Adaptive notch filter for single and multiple narrow-band interference

Selina Kuek Lin Mei

Edith Cowan University

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Adaptive Notch Filter for Single and Multiple Narrow-band Interference

Submitted by: KUEK LIN MEI, SELINA 3993120

SUPERVISOR: Dr Amine Bemak and Dr Ganesh
LOCAL SUPERVISOR: Mr Ma Zongming
ABSTRACT

In this project, the adaptive notch filter for single and Multiple narrow-band interference is implemented using simplified LMS algorithm.

Performances of the LMS adaptive algorithms is evaluated and analysed through simulation on the computer using Matlab. The algorithm are then written in C programme and implemented using Texas Instrument Tool which consist of TMS320C54x EMV board and Code Composer Studio.
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Finally, to everyone, who has in one way or another contributed to the project.
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1 INTRODUCTION

1.1 BACKGROUND

Digital signal processing is one of the fastest growing fields in the last thirty years and it plays a major role in many application areas. The resulting digital signal processing systems are attractive due to their reliability, accuracy, small physical sizes, and flexibility.

One category of digital signal processing known as adaptive signal processing which applications are increasing rapidly. Adaptive signal processing evolved from techniques developed to enable the adaptive control of time-varying systems. It has gained a lot of popularity due to the advances in digital technology that have increased the computing capacities and broadened the scope of digital signal processing. The key difference between classical signal processing techniques and adaptive signal processing method is that the latter deal with time varying digital systems.

An adaptive system is a system whose coefficients could automatically adjust to changing environment or input signal. The transition from implementing digital filters with DSP microprocessors to implementing adaptive digital filters is a natural extension. Adaptive filters are used to their greatest advantage when there is an uncertainty about the characteristics of a signal or when the characteristics change during filter's characteristics no longer change.
Adaptive filter theory could be found applications in such field as biomedical engineering, seismology, astrology, navigation, communication, radar, sonar and control systems. They are used in the area of system identification, channel equalization, signal enhancement, and prediction.

The project will focus on the techniques of using adaptive notch filter in the Noise Cancellation Application.

1.2 OBJECTIVES

In many systems, noise interference is a major problem that could cause the whole system to malfunction or inaccurate readings to be taken. Noise signals normally reside in higher frequencies in the frequency spectrum. So to remove the noise signal, the signal could be passed through a low pass filter so that the higher noise frequency could be removed. However, by doing this, the bandwidth of the signal would be effectively reduced. This is however not desirable as, if there are signals in the higher frequency range that is wanted, then they will be lost.

To overcome this problem, a notch filter could be implemented. The function of this notch filter is to cancel out only the noise frequency. That is, it is simply a band stop filter with a very narrow bandwidth with the notch frequency placed over the noise signal. This is illustrated in Figure 1.1
As can be seen from the frequency response plot of the filter in Figure 1.1, the whole frequency spectrum of the signal is passed through except at the noise frequency. In this way, the bandwidth of the signal is preserved and only the noise component is being removed.

Also if the noise frequency shift up and down, the notch filter must be able to adapt to the shift. That is, the filter must be able to track the noise and cancel it out. This is important feature in noise cancellation as most noise signals are not stationary at a frequency.

The objective of this project is to implement this adaptive notch filter digitally to cancel out single and multiple narrow-band noise in a wide-band signal. It will be implemented on the TMS320C54XX board and demonstrated on audio signal.
1.3 PLANING

1.3.1 PHASE I

The schedule was planned base on weekly basis. The duration to complete a task will vary from one to four weeks depends on its complexity.

The following schedule was planned before the project was started.

<table>
<thead>
<tr>
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<td>Project Proposal</td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>Planning for approval</td>
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<td>Received of approval</td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td>Sourcing for notes, tests and informations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Theoretical Studies</td>
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<td></td>
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</tr>
<tr>
<td>6</td>
<td>Design Approach</td>
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<tr>
<td>7</td>
<td>Reporting</td>
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</tr>
<tr>
<td>8</td>
<td>Final report submission</td>
<td></td>
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</table>

Figure 1.2 Project Phase II schedule

1.3.2 PHASE II

In project II, the schedule was planned according to project I on weekly basis. Due to short time frame, the duration has slightly reduce from one to two weeks depend on the complexity.

Here is the project II schedule:

<table>
<thead>
<tr>
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<th>January</th>
<th>February</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Studies Development Tools</td>
<td>wk1 wk2</td>
<td>wk3 wk4</td>
<td>wk1 wk2</td>
</tr>
<tr>
<td>2</td>
<td>Trying to explore the hardware &amp; the software debugger</td>
<td></td>
<td></td>
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<tr>
<td>3</td>
<td>Discussion on the software approach &amp; assign the task</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Hardeware testing via PC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Self study on the individual Algorithm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Draft report &amp; final simulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Final report</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Figure 1.3 Project Phase II schedule
2 BASIC THEORY

2.1 ADAPTIVE FILTER

Adaptive filters are considered non-linear systems, therefore their behaviour analysis is more complicated than for fixed filters. On the other hand, because the adaptive filters are self-designing filters, from the practitioner's point of view their design can be considered less involved than in the case of digital filters with fixed coefficients.

The general setup of adaptive filtering environment is illustrated in Figure 2.1, where $k$ is the iteration number, $x(k)$ denotes the input signal, $y(k)$ is the adaptive filter output signal, and $d(k)$ defines the desired signal. The error signal $e(k)$ is calculated as $d(k) - y(k)$. The error signal is then used to form a performance function that is required by the adaptation algorithm in order to determine the appropriate updating of the filter coefficients. The minimisation of the objective function implies that the adaptive filter output signal is matching the desired signal in some sense.
The specifications of an adaptive system consists of the following items:

2.1.1 APPLICATION

The type of application is defined by the choice of the signals acquired from the environment to be the input and desired-output signals. Examples are echo cancellation, channels equalization, system identification, signal enhancement, adaptive beamforming, noise canceling and control.

2.1.2 ADAPTIVE FILTER STRUCTURE

The adaptive filter can be implemented in a number of different structures or realizations. The choice of structure can influence the computational complexity (amount of arithmetic operations per iteration) of the process and also the necessary number of iterations to achieve a desired performance level. Basically, there are two major classes of adaptive digital realizations:
For this realization, the output signal is a linear combination of the filter coefficients, that yields a quadratic mean square error (MSE) function with a unique optimal solution. FIR typically required large filter orders to obtain satisfactory sharp cutoff characteristics and hence increase in computational complexity.

2.1.2.1 Finite-duration Impulse Response (FIR) filter

The most widely used adaptive FIR filter structure is the transversal filter which implements an all-zero transfer function with a canonic direct from realization without feedback. The output of the FIR filter can be described by the following equation:

\[ y(n) = \sum_{k=0}^{N} b_k x(n-k) \] ............2.1

The above equation represents a weighted sum of the present and past input to the filter with \( b_k \) is the weight of the (N+1) order filter. The equation may also be represented by the network structure as shown in Figure 2.2

![Figure 2.2 Network structure representation of FIR filter](image-url)
2.1.2.2 Infinite-duration Impulse Response (IIR) Filter

The most widely used adaptive IIR filter structure is the canonic direct-form realization, due to its simple implementation and analysis. The output of the IIR filter can be described by the following equation:

\[
y(n) = \sum_{k=1}^{N} a_k y(n-k) + \sum_{k=0}^{M} b_k x(n-k) \tag{2.2}
\]

Equation (2.2) shows that the output of the filter is a weighted sum of the present and past input of the filter, as well as past values of the output of the filter. The \(a_k\) and \(b_k\) are the weights of the filter and \(N\) & \(M\) is the order of the filter. A network structure representation of a second order IIR filter is illustrated in Figure 2.3:

![Network structure representation of a 2nd order IIR filter](image)

*Figure 2.3 Network structure representation of a 2nd order IIR filter*
Sharp cutoff and constant magnitude response can be obtained using second-order filter sections. However, there are some inherent problems related to recursive adaptive filters which are structured dependent, such as pole-stability monitoring requirement and slow speed of convergence.

2.1.3 ALGORITHM

The algorithm is the procedure used to adjust the adaptive filter coefficient in order to minimize a prescribed criterion. The algorithm is determined by defining the search method (or minimization algorithm), the objective function, and the error signal nature. The choice of algorithm determines several crucial aspects of the overall adaptive process, such as existence of sub-optimal solutions, biased optimal solution, and computational complexity.

2.2 ADAPTIVE NOISE CANCELLATION

The basic concept of adaptive noise cancellation reduces the level of undesired noise by using adaptive filtering techniques with an auxiliary reference signal. This technique takes advantage of the correlation between the noise contaminating the desired signal and a noise-alone reference signal. Figure 2.4 shows the block diagram of an adaptive noise cancellation system:
The canceler has two inputs, the primary input $d(n)$ and the reference input $x(n)$. The primary input $d(n)$ consists of desired signal $u(n)$ plus noise, which is derived from $x(n)$ through the linear filter $P(z)$. The reference input consists of noise $x(n)$ alone.

The objective of the adaptive filter is to use the reference input $x(n)$ to estimate the noise component of $d(n)$ using adaptive filter $W(z)$. The adaptive filter output $y(n)$ is then subtracted from the primary channel signal $d(n)$, producing $e(n)$ as the desired signal plus a small amount of residual noise.

The area of focus for the project is to deduce a method on reducing sinusoidal interference of an audio signal. The conventional method of eliminating such sinusoidal interference is through the use of a notch filter tuned to the frequency of
the interference. A very narrow notch is usually desired in order to filter out interference without seriously distorting the signal of interest.

An adaptive notch can be realised by using an adaptive noise canceler with a sinusoidal reference signal. The advantages of adaptive notch filter are that it offers easy control of bandwidth, an infinite null, and the capability to adaptively track the exact frequency of interference.

2.3 ADAPTIVE ALGORITHMS

Adaptive algorithms are used to adjust the coefficients of the digital filter such that the error signal, $e(k)$, is minimized according to some criterion. There are various algorithms used in digital filter applications, examples, Least Mean Square Algorithm (LMS), Normalised LMS Algorithm (NLMS), Variable Step Size LMS Algorithm (VSLMS), Normalised Variable Step S Algorithm (VSNLMS), Recursive Least Square Algorithm (RLS) and RLS-QR Algorithm (RLS-QR) etc. The most common algorithms that have found widespread application are the Least Mean Square Algorithm (LMS) and Recursive Least Square Algorithm (RLS). In terms of computation and storage requirements, the LMS algorithm is the most efficient. Further, it does not suffer from the numerical instability problem inherent in the other two algorithms. For these reasons, the LMS algorithm has become the first choice in many applications. A more detailed information of the basic LMS adaptive algorithm was introduced.

2.3.1 BASIC LEAST MEAN SQUARE (LMS) ADAPTIVE ALGORITHM

In LMS algorithm, the coefficients are adjusted from sample to sample in such a way as to minimize the Mean Square Error (MSE).
The LMS is based on the steepest descent algorithm where the weight vector is updated from sample to sample as follows:

\[ W_{k+1} = W_k - \mu \Delta_k \]  
\[ \text{(2.3)} \]

where \( W_k \) and \( \Delta_k \) are the weight and the true gradient vectors, respectively, at the \( k \)th sampling instant. \( \mu \) controls the stability and rate convergence.

The LMS algorithm is a practical method of obtaining estimates of the filter weights \( W_k \) in real time. The Widrow-Hopf LMS algorithm for updating the weights from sample to sample is given by

\[ W_{k+1} = W_k + 2\mu e_k \Delta_k \]  
\[ \text{(2.4)} \]

Where:

\[ e_k = y_k - \sum w_k(i)x_{k-1} \]

Clearly, the LMS algorithm above does not require prior knowledge of the signal statistics, but instead uses their instantaneous estimates. The weights obtained by the LMS algorithm are only estimates, but these estimates improve gradually with time as the weights are adjusted and the filter learns the characteristics of the signals. Eventually, the weights converge. The condition for convergence is:

\[ 0 < \mu < 1/\lambda_{\text{max}} \]
where $\lambda_{\text{max}}$ is the maximum eigenvalue of the input data covariance matrix. In practical, $W_k$ never reaches the theoretical optimum $W_{\text{optimum}}$, but fluctuates about it. See the Figure 2.5 below.

![Figure 2.5 Weight Adaption, $W_k$ vs $k$](image-url)
3 PROJECT APPROACH

3.1 NOTCH FILTER TRANSFER FUNCTION

We have decided to use IIR filter structure and LMS algorithm to design and implement the adaptive notch filter after going through the literature studies. The initial task is to obtain the transfer function of the notch filter.

With the constraints and characteristics of a notch filter lead to a direct realisation of transfer function from the poles and zeros diagram. From the pole-zero plot of notch filter shown in Figure 3.1, it converges to a polynomial transfer function with zeros on the unit circle whose angular locations correspond to the signal frequencies (\(w\)). \(r\) is a constant which is slightly less than 1 so that the poles lie in the stability domain. It also determines the relationship between the distance of the pole from the unit circle and the normalised bandwidth.

![Pole-Zero Plot of Notch Filter](image)

*Figure 3.1 Poles & Zero Plot of Notch Filter*
With all the condition stated as above we could derive the transfer function of the adaptive notch filter:

\[ H(z) = \frac{Y(z)}{X(z)} \]

\[ = \frac{(1-e^{jw}z^{-1})^* (1-e^{-jw}z^{-1})}{(1-re^{jw}z^{-1})^* (1-re^{-jw}z^{-1})} \quad |r| < 1 \]

\[ = 1 - z^{-1}(e^{jw} + e^{-jw}) + z^{-2} / 1 - r z^{-1}(e^{jw} + e^{-jw}) + r^2 z^{-2} \quad |r| < 1 \]

\[ = 1 - z^{-1}(2\cos w) + z^{-2} / 1 - r z^{-1}(2\cos w) + r^2 z^{-2} \quad |r| < 1 \]

\[ = 1 - az^{-1} + z^{-2} / 1 - r z^{-1} + r^2 z^{-2} \quad |r| < 1 \quad \text{--- (3.1)} \]

where

\[ a = 2\cos w \]

In measuring the performance of the filter, the stability of the filter is very important. It is critical that the position of the poles of the filter remains within the circle to ensure stability of the output of the filter. If however the position of the poles were allowed to drift out of the unit circle radius in the pole-zero plot, then the output of the filter will become unstable.

By taking the inverse Z-transform of the transfer function, it is easy to show that the output of the filter is given by:

\[ y(n) = x(n) - a(n)x(n-1) + x(n-2) + a(n)y(n-1) - r^2 y(n-2) \quad \text{--------- (3.2)} \]
Comparing equation (3.2) with equation (2.2) mentioned earlier, it could be noted that they are similar. That is, it is a summation of the weighted pasted and present input values as well as weighted past output values. Thus it has the same structure as IIR filter.

3.2 LMS ADAPTIVE ALGORITHM

The Least Mean Square algorithm is chosen due to its simplicity and ease of computation. In addition, it does not require repetition of data. Thus it is generally the best for many different applications of adaptive signal processing.

Generally, the LMS algorithm is applied in transversal tapped (FIR) filters with the structure shown in Figure (2.2). But it can be extended to IIR filters with the structure shown in Figure (2.3).

3.2.1 ADAPTATION OF PARAMETER $a$

In this project, we are only concerned with second order section with one weight. Thus this will simplify the understanding of the algorithm. The algorithm is based on the steepest-descent gradient search. The equation used here will be modified from the one introduced by Widrow–Hopf. Here we are trying to minimise the mean-squared output energy level instead of minimizing the mean-squared error.

This is given by:

$$a(n+1) = a(n) - \mu \left[ \frac{dy(n)^2}{da(n)} \right] \quad (3.3)$$

Differentiating the mean-squared output w.r.t $a(n)$
\[ a(n+1) = a(n) - 2 \mu y(n) \left[ \frac{dy(n)}{da(n)} \right] \]  \hspace{1cm} (3.4)

from equation (2)

\[ \left[ \frac{dy(n)}{da(n)} \right] = -x(n-1) + ry(n-1) \]

Substituting into equation (3)

\[ a(n+1) = a(n) - 2 \mu y(n) [-x(n-1) + ry(n-1)] \]  \hspace{1cm} (3.5)

The above equation (3.5) is the LMS algorithm for this adaptive notch filter. Here \( \mu \) is the gain constant that regulates the speed and stability of adaptation.

Since we are dealing with real time processing, we need a relatively fast way of reaching the minimum. The way that the search is conducted is to set the weight of the filter, that is \( a(n) \) in equation (3.2), to some initial arbitrary value. And it will be adjusted in a stepwise fashion until the minimum is reached. This is shown in Figure 3.2.
When making a step, the size and direction must be considered. Each step will consist of an increment to the weight. If the current value of the weight is to the right of the minimum, then the step will be negative. If the current weight is to the left of the minimum, then the step size will be positive.

Thus the negation of the derivation indicated the proper direction of increment. Since the derivative vanishes at the minimum, it can be used to adjust the step size. And it can be observed that the step size and direction is proportional to the negative of the derivative as in equation (3.3). And repeated iteration of equation (3.3) will cause $a(n)$ to move by steps from its initial value until it reaches the minimum.

Figure 3.2 Search for minimum with stepwise fashion
And since the weight changes at each iteration are based on imperfect gradient estimates, it is expected that the adaptive process to be noisy, i.e. it would not follow the true line of steepest descent on the performance surface.

With the equation obtained in equation (3.5), we can see the simplicity and ease of computation of LMS algorithm. It allows the weight of the filter to be updated averaging, squaring or differentiating.

3.2.2 ADAPTATION OF PARAMETER $r$

The stability of the filter is maintained by constraining the poles of the filter within the unit circle. And to achieve a narrow notch, the poles are kept as close to the unit circle as possible. However, by doing so, because the LMS algorithm adapt by searching the gradient of squared output, it would be less sensitive to noise signals that are far away from the notch.

To be able to track noise signal that is far away from the notch, the parameter, $r$, has to be adapted as well. The idea to start off with a wide notch so that the noise signal can be detected and then to reduce the width of the notch to the narrow notch as before. This is depicted in Figure 3.3 and Figure 3.4.
Figure 3.3 Initial state of adaptation

Figure 3.4 Final adaptation notch with parameter $a$ & $r$
3.3 CASCADE ADAPTIVE NOTCH FILTER

The cascade section of the adaptive IIR notch filter is implemented by having two section of the basic notch filter as shown in the following Figure 3.5. The adaptation is done at the end of the section.

![Figure 3.5 Cascade section of the adaptive filter](image)

This cascading of two sections together allows the filter to have a narrower notch and yet retain its stability by constraining the poles in both sections well within the unit circle.

3.4 MULTIPLE CHANNEL ADAPTIVE NOTCH FILTER

The multiple adaptive IIR Notch filter will be extended to cancel out multiple sinusoidal interference. It is similar to cascade filter but with individual adaptive algorithm as shown in the Figure 3.6.
The frequency response of the multiple notch has the form shown in Figure 3.7.

Figure 3.7 Frequency response of multiple interference adaptive notch filter
3.5 IMPLEMENTATION APPROACH

The derived programmes will be simulated using Matlab for windows Version 5.3.1 for testing the feasibility of the adaptive algorithm. In the initial approach, TMS320C5x DSK board was used as the development tool but it was replaced by TMS320C54x EMV board and the Code Composer simulator in the later phase. The brief description of the TMS320C54x EMV board and the Code Composer Studio will be discussed in Chapter 5.

In order to demonstrate a real-time application, an analogue signal will be injected to the analogue input connector of TMS320C54x EMV board and the analogue output will be monitored.
4 SIMULATION AND DISCUSSION

In this chapter, the theoretical approach of the adaptive notch filters, which had been derived from previous chapter, will be investigated using MATLAB software. The basic, adaptive, cascade and multiple notch filters will be analysed and discussed.

4.1 BASIC IIR NOTCH FILTER

The transfer function of the notch filter has been derived in the previous chapter as shown in equation (3.1).

\[ H(z) = 1 - az^{-1} + z^{-2} / 1 - arz^{-1} + r^2z^{-2} \]

Where

\[ a = 2 \cos \omega \quad \text{and} \quad |r| < 1 \]

There are a few parameters which will effect the performance of the filter, there are poles, zeros, parameter \( a \), \( r \) and sampling frequency. Figure 4.1 shows the frequency response of the transfer function with sampling frequency of 48KHz, notch frequency of 4KHz and \( r = 0.95 \).
4.1.1 POLES AND ZEROS

In measuring the performance of the filter, the stability of the filter is very important. It is critical that the positions of the poles remain within the unit circle to ensure stability of the filter. If the position of the poles drift out of the circle radius, the output will be unstable. It is illustrated in the following figures.
4.1.2 RELATION BETWEEN $a$ AND NORMALISED BANDWIDTH

The relation between the frequency varying parameter, $a$ and the normalised bandwidth is given in Figure 4.4

*Figure 4.2 Output response of the notch filter with poles within the unit circle*
Figure 4.3 Relation between $a$ and normalised bandwidth

4.1.3 RELATION BETWEEN $r$ AND NORMALISED BANDWIDTH

The parameter, $r$ determines both the distance of the pole from the unit circle and the normalised bandwidth. The following figures are plots according the frequency response of different values of $r$. 
Figure 4.4 Frequency Response with $r = 0.95$

Figure 4.5 Frequency Response with $r = 0.90$
Figure 4.6 Frequency Response with $r = 0.80$

Figure 4.7 Frequency Response with $r = 0.75$
Figure 4.8 Frequency Response with $r = 0.70$
Figure 4.10 shows a relation between $r$ and the normalised bandwidth. From the figures, it can be seen that the parameter, $r$ is inversely proportional to the bandwidth of the notch filter.

*Figure 4.9 Relation between parameter $r$ and normalised bandwidth*
4.2 ADAPTIVE IIR NOTCH FILTER

This section will discussed the performance of the single interference adaptive notch filter. The theoretical adaptive equation was implemented using MATLAB and the results were simulated.

The following figures are plotted according to difference input variables of parameters. Figure 4.11 showed a single input frequency of 8KHz and with sampling frequency of 48KHz. Figure 4.12 showed the same frequency input but with a frequency drift of 100Hz. The result of Figure 4.12 showed that the filter is able to adapt the changed of frequency and response accordingly. Figure 4.13 showed the same filter with multiple channel input. The result showed that the filter only attenuated the notch frequency in the input signals.
Single Channel Adaptive Notch Filter

Figure 4.10 Output Response of Adaptive Notch Filter
Figure 4.11 Output Response of Adaptive Notch Filter with Frequency Drift
Figure 4.12 Output Response of Adaptive Notch Filter with Multiple Frequency Input
4.2.1 PARAMETER $u$

The parameter $u$ as shown in the adaptive algorithm equation is the step size which determined the speed and stability of the adaptation. The following few figures are plotted according with same notch frequency and different step size. The input is an 8KHz sine wave and shift to 8.1KHz after 256 samples.

Figure 4.13 Output Response of Adaptive Notch Filter with $u=0.01$
Figure 4.14 Output Response of Adaptive Notch Filter with $u=0.05$
Figure 4.15 Output Response of Adaptive Notch Filter with $u=0.1$
Figure 4.16 Output Response of Adaptive Notch Filter with \( u = 0.2 \)
Figure 4.17 Output Response of Adaptive Notch Filter with $u=0.35$
4.3 CASACADE SECTION OF ADAPTIVE IIR NOTCH FILTER

The following figures show the simulation results of the cascade filter with single frequency, frequency drifting and multiple frequency input sequence. From the simulation results, it showed that the filter is able to track on the drift frequency and attenuate the frequency component in the region of notch frequency.

![Cascade Adaptive Notch Filter with Single Input Frequency](image)

*Figure 4.18 Cascade Notch Filter with Single Input Frequency*
Figure 4.19 Cascade Notch Filter with Frequency Drift
Figure 4.20 Cascade Notch Filter with Multiple Input Frequency
### 4.4 Multiple Adaptive Notch Filter

The following figures showed the simulation output results of the multiple notch adaptive filter with multiple frequencies and frequency drifting input sequence. From the simulation results, it showed that the filter is able to track on the frequency drift and attenuate the frequency component in the region of notch frequency.

![Multiple Channel Adaptive Notch Filter](image)

**Figure 4.21 Multiple Notch Adaptive Filter**
Figure 4.22 Multiple Notch Adaptive Filter with frequency drift
5 DEVELOPMENT TOOL

TEXUS INSTRUMENTS products, the TMS320C54X Evaluation Module (EVM) and the Code Composer Studio™ are used to develop the notch filters. TMS320C5X DSK was initially chosen for hardware implementation. In order to reduce the development cycle, software simulation is essential and it is accomplished by using Code Composer Studio. As the Code Composer Studio does not support the TMS320C5X DSK board, it was replaced by the TMS320C54X EVM.

5.1 TMS320C54X EVALUATION MODULE

5.1.1 OVERVIEW

The TMS320C54x evaluation module (EVM) is a PC/AT plug-in card that allows user to evaluate the performance of the DSP algorithm using the 'C54x digital signal processor (DSP). The software can be created and run on board or expand the system in a variety of ways.

The 'C54x EVM carries a 'C541 DSP on board to allow full-speed verification of 'C54x code. The 'C541 has 5K bytes of on-chip program/data RAM, 28K bytes of on-chip ROM, two serial ports, a timer, access to 64K bytes each of external program and data RAM, and an external analog interface for evaluation of the 'C54x family of devices for a given application.
5.1.2 KEY FEATURES

The 'C54x EVM has the following features:

- 'C541 operating at 40 MIPS with 128K words of zero wait-state memory
- Voice-quality analog interface to line I/O or speaker/microphone (user-selectable)
  via standard RCA connectors
- External serial port
- Parallel I/O expansion bus
- Two 16-bit bidirectional host/target communication channels; one channel contains 64 words of buffering
- Embedded emulation support based on the IEEE 1149.1 standard
- A single 16-bit ISA half card, mappable to one of four I/O locations

5.1.3 FUNCTIONAL BLOCKS DESCRIPTION

Figure 5.1 shows the basic configuration and interconnects of the 'C54x EVM, including the host interface, target memory, analog interface, and emulation interface.

The 'C54x EVM supports a 16-bit PC/AT-host interface. The PC/AT interface provides the buffering, host I/O decode, and access control. The PC/AT host communicates to the 'C54x EVM via 38 16-bit I/O locations. Each I/O location is defined by the I/O page 0 address described by an offset. The first 32 I/O locations support emulation. The remaining six locations support host/target communications and control.
Figure 5.1 Configuration and Interconnection of TMS320C54X EVM

The 'C54x interfaces to 64K words of zero wait-state program memory and 64K words of zero wait-state data memory, in the total of 128K. Host target interface communicates through two independent channels, Channel A and Channel B. An external I/O interface supports 16 parallel I/O ports, a serial port, and other I/O features. A single single channel of voice-band analog input and output was provided by the EVM with programmable filtering, scaling, and sampling based on the TLC320AC01 analog interface circuit. Two RCA connectors provide analog input and output.

5.2 TMS320C5000 CODE COMPOSER STUDIO™ 1.2

In this Chapter, a brief description of the Code Composer Studio will be introduced. This includes the features, benefits and the project development cycle.
5.2.1 INTRODUCTION

Code Composer Studio is a fully integrated suite of easy-to-use DSP software development tools, incorporating TI's efficient 'C5000 C compiler with the Code Composer Integrated Development Environment (IDE), DSP/BIOS™ and Real-Time Data Exchange(RTDX™) technologies. Code Composer Studio's real-time analysis and data visualization capabilities, open architecture and advanced code generation tools greatly reduce the complexity of DSP development, enabling you to focus your resources and creativity on adding value to your applications.

5.2.2 FEATURES AND BENEFITS

Code Composer Studio has two kinds of tool features, compiler tools and debug tools.

Compiler tools includes C Compiler, Linker and IDE Simulator and debug tools includes Code Composer IDE C54x/C55x Emulation Debug Software, RTDX and DSP BIOS II.

In this project, the Code Composer IDE Simulator is used for our software development. The Code Composer Simulator could be used to simulate the actual execution of DSP code without the presence of a DSP chip, in parallel with hardware development. The advantages are the developers can also use the simulator for concurrent and field development and the simulator reduces costs by providing a team of developers access to the development environment through a software interface rather than through hardware.
5.2.3 PROJECT DEVELOPMENT CYCLE

In this section, the initial set up of the system and the development cycle will be discussed in brief.

5.2.3.1 INITIAL SET UP

After installing the TMS320C5000 Code Composer Studio, an initial import configuration will prompt to add available system to the code composer setup. The C54x simulator will be chosen and added to the system.

The Code Composer Setup allow you to chose the available board or simulator types to add onto your system. In this case, the C54xx simulator type was chosen for our software simulation. In the later stage, the C54xx parallel port will be chosen to communicate with C54xx EMV board.

This above set up only need to be done once, hence the C54x simulator could be used anytime.

5.2.3.2 DEVELOPMENT CYCLE

Step 1. Project Management system - The C54x simulator provides the Visual Project Management system which is a fast way of visualizing, accessing, and manipulating all project files from the same window. In the project view, files are organized into functional categories such as source files, include files, libraries, config and GEL script files. All compile options are saved with the project for easy retrieval.
Step 2. Build and Compile - Once a project file is created, use the compiler and builder to compile and build the programme. If the programme is successfully build, a .out file will be created. Load the .out file and you could start to run your programme.

Step 3. Edit within the IDE - Code Composer Studio's™ integrated development environment (IDE) is similar to MS-Visual C++. The source code editor is tuned specifically for writing C and DSP assembly code to let you work more efficiently. The editor is integrated with all other tools in Code Composer Studio™ like the background build facility, the debugger, etc. This allows you to easily edit your code and see source and disassembly while coding and editing.

Step 4. Debug within IDE - Code Composer Studio's integrated debugger has DSP-specific capabilities and advanced breakpoints to simplify development. Conditional or hardware breakpoints are based on full C-expressions, local variables or CPU register symbols. A Probe Point™, a unique feature in Code Composer Studio™, is a sophisticated form of a breakpoint. It allows you to define a point in the algorithm where you can perform an oscilloscope-type function. Unlike a breakpoint, program execution resumes after hitting a Probe Point™ and performs the connected activity (e.g. inject or extract signal data, observe signals, execute GEL script). Probe Points™ may be easily set, removed, or moved to other areas in the algorithm simply by clicking on the icon in the toolbar.

Step 5. I/O Data signal - Using Probe Points Execution reaches 1st Probe Point™: Inject known signal values from a file into DSP target to simulate
conditions. Execution reaches 2nd Probe Point™: Execute GEL function (e.g. diagnostic test cases) and send a set of memory locations to disk. Execution reaches Third Probe Point™: Take snap shot of memory and display graphically.

Step 6. Analyze – Profile interactive is a quick measurement of code performance and how well the DSP target's resources are being used during your debugging and development session. Profile Points are similar to breakpoints but instead of halting the target processor, they accumulate hits and collect statistics on the number of instruction cycles or other events that have elapsed since the previous profile point was hit. This lets you target high usage areas in your optimization to produce finely tuned code. Tightly integrated data visualization also allows you to view data and signals in their native format for easy interpretation and analysis with many display types. As the program animates, a snapshot of the signal is taken at each probe point connected to a data visualization window allowing you to see the signal as it progresses through an algorithm during debugging.

Step 7. Real time analysis using DSP/BIOS - Probe, trace, and monitor a DSP application while it runs! These utilities are based on a real-time link and awareness between the Code Composer Studio™ host environment and the target. Even after the program has been halted, information already captured through the real-time analysis tools can provide invaluable insight into the sequence of events that led up to the current point of execution. Real-time analysis tools are used later in the development cycle when transitioning from the debug phase to the runtime phase of development.
6 IMPLEMENTATION

6.1 SOFTWARE IMPLEMENTATION

The simulation was done using Matlab for windows Version 5.3.1 for testing the feasibility of the adaptive algorithm and it had been discussed in Chapter 4. This will enable verification before actual implementation on the TMS320C54xx Digital Signal Processing.

In this chapter, the software implementation on TMS320C54xx Digital Signal Processing will be discussed. The sequence, description of the programs and the graphical results of the simulation will also be discussed in the following section. The programme listings are attached in Appendix X.

6.1.1 OVERVIEW

The software development system of TMS320C54xx is called Code Composer Studio. It consists of a set of modules. Figure 6.1 shows the software development flow diagram. The C compiler accepts C source code and produces assembly language source code. The assembler translates assembly language source files into machine language object files. The machine language is based on common object file format (COFF). The linker combines object files into a single executable object module. As it creates the executable module, it performs relocation and resolves external references. The linker accepts relocatable COFF object files and object libraries as input. While in the simulation, all the programmes were successfully generated. However, the hardware interface is yet to be performed.
6.1.2 DATA REPRESENTATION

The data representation is in the Q15 format. That is, the dynamic range $-1$ to $+0.999$ corresponds to hexadecimal range of $8000$ to $7FFF$. The hardware limits the input range of the noise signals and the output range of the cancelling signals to a certain range, therefore, a format conversion is needed to comply with the Q15 format. This involves shifting the data by 8 bits to the left and, then exclusive OR it with hexadecimal number $8000$. 

Figure 6.1 Software Development Flow
6.1.3 PROGRAMME STRUCTURE

In this project, the programme development is using the same sequence of flow as the Matlab simulation. The sampling frequency is set to 48KHz (using audio bandwidth of 22.1KHz). The input signal frequency is fixed at 8KHz and the number of sampling is limited to 200.

There are 4 different of programs being generated according to the different signal input, step size and coefficient. The first programme is a Basic Notch Filter where the coefficient “a” is fixed at a frequency. The second programme is an Adaptive Notch Filter where the coefficient “a” is adapted according to drift frequency. The programme also depends on the step size to generate a fast or slow adaptation. The third programme is a Cascaded Notch Filter where it gives a better performance than the basic notch filter. The fourth programme is a Multiple Notch filter where the capability is to notch off two notch frequency. The programme flow chart of the 4 programs is shown at Figure 6.2
The programme started with the initialisation of relevant parameters and variables, and followed by adding an input noise signal to the file I/O. Both input data file and output results will be assigned to a probe point so that we could view the simulation results in a graphical diagram. The programme will enter a loop of 200 sample and within the loop, the equation (3.2) is generated and all the input and output delay variables are assigned to the previous input. For adaptive algorithm, the equation (3.5) will be used for adapting the input notch frequency and it is insert immediately after the equation (3.5). Finally, the output array of 200 sample will be generated and output to equation (3.3). With the sampling frequency of 48000Hz, that is, sampling period of 20us, the max instruction cycle is approximated 1040.

Figure 6.2 Programme Flow
6.1.4 RESULTS

In this section, all the development results presented here are generated using the simulator program, C54x Code Composer Studio (Simulator/CPU).

6.1.4.1 Basic IIR Notch Filter

The basic notch filter is generated using equation (3.2). The input signal frequency is at 8KHz and the radian, \( r \) is set to 0.9 or 0.75. In this case, the coefficient, \( a \) is fixed. The graphical result is shown in Figure 6.3 and Figure 6.4.

From the graphs, the results showed that there is a different when \( r \) drops from 0.9 to 0.75. It showed that the smaller the value of \( r \), it required lesser sample to notch off the noise signal frequency but the disadvantages is as the \( r \) get smaller, the notch will be wider.
Figure 6.3 Basic Notch Filter with single input, $r = 0.9$

Figure 6.4 Basic Notch Filter with single input, $r = 0.75$
The following figures show multiple sinusoidal input noise signal frequency of 4KHz and 8KHz and the radian $r$ value at 0.9 and 0.75. The graphical results are shown at Figure 6.5 & Figure 6.6.

From the graphs, the results showed that the frequency input of 8KHz has been notch off and left the 4KHz signal.

*Figure 6.5 Basic Notch Filter with Multiple input, $r=0.9$*
6.1.4.2 Adaptive IIR Notch Filter

The adaptive notch filter is implemented using equation (3.2) and equation (3.3).

The following figures will show the adaptive notch filter output with the step size varies from 0.1 to 0.3. A single input signal with a drift of 8Khz to 8.1Khz was generated. The r will set to 0.9.

From the figures, it shows that, the smaller the step size the more accurate the notch frequency but at the expense of a large number of samples. That is, it takes a longer time to adapt.
Figure 6.7 Adaptive Notch Filter with Single input, $u = 0.1$

Figure 6.8 Adaptive Notch Filter with Single input, $u = 0.15$
Figure 6.9 Adaptive Notch Filter with Single input, $u = 0.2$

Figure 6.10 Adaptive Notch Filter with Single input, $u = 0.25$
Figure 6.11 Adaptive Notch Filter with Single input, $u = 0.3$
The following figures will show the multiple input noise signal of 4Khz and 8Khz. The results of Figure 6.11 and Figure 6.12 will showed that the step size must be very small ($u = 0.1$) in order to notch off one of the noise signal frequency.

Figure 6.12 Adaptive Notch Filter with Multiple input, $u = 0.1$
Figure 6.13 Adaptive Notch Filter with Multiple input, $u = 0.15$
6.1.4.3 Cascade Adaptive IIR Notch Filter

The cascade filter is implemented by having two section of the basic notch filter and adapting at the end of the second section. Figure 6.13 and Figure 6.14 show simulation result.

When compared this Figure 6.13 with the basic notch filter at Figure 6.3, the results showed that the cascade notch filter has improved the amplitude as the sample increase. This proved that the cascade managed to cancel the noise signal at a faster rate.

Figure 6.14 Cascade Notch Filter with Single input, \( u = 0.25 \)
Figure 6.15 Cascade Notch Filter with Multiple input, $u = 0.25$
6.1.4.4 Multiple Notch Filter

The cascaded notch filter is extended to cancel out the multiple sinusoidal noise interference. It is implemented by having two different notch frequencies. The simulated output result is shown in Figure 6.15 and Figure 6.16.

The graph showed that the multiple notch filter is able to cancel off multiple signals.

![Graph showing multiple notch filter results](image)

*Figure 6.16 Multiple Notch Filter with Multiple input*
Figure 6.17 Multiple Notch Filter with Multiple input
6.2 HARDWARE IMPLEMENTATION

6.2.1 OVERVIEW

As mention in chapter 5, TMS320C54x EMV board was chosen for the hardware implementation. The following section will mention the hardware configuration.

6.2.2 CONFIGURATION

The 'C54x EVM board is a PC/AT half-length board that installs in a vacant 16-bit slot in the PC as shown in Figure 6.17. The C54x EMV board have an analogue input and output connector at the end of the board. The input signal from the signal generator will inject into ADC (input connector) and the output results will go through the DAC(output connector) to display at the oscilloscope.

To communicate from the host to the target board, two things must be initial at the beginning of the programme. The first initialisation is the sampling clock frequency and second initialisation is the AIC interrupt routine. Once the initialisation is done, compile and build the programme. Download the programme to the target board and inject a single noise signal frequency into the ADC connector and the output from the oscilloscope will the results.
This will slot into the PC

Debugger Tool

Signal Generator or Frequency Generator
Input to the ADC

Oscilloscope
Get output from DAC

Figure 6.18 TMS320C54x EMV board connection
PROBLEMS AND RECOMMENDATIONS

In this chapter, some problems and recommendations are mentioned as below.

a) In phase I, the students encountered concept problem when deriving the adaptive algorithm, and hence a lot of research have to be done before the students derived this simplified LMS adaptive algorithm. Due to shortage of time the students did not further explore on the RLS algorithm. Suggested the next batch students could work on RLS algorithm.

b) In the initial stage, the TMS320C5x was chosen as our hardware implementation but due to some software problems, the students have decided to source for alternative board. Finally, the students managed to get TMS320C54x as the replacement. The reason why this board was replaced was, the TMS320C54x EMV is the second available board in the company. Suggested that MMC should provide the required board.

c) During the software simulation, the student encountered difficulty with the Code Composer Studio interface. As this simulator is very new to the student, the student have to struggle at least 1 to 2 weeks on the user guidebooks in order to familiarise with the operation.

d) The auto-tracking effect was not successfully evaluated. The simulation result did not produce the desired response as describe theoretically in Project Approach.
e) Due to host and target communication and programming problems, the hardware communication part was not successfully implemented even the project deadline is meet.
CONCLUSION
In this project, the simplicity and ease of computation of the LMS algorithm was shown using IIR structure. The effectiveness of the algorithm on different notch filters was successfully demonstrated by means of using Matlab and Code Composer Simulator to generate the software simulation. The different notch filters consist of basic notch filter, Adaptive notch filter, Cascade notch filter and Multiple notch filter.

In applying to the TMS320C54x EMV board, unfortunately due to the some hardware communication and programming problems the students are not able demonstrate the real-time application.

Though the students have not been able to successfully conclude the project, Much details about the Code Composer simulators and theoretical hardware (TMS320C54x EMV board) have been learnt which would otherwise be taken for granted.
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APPENDIX A - Matlab Simulation Programmes

% Basic Notch filter
% Filename: Frcq_RspR70.m
% Description: Plot frequency response with different values of r

fs=48000; % sampling frequency in Hz
fc=8000; % angular frequency of the notch in Hz
w=2*pi*fc/fs; %
a=2*cos(w);

r=0.70;
den=[1,-a*r,r^2]; % Denominator of the response
nume=[1,-a,1]; % Numerator for the response

[H,F]=freqz(nume,den,512,fs); % Compute Frequency response
HdB=20*log10(H);
plot(F,HdB);
xlabel('Frequency in Hz');ylabel('Gain in dB');
title('r=0.70');

% Basic Notch filter
% Filename: Freq_RespR75.m
% Description: Plot frequency response with different values of r

fs=48000; % sampling frequency in Hz
fc=8000; % angular frequency of the notch in Hz
w=2*pi*fc/fs; %
a=2*cos(w);

r=0.75;
den=[1,-a*r,r^2]; % Denominator of the response
nume=[1,-a,1]; % Numerator for the response

[H,F]=freqz(nume,den,512,fs); % Compute Frequency response
HdB=20*log10(H);
plot(F,HdB);
xlabel('Frequency in Hz');ylabel('Gain in dB');
title('r=0.75');
%% Basic Notch Filter
%% Filename: Freq RespR80.m
%% Description: Plot frequency response with different values of r

fs=48000; % sampling frequency in Hz
fc=8000; % angular frequency of the notch in Hz
w=2*pi*fc/fs; %
a=2*cos(w);
r=0.80;
den=[1,-a*r,r^2]; % Denominator of the response
tnum=[1,-a,1]; % Numerator for the response
[H,F]=freqz(nume,den,512,fs); % Compute Frequency response
HdB=20*log10(H);
plot(F,HdB);
xlabel('Frequency in Hz'); ylabel('Gain in dB');
title('r=0.80');

%% Basic Notch Filter
%% Filename: Freq RespR90.m
%% Description: Plot frequency response with different values of r

fs=48000; % sampling frequency in Hz
fc=8000; % angular frequency of the notch in Hz
w=2*pi*fc/fs; %
a=2*cos(w);
r=0.90;
den=[1,-a*r,r^2]; % Denominator of the response
tnum=[1,-a,1]; % Numerator for the response
[H,F]=freqz(nume,den,512,fs); % Compute Frequency response
HdB=20*log10(H);
plot(F,HdB);
xlabel('Frequency in Hz'); ylabel('Gain in dB');
title('r=0.90');
% Basic Notch filter  
% Filename: Freq_RespR95.m  
% Description: Plot frequency response with different values of r

fs=48000; % sampling frequency in Hz
fc=4000; % angular frequency of the notch in Hz
w=2*pi*fc/fs; %
a=2*cos(w);
r=0.95;
den=[1,-a*r,r^2]; % Denominator of the response
nume=[1,-a,1]; % Numerator of the response
[H,F]=freqz(nume,den,512,fs); % Compute Frequency response
HdB=20*log10(H);
plot(F,HdB);
xlabel('Frequency in Hz'); ylabel('Gain in dB');
title('r=0.95');
%Filename :Single_adaptive.m
%Description: The file plot the output response of the adaptive notch filter
with a single frequency input.

fs=48000; %sampling frequency in Hz
fc=8000; %angular frequency of the notch in Hz
fi=8000; %angular input frequency in Hz
w=2*pi*fc/fs;
a=2*cos(w);
u=0.01; %step size
r=0.90;
nT=0:255;
x=sin(2*pi*fi*nT/fs); %input sequence

x1=0;
x2=0;
y1=0;
y2=0;
a1=0;

for i=1:255,
    y(i)=x(i)-a*x1+x2+a*r*y1-r*y2;
a1=a+2*u*y(i)*(x1-r*y1);
    a=a1;
y2=y1;
y1=y(i);
x2=x1;
x1=x(i);
end

subplot (2,1,1), plot(x);title ('Single Channel Adaptive Notch Filter');
xlabel('No. of Samples');ylabel('Input Sequence');
subplot (2,1,2), plot(y);ylabel('Output Sequence');
%Filename :Single_drift.m
%Description : The file plot the output response of the adaptive notch filter
% with a single frequency input with frequency drift
% after 128 samples.

fs=48000; %sampling frequency in Hz
fc=8000; %angular frequency of the notch in Hz
fi=8000; %angular input frequency in Hz
w=2*pi*fc/fs;
a=2*cos(w);
u=0.01; %step size
r=0.90;

nT=0:127;
x=sin(2*pi*fi*nT/fs);%input sequence
x(128:255)=sin(2*pi*fi*nT/fs);% Frequency drift by 100Hz

x1=0; %initialisation
x2=0;
y1=0;
y2=0;
a1=0;

for i=1:255,
    y(i)=x(i)-a*x1+x2+a*r*y1-r*r*y2;
a1=a+2*u*y(i)*(x1-r*y1);

    a=a1;
y2=y1;
y1=y(i);
x2=x1;
x1=x(i);
end

subplot (2,1,1), plot(x), title ('Single Channel Adaptive Notch Filter with Frequency Drift');
xlabel('No. of Samples'), ylabe('Input Sequence');
subplot (2,1,2), plot(y), ylabel('Output Sequence');
%Filename : Single_multi.m
%Description : The file plot the output response of the adaptive notch filter
% with multiple frequency input

fs=48000; %sampling frequency in Hz
fc=8000; %angular frequency of the notch in Hz
fl=8000; %angular input frequency in Hz
f2=4000; % Second input frequency in Hz
w=2*pi*fc/fs;
a=2*cos(w);
u=0.01; %step size
r=0.90;
nT=0:255;
x=sin(2*pi*fl*nT/fs)+sin(2*pi*f2*nT/fs); %input sequence

x1=0; %Initialisation
x2=0;
y1=0;
y2=0;
a1=0;

for i=1:255,
    y(i)=x(i)-a*x1+x2+a*r*y1+r*y2;
    a1=a+2*u*y(i)*(x1-r*y1);
    a=a1;
y2=y1;
y1=y(i);
x2=x1;
x1=x(i);
end

subplot (2,1,1), plot(x); title('Single Channel Adaptive Notch Filter with Multiple Frequency Input');
xlabel('No. of Samples'); ylabel('Input Sequence');
subplot (2,1,2), plot(y); ylabel('Output Sequence');
%Filename :Single_u001.m
%Description : The file plot the output response of the adaptive notch filter with a single frequency input and drift after 128 samples.

fs=48000; %sampling frequency in Hz
fc=8000; %angular frequency of the notch in Hz
fi=8000; %angular input frequency in Hz
w=2*pi*fc/fs;
a=2*cos(w);
u=0.01; %step size
r=0.90;
T=0:127;
x=sin(2*pi*fi*T/fs); %input sequence
x(128:255)=sin(2*pi*fi*T/fs); % Frequency drift by 100Hz

x1=0; %Initialisation
x2=0;
y1=0;
y2=0;
a1=0;

for i=1:255,
    y(i)=x(i)-a*x1+x2+a*r*y1-r*r*y2;
    a1=a+2*u*y(i)*(x1-r*y1);
    a=a1;
    y2=y1;
    y1=y(i);
    x2=x1;
    x1=x(i);
end

subplot (2,1,1), plot(x);title ('Single Channel Adaptive Notch Filter with u=0.01'); xlabel('No. of Samples');ylabel('Input Sequence');
subplot (2,1,2), plot(y);ylabel('Output Sequence');
%Filename : Single_u005.m
%Description : The file plots the output response of the adaptive notch filter
% with a single frequency input and drift after 128 samples.

fs=48000; %sampling frequency in Hz
fc=8000; %angular frequency of the notch in Hz
fi=8000; %angular input frequency in Hz
w=2*pi*fc/fs;
a=2*cos(w);
u=0.05; %step size
r=0.90;
nT=0:127;
x=sin(2*pi*fi*nT/fs); %input sequence
x(128:255)=sin(2*pi*fi*nT/fs); % Frequency drift by 100Hz

x1=0; %Initialisation
x2=0;
y1=0;
y2=0;
a1=0;

for i=1:255,
    y(i)=x(i)-a*x1+x2+a*r*y1-r*r*y2;
a1=a+2*u*y(i)*(x1-r*y1);
    a=a1;
y2=y1;
y1=y(i);
x2=x1;
x1=x(i);
end

subplot (2,1,1), plot(x); title('Single Channel Adaptive Notch Filter with u=0.05');
xlabel('No. of Samples'); ylabel('Input Sequence');

subplot (2,1,2), plot(y); ylabel('Output Sequence');
% Filename : Single_u01.m
% Description: The file plot the output response of the adaptive notch filter
% with a single frequency input and drift after 128 samples.

fs = 48000; % sampling frequency in Hz
fc = 8000; % angular frequency of the notch in Hz
fi = 8000; % angular input frequency in Hz
w = 2 * pi * fc / fs;
a = 2 * cos(w);
u = 0.1; % step size
r = 0.90;
nT = 0:127;
x = sin(2 * pi * fi * nT / fs); % input sequence
x(128:255) = sin(2 * pi * fi * nT / fs) % Frequency drift by 100 Hz

x1 = 0; % initialisation
x2 = 0;
y1 = 0;
y2 = 0;
a1 = 0;

for i = 1:255,
    y(i) = x(i) - a * x1 + x2 + a * r * y1 - r * r * y2;
a1 = a + 2 * u * y(i) * (x1 - r * y1);
a = a1;
y2 = y1;
y1 = y(i);
x2 = x1;
x1 = x(i);
end

subplot (2,1,1), plot(x); title('Single Channel Adaptive Notch Filter with u=0.1');
xlabel('No. of Samples'), ylabel('Input Sequence');
subplot (2,1,2), plot(y); ylabel('Output Sequence');
fs=48000; %sampling frequency in Hz
fc=8000; %angular frequency of the notch in Hz
fi=8000; %angular input frequency in Hz
w=2*pi*fc/fs;
a=2*cos(w);
u=0.2; %step size
r=0.90;
nT=0:127;
x=sin(2*pi*fi*nT/fs);%input sequence
x(128:255)=sin(2*pi*fi*nT/fs)% Frequency drift by 100Hz

x1=0; %Initialisation
x2=0;
y1=0;
y2=0;
a1=0;

for i=1:255,
    y(i)=x(i)-a*x1+x2+a*r*y1-r*r*y2;
a1=a+2*u*y(i)*(x1-r*y1);
    a=a1;
y2=y1;
y1=y(i);
x2=x1;
x1=x(i);
end

subplot (2,1,1), plot(x);title ('Single Channel Adaptive Notch Filter with u=0.2');
xlabel('No. of Samples');ylabel('Input Sequence');
subplot (2,1,2), plot(y);ylabel('Output Sequence');
%Filename:Single_u035.m
%Description: The file plot the output response of the adaptive notch filter
% with a single frequency input and drift after 128 samples.

fs=48000; %sampling frequency in Hz
fc=8000; %angular frequency of the notch in Hz
fi=8000; %angular input frequency in Hz
w=2*pi*fc/fs;
a=2*cos(w);
u=0.35; %step size
r=0.90;
nT=0:127;
x=sin(2*pi*fi*nT/fs); %input sequence
x(128:255)=sin(2*pi*fi*nT/fs); % Frequency drift by 100Hz

x1=0; %Initialisation
x2=0;
y1=0;
y2=0;
a1=0;

for i=1:255,
    y(i)=x(i)-a*x1+x2+a*r*y1-r*r*y2;
a1=a+2*u*y(i)*(x1-r*y1);
    a=a1;
y2=y1;
y1=y(i);
x2=x1;
x1=x(i);
end

subplot (2,1,1), plot(x);title ('Single Channel Adaptive Notch Filter with u=0.35');
xlabel('No. of Samples');ylabel('Input Sequence');
subplot (2,1,2), plot(y);ylabel('Output Sequence');
% Filename: cascade_ad.m
% Description: The file plots the output response of the cascade adaptive notch filter
% with a single frequency input.

fs = 48000; % sampling frequency in Hz
fc = 8000; % angular frequency of the notch in Hz
fi = 8000; % angular input frequency in Hz
w = 2*pi*fc/fs;
a = 2*cos(w);
u = 0.25; % step size
r = 0.90;
nT = 0:255;
x = sin(2*pi*fi*nT/fs); % input sequence

x1 = 0;
x2 = 0;
y1 = 0;
y2 = 0;
a1 = 0;
z1 = 0;
z2 = 0;

for i = 1:255,
    y(i) = x(i) - a*x1 + x2 + a*r*y1 - r*r*y2;
    z(i) = y(i) - a*y1 + y2 + a*r*z1 - r*r*z2;
    a1 = a + 2*u*z(i)*(y1 - r*z1);
    a = a1;
    an(i) = a1;
    y2 = y1;
    y1 = y(i);
    x2 = x1;
    x1 = x(i);
    z2 = z1;
    z1 = z(i);
end

subplot(2,1,1), plot(x);
title('Cascade Adaptive Notch Filter with Single Input Frequency');
xlabel('No. of Samples'); ylabel('Input Sequence');
subplot(2,1,2), plot(z); ylabel('Output Sequence');
%Filename :cascade_drift.m
%Description : The file plot the output response of the cascade adaptive notch filter
% with frequency drift.

fs=48000; %sampling frequency in Hz
fc=8000; %angular frequency of the notch in Hz
fi=8000; %angular input frequency in Hz
w=2*pi*fc/fs;
a=2*cos(w);
u=0.25; %step size
r=0.90;

nT=0:127;
x=sin(2*pi*fi*nT/fs); %input sequence
x(128:255)=sin(2*pi*(fi+200)*nT/fs); %Frequency drift by 200Hz
x1=0;
x2=0;
y1=0;
y2=0;
a1=0;
z1=0;
z2=0;

for i=1:255,
y(i)=x(i)-a*x1+x2+a*r*y1-r*r*y2;
z(i)=y(i)-a*y1+y2+a*r*z1-r*r*z2;
a1=a+2*u*z(i)*(y1-r*z1);
a=a1;
an(i)=a1;
y2=y1;
y1=y(i);
x2=x1;
x1=x(i);
z2=z1;
z1=z(i);
end

subplot (2,1,1), plot(x);
title ('Cascade Adaptive Notch Filter with Frequency Drift ');
xlabel('No. of Samples');ylabel('Input Sequence');
subplot (2,1,2), plot(z);ylabel('Output Sequence');
%Filename: cascade_multi.m
%Description: The file plot the output response of the cascade adaptive notch filter
% with multiple frequencies input.

fs=48000; %sampling frequency in Hz
fc=8000; %angular frequency of the notch in Hz
fi=8000; %angular input frequency in Hz
w=2*pi*fc/fs;
a=2*cos(w);
u=0.25; %step size
r=0.90;
nT=0:255;
x=sin(2*pi*fi*nT/fs)+sin(2*pi*1000*nT/fs); %input sequence

x1=0;
x2=0;
y1=0;
y2=0;
a1=0;
z1=0;
z2=0;

for i=1:255,
    y(i)=x(i)-a*x1+x2+a*r*y1-r*r*y2;
    z(i)=y(i)-a*y1+y2+a*r*z1-r*r*z2;
    a1=a+2*u*z(i)*(y1-r*z1);
    a=a1;
    an(i)=a1;
    y2=y1;
    y1=y(i);
    x2=x1;
    x1=x(i);
    z2=z1;
    z1=z(i);
end

subplot(2,1,1), plot(x);
title('Cascade Adaptive Notch Filter with Multiple Frequency Input');
xlabel('No. of Samples'); ylabel('Input Sequence');
subplot(2,1,2), plot(z); ylabel('Output Sequence');
%Filename : cascade_na.m
%Description : The file plots the output response of the cascade adaptive notch filter
% with a single frequency input.

fs=48000; % sampling frequency in Hz
fc=8000; % angular frequency of the notch in Hz
fi=8000; % angular input frequency in Hz
w=2*pi*fc/fs;
a=2*cos(w);
u=0.01; % step size
r=0.90;
nT=0:255;
x=sin(2*pi*fi*nT/fs); % input sequence

x1=0;
x2=0;
y1=0;
y2=0;
a1=0;
z1=0;
z2=0;

for i=1:255,
    y(i)=x(i)-a*x1+x2+a*r*y1-r*r*y2;
z(i)=y(i)-a*y1+y2+a*r*z1-r*r*z2;
    % a1=a+2*u*y(i)*(x1-r*y1);
    % a1=a1;
    % a1(i)=a1;
y2=y1;
y1=y(i);
x2=x1;
x1=x(i);
    % z2=z1;
z1=z(i);
end

subplot(2,1,1), plot(x);
subplot(2,1,2), plot(z);
% Filename: multiple_drift.m
% Description: The file plots the output response of the multiple channel adaptive notch filter with frequency drift.

fs=48000; % sampling frequency in Hz
fc1=8000; % angular frequency of the notch in Hz
fc2=4000;
f1=4000; % angular input frequency in Hz
f2=8000;
w1=2*pi*fc1/fs;
w2=2*pi*fc2/fs;
a1=2*cos(w1);
a2=2*cos(w2);
u=0.001; % step size
r=0.90;
T=0:127;
x=sin(2*pi*f1*nT/fs)+sin(2*pi*f2*nT/fs); % input sequence
x(128:255)=sin(2*pi*(f1+100)*nT/fs)+sin(2*pi*(f2+100)*nT/fs); % Frequency drift by 100 Hz
x1=0;
x2=0;
y1=0;
y2=0;
a11=0;
a21=0;
z1=0;
z2=0;
for i=1:255,
    y(i)=x(i)-a1*x1+x2+a1*r*y1-r*r*y2;
a11=a1+2*u*y(i)*(x1-r*y1);
z(i)=y(i)-a2*y1+y2+a2*r*z1-r*r*z2;
a21=a2+2*u*z(i)*(y1-r*z1);
    a1=a11;
a2=a21;
    y2=y1;
y1=y(i);
x2=x1;
x1=x(i);
z2=z1;
z1=z(i);
end
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```matlab
clear all;
plot (2,1,1), plot(x);
title ('Multiple Channel Adaptive Notch Filter with Frequency Drift');
xlabel('No. of Samples');ylabel('Input Sequence');
subplot (2,1,2), plot(z);ylabcl('Output Sequence');

% Filename: multiplc_frcq.m
% Description: The file plot the output response of the cascade adaptive notch filter
% with a single frequency input.

fs=48000;  % sampling frequency in Hz
fc1=8000;  % angular frequency of the notch in Hz
fc2=4000;
fi1=4000;  % angular input frequency in Hz
fi2=8000;
w1=2*pi*fc1/fs;
w2=2*pi*fc2/fs;
al=2*cos(w1);
a2=2*cos(w2);

u=0.001;  % step size
r=0.90;
nT=0:255;
x=sin(2*pi*fi1*nT/fs)+sin(2*pi*fi2*nT/fs);  % input sequence
%x(128:255)=sin(2*pi*(fi+200)*nT/fs);  % frequency drift by 200 Hz
x1=0;
x2=0;
y1=0;
y2=0;
a11=0;
a21=0;
z1=0;
z2=0;

for i=1:255,
    y(i)=x(i)-al*x1+x2+al*r*y1-r*r*y2;
a11=a11+2*u*y(i)*(x1-r*y1);
z(i)=y(i)-a2*y1+y2+a2*r*z1-r*r*z2;
a21=a21+2*u*z(i)*(y1-r*z1);
    a1=a11;
a2=a21;
y2=y1;
y1=y(i);
x2=x1;
x1=x(i);
end
```

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\[ z_2 = z_1; \]
\[ z_1 = z(i); \]
end

subplot (2,1,1), plot(x);
subplot (2,1,2), plot(z);

\%Filename :Multi[le_nonad.m
\%Description : The file plot the output response of the multiple channel adaptive
notch filter
\% with a single frequency input.

fs=48000;  \%sampling frequency in Hz
fc1=8000;  \%angular frequency of the notch in Hz
fc2=4000;
fi1=8000;  \%angular input frequency in Hz
fi2=4000;
w1=2*pi*fc1/fs;
w2=2*pi*fc2/fs;
a1=2*cos(w1);
a2=2*cos(w2)
u=0.25; \%step size
r=0.90;
nT=0.255;
x=sin(2*pi*fi1*nT/fs)+sin(2*pi*fi2*nT/fs); \%input sequence
\%x(128:255)=sin(2*pi*(fi+200)*nT/fs); \%Frequency drift by 200Hz
x1=0;
x2=0;
y1=0;
y2=0;
z1=0;
z2=0;

for i=1:255,
\[ y(i)=x(i)-a1*x1+x2+a1*r*y1-r*r*y2; \]
\[ z(i)=y(i)-a2*y1+y2+a2*r*z1-r*r*z2; \]
\[ y2=y1; \]
\[ y1=y(i); \]
\[ x2=x1; \]
\[ x1=x(i); \]
\[ z2=z1; \]
\[ z1=z(i); \]
end

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subplot (2,1,1), plot(x);
title ('Multiple Channel Adaptive Notch Filter');
xlabel('No. of Samples');ylabel('Input Sequence');
subplot (2,1,2), plot(z);ylabel('Output Sequence');
APPENDIX B – C Language Programming

/*Basic Notch Filter r = 0.9*/

#include <stdio.h>

#define r 0.9
#define a 1.0 // 2cos(2pix(8KHz/48KHz))

float output[200];
float input[200];

void main(void)
{

float y = 0;
float x = 0;
float x1 = 0;
float x2 = 0;
float y1 = 0;
float y2 = 0;
int i;

printf("input...\n");

    for (i=0; i<200; i++)
    {
        x=input[i];

        y = x-a*x1+x2+a*r*y1-r*r*y2;
        y2 = y1;
        y1 = y;
        x2 = x1;
        x1 = x;

        output[i]=y;
    }

printf("output...\n");

} /*Basic Notch Filter r = 0.75*/
#include <stdio.h>

#define r 0.75
#define a 1.0 // 2cos(2pix(8KHz/48KHz))

float output[200];
float input[200];

void main(void)
{

float y = 0;
float x = 0;
float x1 = 0;
float x2 = 0;
float y1 = 0;
float y2 = 0;
int i;

printf("input..\n");

for (i=0; i<200; i++)
{
    x=input[i];

    y = x-a*x1+x2+a*r*y1+r*r*y2;
    y2 = y1;
    y1 = y;
    x2 = x1;
    x1 = x;

    output[i]=y;
}

printf("output..\n");

} /*Adaptive Notch Filter u – 0.2*/
#include <stdio.h>

#define r 0.9
#define u 0.2 //Step Size
//define a 1.0 // 2cos(2pix(8KHz/48KHz))

float output[200];
float input[200];

void main(void)
{
    float y = 0;
    float x = 0;
    float x1 = 0;
    float x2 = 0;
    float y1 = 0;
    float y2 = 0;
    float a = 0;
    float a1 = 0;
    int i;

    printf("input...../n");
    
    for (i=0; i<200; i++)
    {
        x=input[i];
        y = x-a*x1+x2+a*r*y1-r*r*y2;
        a1 = a+2*u*y*(x1-r*y1);
        
        y2 = y1;
        y1 = y;
        x2 = x1;
        x1 = x;
        a = a1;
        
        output[i]=y;
    }
    printf("output...../n");
}
/*Cascade Notch Filter*/
#include <stdio.h>
#define r 0.9
#define u 0.25 /*Step Size*/

float output[200];
float input[200];

void main(void)
{
    float q = 0;
    float q1 = 0;
    float q2 = 0;
    float y = 0;
    float x = 0;
    float x1 = 0;
    float x2 = 0;
    float y1 = 0;
    float y2 = 0;
    float a = 1.0;
    float a1 = 0;
    int i;

    printf("input...../n");

    for (i=0; i<200; i++)
    {
        x=input[i];

        q = x-a*x1+x2+a*r*q1-r*r*q2;
        y = q-a*q1+q2+a*r*y1-r*r*y2;
        a1 = a+2*u*y*(q1-r*y1);

        q2 = q1;
        q1 = q;
        x2 = x1;
        x1 = x;
        y2 = y1;
        y1 = y;

        a = a1;
        output[i]=y;
    }

    printf("output...../n");
}

/*Multiple Notch Filter*/

#include <stdio.h>

#define r 0.9
#define u 0.25 //Step Size

float output[200];
float input[200];

void main(void)
{
    float q = 0;
    float q1 = 0;
    float q2 = 0;
    float y = 0;
    float x = 0;
    float x1 = 0;
    float x2 = 0;
    float y1 = 0;
    float y2 = 0;
    float a = 1.73;
    float a1 = 0;
    float b = 1.73;
    float a2 = 0;
    int i;

    printf("input.....\n");

    for (i=0; i<200; i++)
    {
        x=input[i];

        q = x - a*x1+x2+a*r*q1-r*r*q2;
        a1 = a+2*u*y*(q1-r*y1);
        y = q - b*q1+q2+b*r*y1-r*r*y2;
        a2 = b+2*u*y*(q1-r*y1);

        q2 = q1;
        q1 = q;
        y2 = y1;
        y1 = y;
        x2 = x1;
        x1 = x;
        a = a1;
        b = a2;
    }

}
output[i]=y;
}

printf("output....\n");
}
/*Single Sine Wave Generator*/

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <conio.h>

float f(float t, unsigned int flag)
{
    float y;
    static float f,a;
    if(flag!=0)
    {
        printf("Sine wave function initialisation.");
        printf("nEnter frequency (Hz) :");
        scanf("%f",&f);
        printf("nEnter amplitude (0-16384) :");
        scanf("%f",&a);
    }
    y=sin(2*3.14*f*t);
    return(y);
}

main()
{
    char out_file[10];
    float T,y;
    int N,n;
    FILE *fp;

    while(1)
    {
        printf("nEnter output filename :");
        fflush(stdin);
        scanf("%s",out_file);
        fp=fopen(out_file, "a");
        if (fp!=0)
            break;
        printf("Cannot open file '%s'.",out_file);
    }

    printf("nEnter sampling period :");
    scanf("%f",&T);

    while(1)
    {

printf("Enter no. of output samples : ");
scanf("%d",&N);
if (N==0)
exit(0);
f(0,1);

for (n=0;n<N;n++)
{
    y=f(n*T,0);
    fprintf(fp,"%d\n",(int)y);
}
exit(0);
/*Multiple Sine Wave Generator*/

#include <stdio.h>
#include <stdlib.h>
#include <rmuh.h>
#include <conio.h>

float f(float t, unsigned int flag)
{
    float y;
    static float f1,a;
    if(flag!=0)
    {
        printf("Sine wave function initialisation.");
        printf("Enter frequency (Hz) : ");
        scanf("%f", &f);
        printf("Enter frequency (Hz) : ");
        scanf("%f", &f1);
        printf("Enter amplitude (0-16384) : ");
        scanf("%f", &a);
    }
    y=a*(sin(2*3.142*f*t)+sin(2*3.142*f1*t));
    return(y);
}

void main(void)
{
    char out_file[10];
    float T,y;
    int N,n;
    FILE *fp;

    while(1)
    {
        printf("Enter output filename : ");
        fflush(stdin);
        scanf("%s", out_file);
        fp=fopen(out_file, "a");
        if (fp!=0)
            break;
        printf("Cannot open file '%s'.", out_file);
    }

    printf("Enter sampling period : ");
    scanf("%f", &T);
}
while(1)
{
    printf("Enter no. of output samples : ");
    scanf("%d",&N);
    if (N==0)
        exit(0);
    f(0,1);

    for (n=0;n<N;n++)
    {
        y=f(n*T,0);
        fprintf(fp,"%d\n",(int)y);
    }
    exit(0);
}