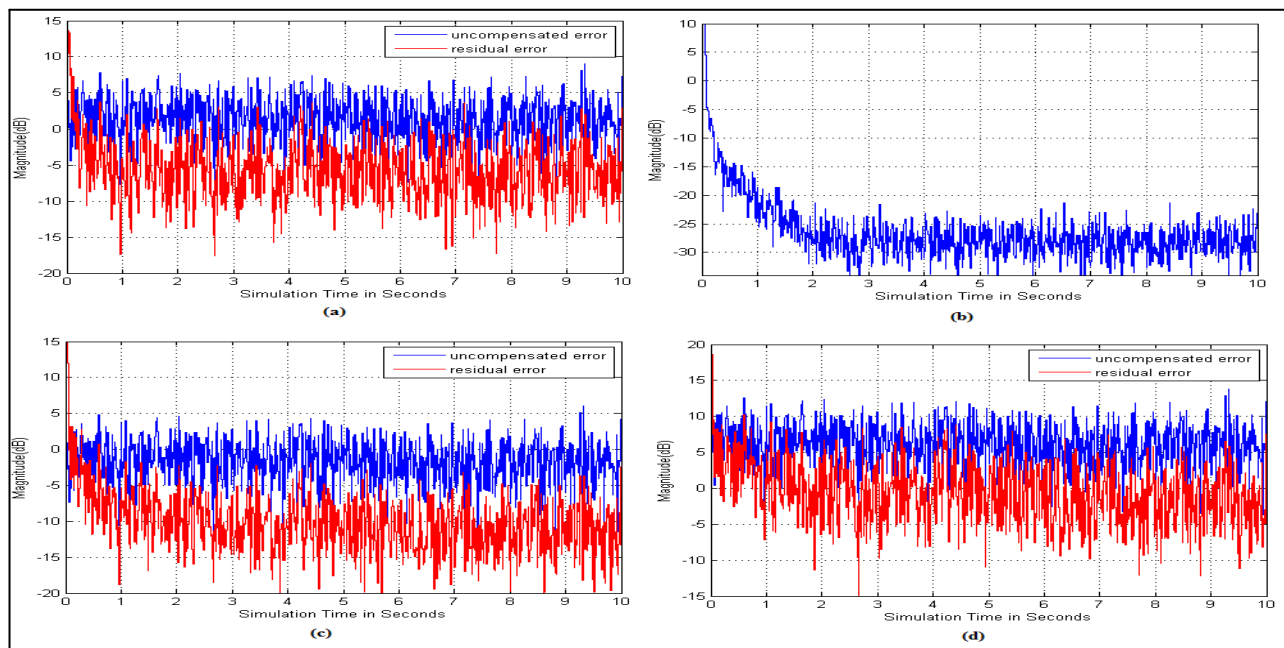


Figure 6. Results of Performance Measurement

4. Performance Measurement

As stated earlier the primary, secondary and feedback paths were modeled using FIR filters. The input noise was introduced by the random number block from Simulink with zero mean and unit variance and sampling frequency of 2000 Hz. The variance of the input noise was changed during the experiment leading to practical situation where the noise power can vary and the system performance was measured for different input variances. The simulations were done for 10 s. In traditional ANC systems offline modeling is used before starting the online modeling, but in this work no offline modeling was used. Even more satisfactory results will be obtained if offline modeling is used.

Fig. 6(a) shows the performance measurement of the ANC system with the reduction of residual error with time. Fig. 6(b) shows the reduction of injected white noise with time as the residual error decreases, showing the performance of gain control block. Fig. 6(c) shows the performance of the system with input noise power half and in 7(d) the input noise power of five folds. In both cases the residual error is reduced over time. This shows the robustness of the system with the change in input noise power as desired in real life systems.

5. Conclusions

The goal of this paper was to set up simulation platforms in MATLAB and Simulink for ease of further research of ANC algorithms, and this has been fulfilled. In addition a method for simultaneous solution of feedback and secondary path has been tested which in the knowledge of the authors is not frequently done. The proposed method needs further research but this was out of the scope of this project.

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