5-20-1992

Applications of Digital Signal Processing with Cardiac Pacemakers

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Recommended Citation

Tran, Merry Thi, "Applications of Digital Signal Processing with Cardiac Pacemakers" (1992). *Dissertations and Theses.* Paper 4582.

10.15760/etd.6466

AN ABSTRACT OF THE THESIS OF Merry Thi Tran for the Master of Science in Electrical Engineering presented May 20, 1992.

Title: Applications of Digital Signal Processing with Cardiac Pacemakers.

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Because the voltage amplitude of a heart beat is small compared to the amplitude of exponential noise, pacemakers have difficulty registering the responding heart beat immediately after a pacing pulse. This thesis investigates use of digital filters, an inverse filter and a lowpass filter, to eliminate the effects of exponential noise following a pace pulse. The goal was to create a filter which makes recognition of a haversine wave less dependent on natural subsidence of exponential noise.

Research included the design of heart system, pacemaker, pulse generation, and sensor system simulations. The simulation model includes the following components:

- Signal source, A MATLAB generated combination of a haversine signal, exponential noise, and myopotential noise. The haversine signal is a test signal used to simulate the QRS complex which is normally recorded on an ECG trace as a representa-

tion of heart function. The amplitude is approximately 10 mV. Simulated myopotential noise represents a uniformly distributed random noise which is generated by skeletal muscle tissue. The myopotential noise has a frequency spectrum extending from 70 to 1000 Hz. The amplitude varies from 2 to 5 mV. Simulated exponential noise represents the depolarization effects of a pacing pulse as seen at the active cardiac lead. The amplitude is about ˜1 volt, large in comparison with the haversine signal.

- A/D converter, A combination of sample & hold and quantizer functions translate the analog signal into a digital signal. Additionally, random noise is created during quantization.
- Digital filters, An inverse filter removes the exponential noise, and a lowpass filter removes myopotential noise.
- Threshold level detector, A function which detects the strength and amplitude of the output signal was created for robustness and as a data sampling device.

The simulation program is written for operation in a DOS environment. The program generates a haversine signal, myopotential noise (random noise), and exponential noise. The signals are amplified and sent to an A/D converter stage. The resultant digital signal is sent to a series of digital filters, where exponential noise is removed by an inverse digital filter, and myopotential noise is removed by the Chebyshev type I lowpass digital filter. The output signal is "detected" if its waveform exceeds the noise threshold level.

To determine what kind of digital filter would remove exponential noise, the spectrum of exponential noise relative to a haversine signal was examined. The spectrum of the exponential noise is continuous because the pace pulse is considered a non-periodic signal (assuming the haversine signal occurs immediately after a pace pulse). The spectrum of the haversine is also continuous, existing at every value of frequency ω. The spectrum of the haversine is overlapped by the spectrum of and amplitude of the exponential, which is several orders of magnitude larger. The exponential cannot be removed by conventional filters. Therefore, an inverse filter approach is used to remove exponential noise. The transfer function of the inverse filter of the model has only zeros. This type of filter is called FIR, all-zero, non recursive, or moving average.

Tests were run using the model to investigate the behavior of the inverse filter. It was found that the haversine signal could be clearly detected within a 5% change in the time constant of the exponential noise. Between 5% and 15% of change in the time constant, the filtered exponential amplitude swamps the haversine signal. The sensitivity of the inverse filter was also studied: when using a fixed exponential time constant but changing the location of the transfer function, the effect of the exponential noise on the haversine is minimal when zeros are located between 0.75 and 0.85 of the unit circle.

After the source signal passes the inverse filter, the signal consists only of the haversine signal, myopotential noise, and some random noise introduced during quantization. To remove these noises, a Chebyshev type I lowpass filter is used.

APPLICATIONS OF DIGITAL SIGNAL PROCESSING WITH CARDIAC PACEMAKERS

by

MERRY THI TRAN

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
ELECTRICAL ENGINEERING

Portland State University
1992

TO THE OFFICE OF THE GRADUATE SUDIES:

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ACKNOWLEDGEMENTS

I would like to take this opportunity to thank those who have contributed to the completion of this thesis. First, I deeply appreciate contributions from Dr. Y.C. Jenq, professor at Portland State University; Mr. Bob Weyant, Vice President of System Design and Development at Micro Systems Engineering, Inc.; and Mr. Dick Schomburg, Principal Engineer from the same above company, for their guidance during the writing of this paper. I would also like to thank Miss Laura Riddell for her typing contribution. Finally, I greatly appreciated my friends Mr. John Sandbo, Mr. Rick Sanborn, Mr. Roger Hoffman, engineers at Micro Systems Engineering, Inc. who have provided me with their support thoughout the execution of this thesis.

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CHAPTER I

INTRODUCTION

PACEMAKERS

A pacemaker feeds electrical stimulating pulses to the heart to keep the heart beating at a steady, healthy rhythm. The pacemaker is a pulse generating system, including a battery and a circuit. The unit operates continuously from the day of manufacture.

The circuit is sometimes encapsulated in epoxy and silicone rubber, and is always covered with metal (titanium). The unit contains a battery, usually of 4 or 5 cells. Almost all pacemakers made today use mercury-zinc cell battery packs with lithium anodes. A flexible electrical wire (pacing lead) is plugged into the pulse generator, and carries the stimulating pulses to the heart. The pacing lead is also used as a sensor which receives heart status data. The received data are used to control the output of the pulse generator.

Several lead configurations exist. A unipolar lead has one conducting wire and an electrode. The pulse generator uses body fluids for its return pathway. A bipolar lead has two conducting wires inside its insulation. The electrical signal travels down one wire to an electrode, passes through the myocardium, causes the heart tissue to depolarize, and then returns by the second electrode. Multiple lead configurations also exist.

The simplest pulse generator consists of a power source and a timing device which deliver electrical signals often enough to maintain an adequate cardiac output. A small electrical charge is delivered from the pulse generator, through the pacing lead, and to the heart in pulses separated by an appropriate interval to produce a desired heart rate.

THE PROBLEM

Contact between the pacing lead and tissue produces noise which is called exponential noise. Exponential noises have a large voltage amplitude. Because the voltage amplitude of a heart beat is small compared to the amplitude of exponential noise, pacemakers have difficulty registering the responding heart beat immediately after a pacing pulse.

This problem is called a "stimulus recognition" problem. This problem is very important because it controls the actions of the pacemaker. As soon as the heart beat can be sensed, the pacemaker emits or suppresses a pace pulse based on the strength of the heart beat. Solving the sensing problem requires a filter structure that will sense haversine type signals in the presence of non-periodic exponential signals resulting from a pace pulse and myopotential noise.

This thesis investigates use of digital filters, an inverse filter and a lowpass filter, to eliminate the effects of exponential noise following a pace pulse. The goal was to create a filter which will eliminate the effect of the large exponential noise and make recognition of a haversine wave easier. Comparison of Figures 4 and 22 (exponential #3) shows that the exponential noise is several orders of magnitude larger than the typical haversine signal.

THE SOLUTION

In order to research the problem stated above, it was necessary to design heart system, pacemaker, pulse generation, and sensor system simulations. The simulation model includes the following components:

- Signal source, A MATLAB generated combination of a haversine signal, exponential noise, and myopotential noise. The haversine signal is a test signal used to simulate the QRS complex which is normally recorded on an ECG trace as a representation of heart function. The amplitude is approximately 10 mV. Simulated myopotential noise represents a uniformly distributed random noise which is generated by skeletal muscle tissue. The myopotential noise has a frequency spectrum extending from 70 to 1000 Hz. The amplitude varies from 2 to 5 mV. Simulated exponential noise represents the depolarization effects of a pacing pulse as seen at the active cardiac lead. The amplitude is about ˜1 volt, large in comparison with the haversine signal.

- A/D converter, A combination of sample & hold and quantizer functions translate the analog signal into a digital signal. Additionally, random noise is created during quantization.

- Digital filters, An inverse filter removes the exponential noise, and a lowpass filter removes myopotential noise.

- Threshold level detector, A function which detects the strength and amplitude of the output signal was created for robustness and as a data sampling device.

The simulation program is written for operation in a DOS environment. The program generates a haversine signal, myopotential noise (random noise), and exponential noise. The signals are amplified and sent to an A/D converter stage. The resultant digital signal is sent to a series of digital filters, where exponential noise is removed by an inverse digital filter, and myopotential noise is removed by the Chebyshev type I lowpass digital filter. The output signal is "detected" if its waveform exceeds the noise threshold level.

To determine what kind of digital filter would remove exponential noise, the spectrum of exponential noise relative to a haversine signal was examined. The spectrum of the exponential noise is continuous because the pace pulse is considered a non-periodic signal (assuming the haversine signal occurs immediately after a pace pulse). The spectrum of the haversine is also continuous, existing at every value of frequency ω. The spectrum of the haversine is overlapped by the spectrum of and amplitude of the exponential, which is several orders of magnitude larger. The exponential cannot be removed by conventional filters. Therefore, an inverse filter approach is used to remove exponential noise. The transfer function of the inverse filter of the model has only zeros. This type of filter is called FIR, all-zero, non recursive, or moving average.

CONCLUSIONS

Tests were run using the model to investigate the behavior of the inverse filter. It was found that the inverse filter method is very effective. Sensing problems were also studied and it was found that the haversine signal can be clearly sensed if there is a 5% change in the time constant of the exponential. Between 5% and 15% of change in the time constant, the filtered exponential amplitude swamps the haversine signal (Presented in Tables I, II, III, and IV). The sensitivity of the inverse filter was also studied. When using a fixed exponential time constant but changing the location of the zeros, the effect of the exponential noise on the haversine is minimal when zeros are located between 0.75 and 0.85 of the unit circle (Presented in Tables V, VI, VII, and VIII).

After the source signal passes the inverse filter, the signal consists only of the haversine signal, myopotential noise, and some random noise introduced during quantization. To remove these noises, a Chebyshev type I lowpass filter is used.

ORGANIZATION OF THE THESIS

- Chapter I describes the difficulties pacemakers have with myopotential and exponential noise. The solution discussed in this thesis is also outlined.

- Chapter II describes the simulation model which consist of a source signal generator, an amplifier, an A/D converter, digital filters, and a threshold detector. The model in this chapter provides a context for discussion by isolating and identifying components and their relationships to one another. Further details about each stage of the model appear in later chapters.
- Chapter III describes normal cardiac contraction, the QRS wave which describes contraction on an ECG trace, and the haversine signal which can replace the QRS for laboratory purposes. The chapter then describes the atrial waveform of the haversine signal, the ventricular waveform of the haversine signal, the ventricular wave spectrum, and the atrial ventricular representation by haversine signals. Finally, the chapter provides a MATLAB listing of the FFT translation of ECG data to a haversine signal.
- Chapter IV describes natural occurrence of myopotential noise, the sensitivity range for detection of myopotential noise, and the conflict between myopotential noise and ventricular output. Finally, code for creation of laboratory simulated myopotential noise is presented.
- Chapter V defines and describes the "pulse interval". The division of a pacing pulse into 2 parts, the conflict between exponential noise and the pacemaker's ability to register the heart's response to a pacing pulse, the possible causes of exponential noise, and the reasons a bandpass filter can not remove exponential noise are described. Finally, the code used to simulate exponential noise is presented.
- Chapter VI describes the test input signal and provides a code sample that combines haversine, exponential, and myopotential signals to create the test input.
- Chapter VII describes the need for a signal amplifier and provides a code sample which simulates the signal amplification done by a normal pacemaker.

- Chapter VIII describes an analog to digital converter, the sample and hold function, and presents the code sample for the test sample and hold functionality. The chapter then describes the quantization process and the introduction of random noise into the quantized signal. Finally, the code which represents the quantization process is presented.
- Chapter IX describes the need for and inadequacy of a digital filter, the instability of inverse digital filters, the use of a stable psuedo-inverse filter to remove the presence of the exponential noise, the effects of the filter on the test signal, and the use of a lowpass filter to minimize myopotential noise.
- Chapter X presents conclusions based on the test system. The conclusions include a description of limitations suggested by test runs of the simulation.
- Appendix A contains the simulation software listing. MATLAB was used as supporting software. MATLAB functions are detailed in the body text where necessary.
- Appendix B contains a Glossary of terms used in this document.

CHAPTER II

THE MODEL

This chapter presents the simulation model used to test the inverse filter and the lowpass filter. Figure 1 shows the entire model. The remaining chapter presents details used throughout the remainder of this paper.

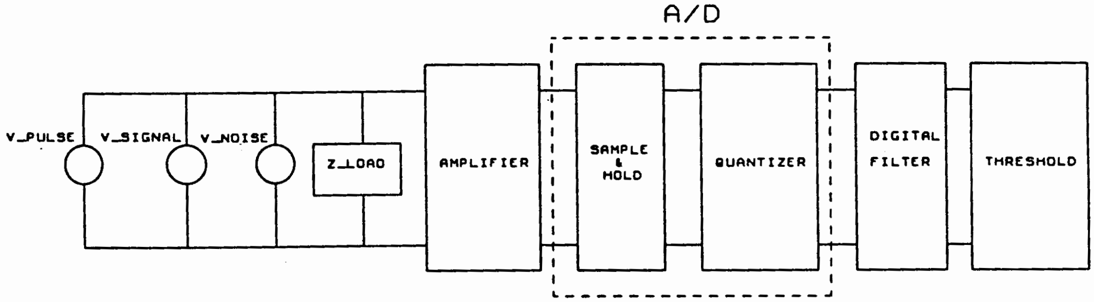


Figure 1. Model.

During normal operation a pacemaker sends a pace pulse. The pace pulse is impressed on the heart by the implanted leads. The heart then contracts, producing the ECG's record of polarization, the QRS trace. How a QRS trace can be replaced with a haversine waveform for test purposes is described in Chapter III. In the model shown in Figure 1, the QRS corresponds to V_signal. The pacemaker can detect the QRS through the implanted leads.

After the trailing edge of the pace pulse, an exponential decay signal appears (exponential noise). V_pulse, shown in Figure 1, represents the appearance of exponential noise. Until the exponential noise subsides, it is difficult for the pacemaker to sense the V_signal.

To make matters more complicated, the V_signal is also overlaid with myopotential noise (V_noise in Figure 1) caused by the surrounding skeletal muscle.

Zload in Figure 1 represents a 500 Ω ringers solution load. Ringers solution is a combination of 8.6g NaCl, 0.3g KCl, 0.44g CaCl.2H20 in one liter of water. It is an essentially isotonic medium present in many animal tissues.

The V_signal amplitude is very small compared to the pacing pulse (V_pulse). Therefore, the signal is passed through an amplification stage before it is manipulated.

The output of the amplifier is sent to an analog to digital converter (A/D converter) which contains a sample and hold function and a quantizer. The signal, which would be used as an analog signal in many applications, is converted to a digital signal previous to manipulation by the filters presented and studied in this paper.

The converted digital signal then passes through a two digital filters, an inverse filter and a lowpass filter. The inverse filter removes the residual exponential noise from the pacing pulse. The lowpass filter removes the myopotential noise. Output of the digital filters is the unencumbered V_signal produced by the heart muscle.

Finally, the threshold detector records the V_signal when the V_signal rises above the level of residual unfiltered noise.

For the purposes of textual discussion, V_pulse is referred to as exponential noise; V_signal is referred to as haversine signal; and V_noise is myopotential noise.

CHAPTER III

HAVERSINE SIGNAL

This chapter describes normal cardiac contraction, the QRS wave which describes contraction on an ECG trace, and the haversine signal which can replace the QRS for laboratory purposes. The chapter then describes the atrial waveform of the haversine signal, the ventricular waveform of the haversine signal, the ventricular wave spectrum, and the atrial ventricular representation by haversine signals. Finally, the chapter provides a MATLAB listing of the FFT translation of ECG data to a haversine signal.

CARDIAC CONDUCTION SYSTEM

The cardiac conduction system is composed of specialized muscle tissues which transfer electrical impulses across the tissue of the heart. The impulses determine the moment of contraction for the various chambers of the heart. This system provides stimulating pulses at a rate appropriate for the body's needs. The system then conducts these impulses rapidly to all the muscle fibers of the ventricular chamber. Figure 2 shows the structures of the cardiac conduction system.

Of specific interest are the sinus-atrial node (the S-A node) and the atrial-ventricular node (A-V node). The former triggers atrial contractions. The latter triggers ventricular contractions.

A muscle cell receiving a stimulus and contracting or a nerve cell receiving stimulus and transmitting the stimulus to the next nerve cell is called depolarization. Recovery of the cell, so that it is ready to receive the next stimulus, is called repolarization. A pacemaker provides the trigger stimulation for heart contractions when the A-V node, the S-A node, or both do not properly trigger depolarization.

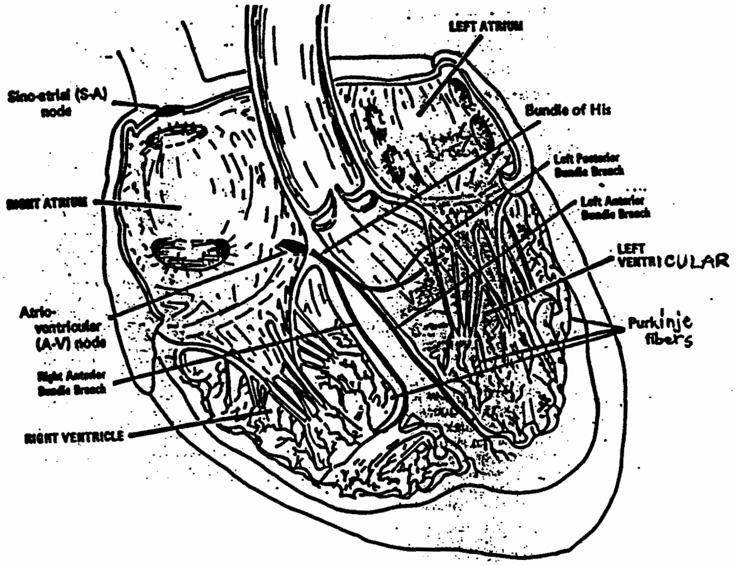


Figure 2. Heart.

From the electrical point of view, one cardiac cycle can be described as follows:

1. Based on chemical information in the blood stream, the Sino-atrial (S-A node) fires and depolarization spreads through the atrial chamber.
2. Depolarization spreads through the atrium and stimulates the Atrio-Ventricular node (A-V node).
3. The atrial chamber starts to contract, emptying blood into the ventricular chamber. The atrial chamber remains at rest for the remainder of the cycle.
4. After a 1/10 -sec delay during which the atrial empties and the ventricular is filled, the A-V node fires and the ventricular contracts to empty blood into the arteries.
5. The QRS waveform (depicted in Figure 3) is recorded with an ECG.

6. Repolarization begins immediately.

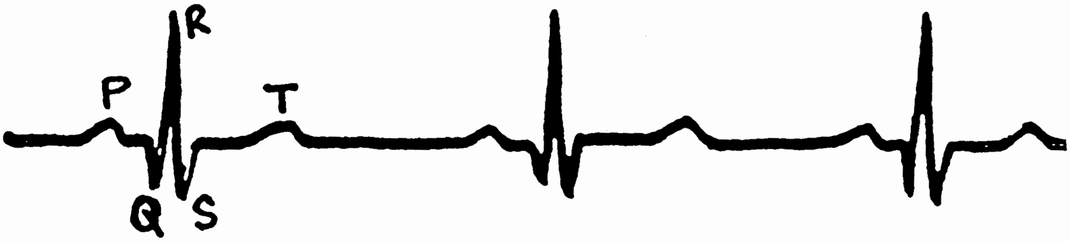


Figure 3. QRS complex.

In Figure 3, the components of the cardiac cycle can be seen on an ECG trace. The small P wave represents the depolarization of sino-atrial tissues. The QRS wave, or R wave, is produced by the relatively large voltage caused by the depolarization of the atrio-ventricular tissues. The T wave is very small, and results from ventricular repolarization.

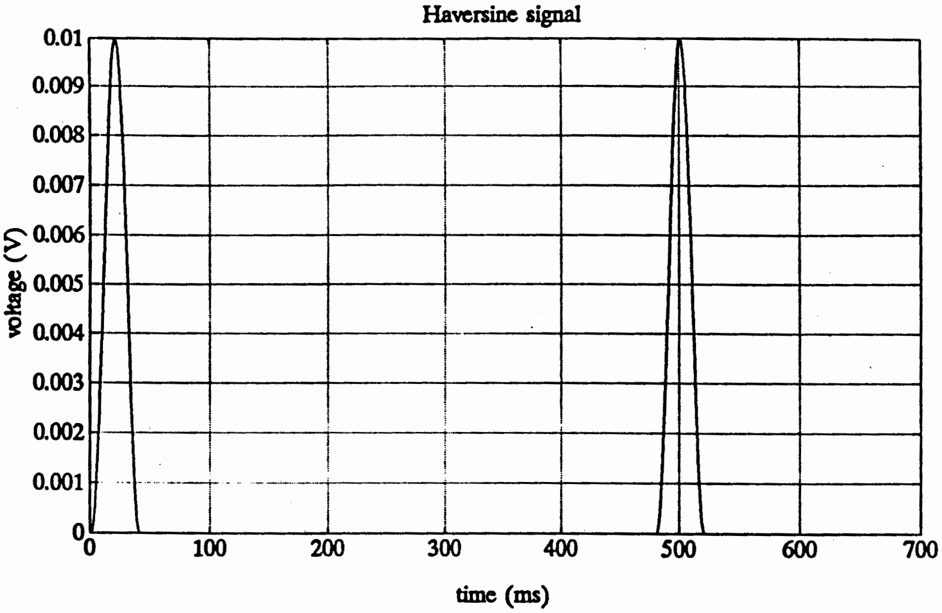
A QRS complex, called the QRS wave, or simply an R wave, is a large signal generated during depolarization of the ventricular. This is the beginning of ventricular contraction. When a pacing pulse is delivered to the heart, the response is almost immediate. The QRS commences within 1/100 sec.

For laboratory purposes, the QRS complex can be replaced by a single peak signal called the haversine signal. Figure 4 illustrates a haversine signal with an amplitude of 10 mV, a pulse width of 40 msec, and a period of 480 msec.

An expression for the haversine signal is presented below:

1A: $y(t) = Amp/2 * (1 - \cos(2 \pi t/PW)), \quad 0 < t \leq PW$

1B: $y(t) = 0 \quad , PW < t \leq Per$



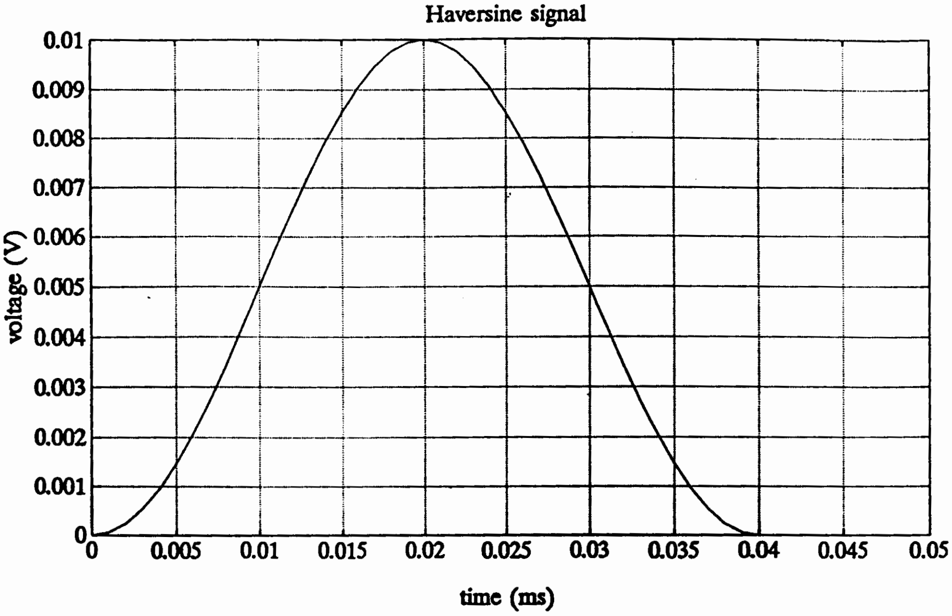


Figure 4. y(t) Haversine signal.

PW is the pulse width of the haversine in milliseconds (msec), Amp is the amplitude of the haversine in milli-volts (mV), Per is the period of the haversine in milliseconds (msec), and bpm defines the beats per minute (60,000/period), ppm defines the pulses per minute (60,000/period).

Figure 5 h(t) displays the waveform of equation (1A) and Figure 5 p(t) displays the rectangular waveform. By analyzing the equation (1A) and the rectangular waveform equation, multiplying the results, the haversine signal is formed as it is displayed in Figure 4. This method is applied in MATLAB to generate the haversine signal. The duty cycle of the rectangular waveform can be adjusted in the simulation to meet with requirements in the simulation.

The results of the Fourier transform applied to achieve the waveform displayed in Figure 4 are as follows:

From definition of the Fourier transform,

$$G(w) = \int_{-\infty}^{\infty} g(t)\, e^{(-j.w.t)} dt$$

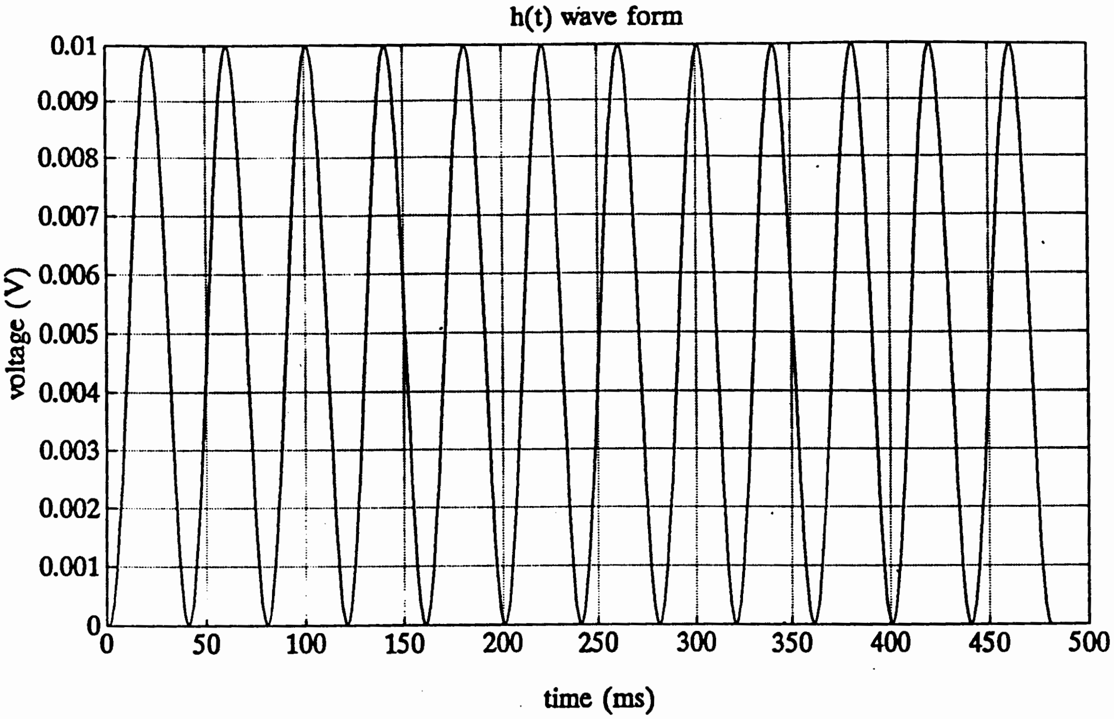
$$g(t) = h(t)*p(t)$$

$$h(t) = \frac{Amp}{2} \cdot \left(1 + \cos\left(2\pi \frac{t}{pw}\right)\right)$$

$$g(t) = \frac{Amp}{2} \cdot p(t) + \frac{Amp}{2} \cdot p(t) \cdot \cos\left(\frac{2\pi t}{pw}\right)$$

Amp = amplitude, pw = pulse width

$$\Longrightarrow G(w) = \frac{Amp \sin \frac{pw.w}{2}}{w} \cdot \frac{-4\pi^2 / pw^2}{w^2 - \frac{4\pi^2}{pw^2}}$$



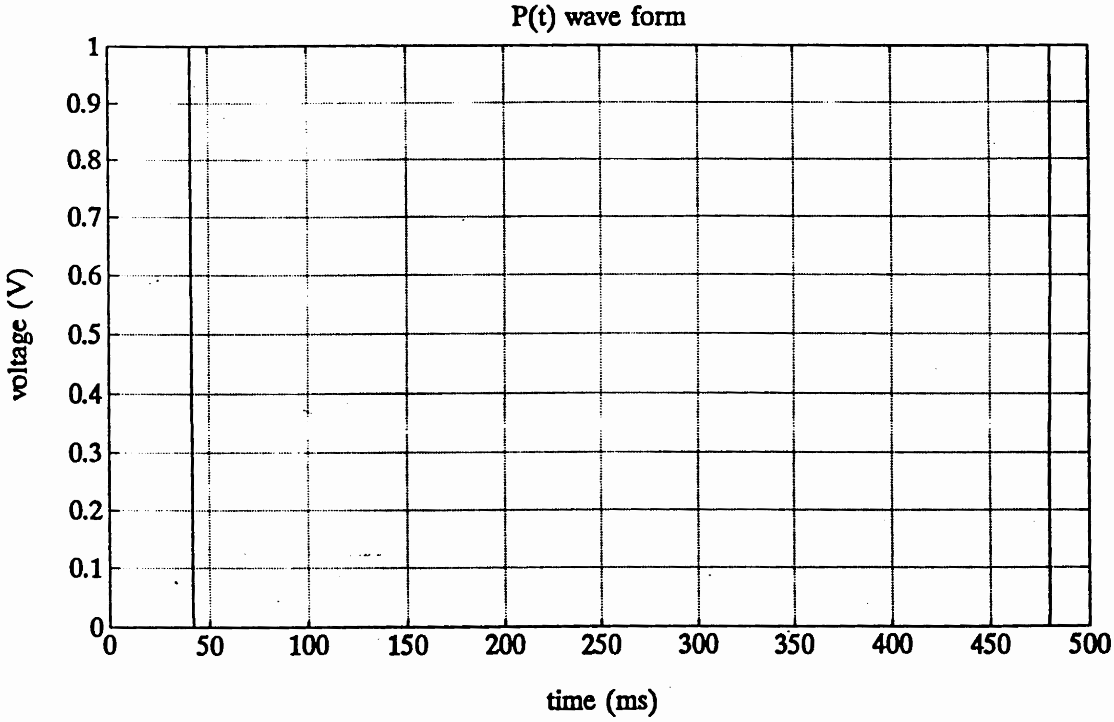


Figure 5. Graphs of waveform h(t) and P(t).

ATRIAL REPRESENTATION

In order to create a model to test the proposed filters, it was necessary to simulate the atrial contraction as represented by a haversine signal waveform. The depolarization and subsequent contraction of the atrial produces a P wave with the following characteristics:

- Amp = 5 mV peak (amplitude)
- PW = 15 msec (pulse width)
- Per = 400 to 1000 msec (period)

Atrial Waveform

The haversine waveform component represented by: y(t) = h(t) * P(t), P(t) is a square wave. The duty cycle of this wave (P(t)) can be adjusted in the simulation to meet with requirements in the simulation.

Figure 6 shows the waveform of the atrial haversine signal with the amplitude is 5 mV, pulse width is 15 msec, period is 480 msec.

Atrial Spectrum

The spectrum of the atrial haversine is continuous, exiting at every value of fr equency w.

At w = 0, the amplitude of the spectrum represents the area under the haversine curve. FFT is calculated at the sampling frequency of 1000 Hz, with 1024 points FFT, and one period interval.

Since f(n) = Td * f(n*Td), the result of the magnitude spectrum are multiplied by the sampling period.

Figure 7 shows the frequency spectrum of the atrial haversine. At w = 0 Hz, the magnitude spectrum is 0.0375. So, the dc level of the atrial haversine is 0.0375 mV (a dc signal has only one frequency component at w = 0) .

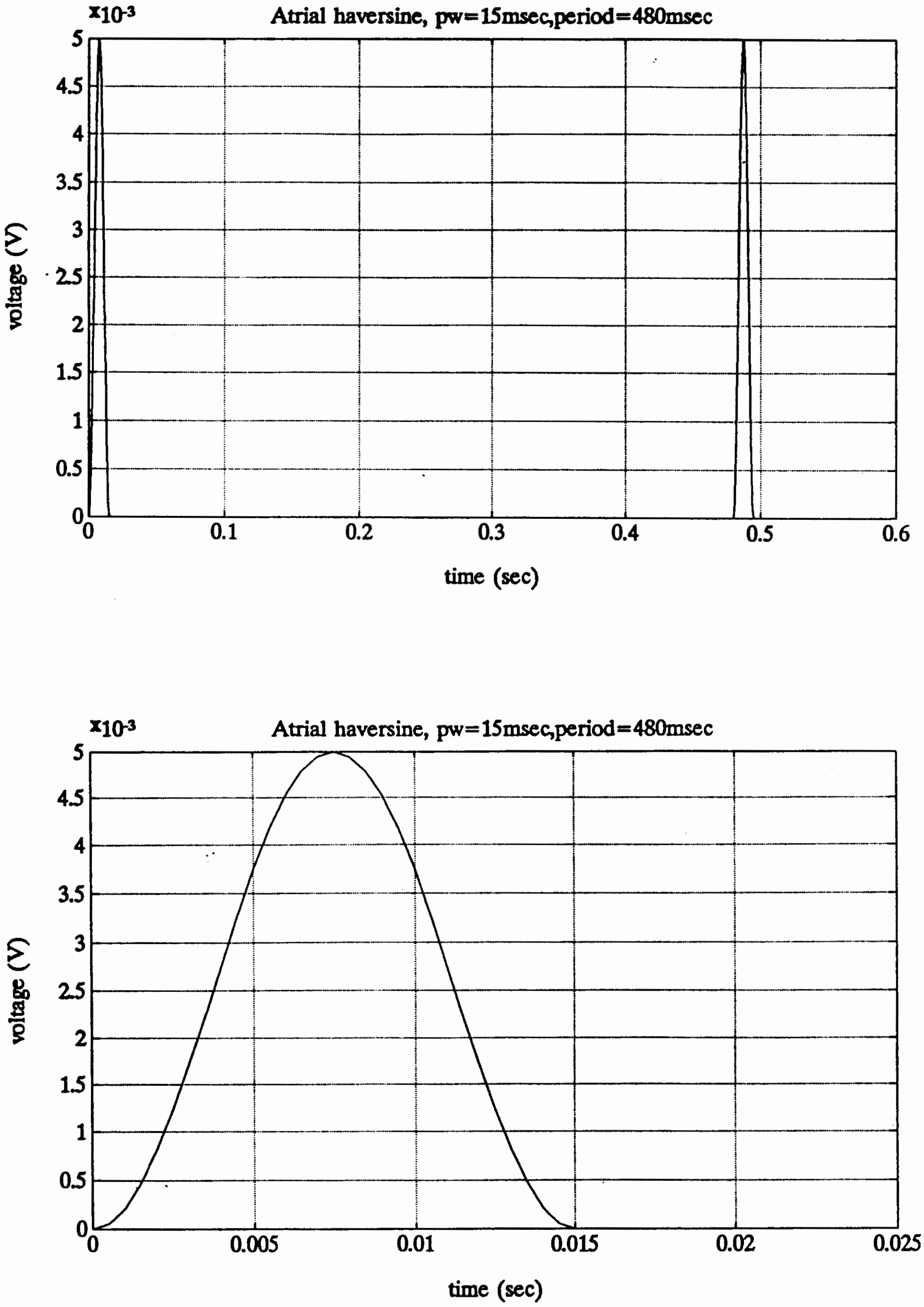


Figure 6. Atrial signal.

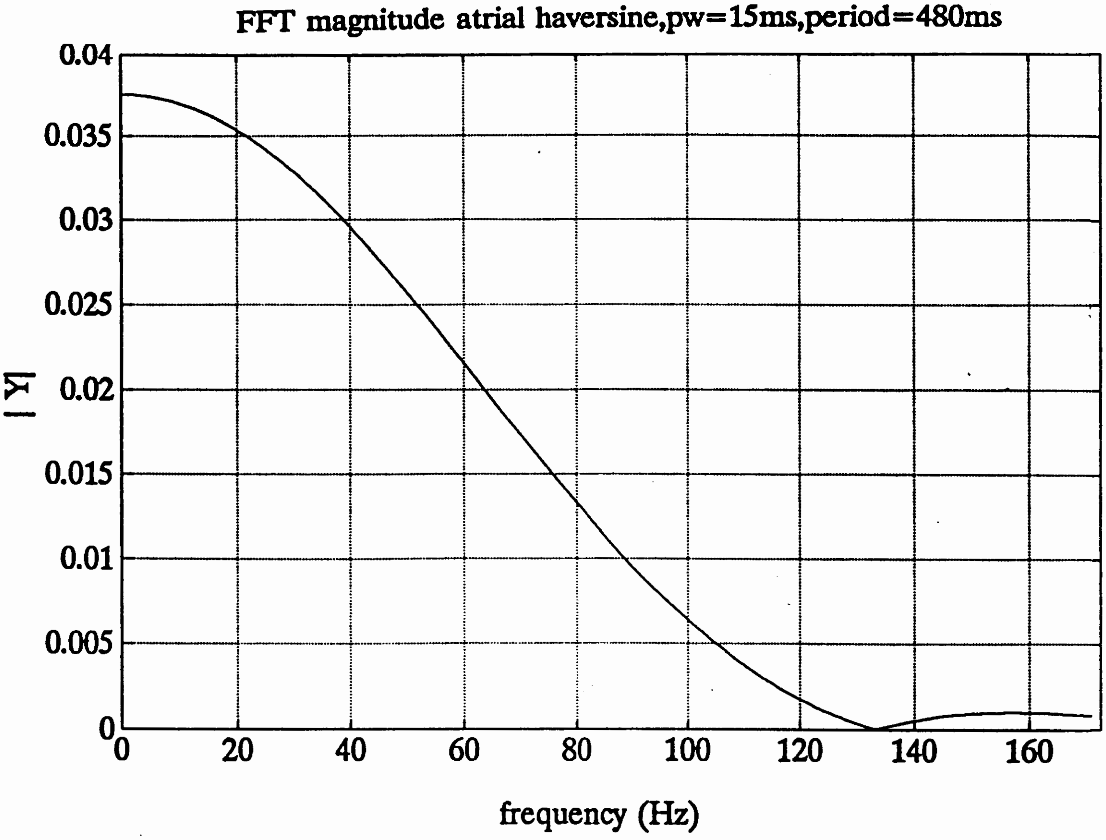


Figure 7. Atrial spectrum analysis.

VENTRICULAR REPRESENTATION

In order to create a model to test the proposed filters, it was necessary to simulate the ventricular contraction as represented by a haversine signal waveform. The depolarization and subsequent contraction of the ventricular produces a QRS wave with the following characteristics:

- Amp = 10 mV peak (amplitude)
- PW = 40 msec (pulse width)
- Per = 400 to 1000 msec (period)

Ventricular Waveform

In Figure 8, the haversine waveform component represented by: y(t) = h(t) * P(t), P(t) is a square wave. The duty cycle of this wave can be adjusted in the simulation to meet with requirements in the simulation.

Ventricular Spectrum

The spectrum of the ventricular haversine is continuous, exiting at every value of frequency w.

At w = 0, the amplitude of the spectrum represents the area under the haversine curve. The FFT is calculated at the sampling frequency of 1000 Hz, with 1024 points FFT , and one period interval.

Since f(n) = Td * f(n*Td), the result of the magnitude spectrum are multiplied by the sampling period.

Figure 9 shows the frequency spectrum of the ventricular haversine. At w = 0 Hz , the magnitude spectrum is 0.2. So, the dc level of the ventricular haversine is 0.2 mV (a dc signal has only one frequency component at w = 0). This number 0.2 mV is very important because it is compared with the magnitude spectrum of the exponential noise in later chapter.

Calculating the FFT of the haversine signal, the exponential noise and the myopotential noise will define what type of digital filters can be used to remove the exponential noise and the myopotential noise.

Remember that, if the voltage amplitude of the pacing pulse is large enough to stimulate the heart then the haversine signal will respond immediately after the pacing pulse.

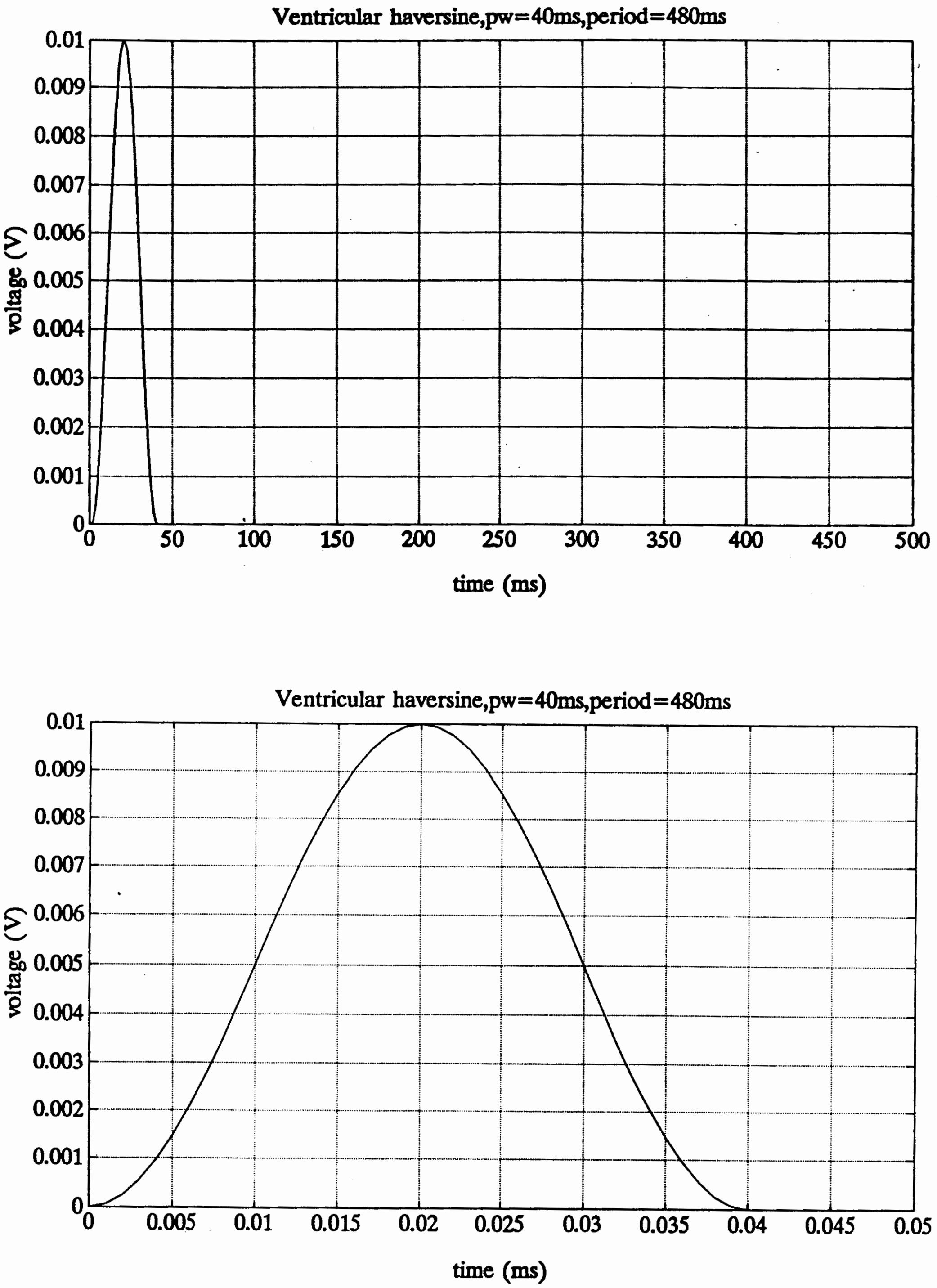
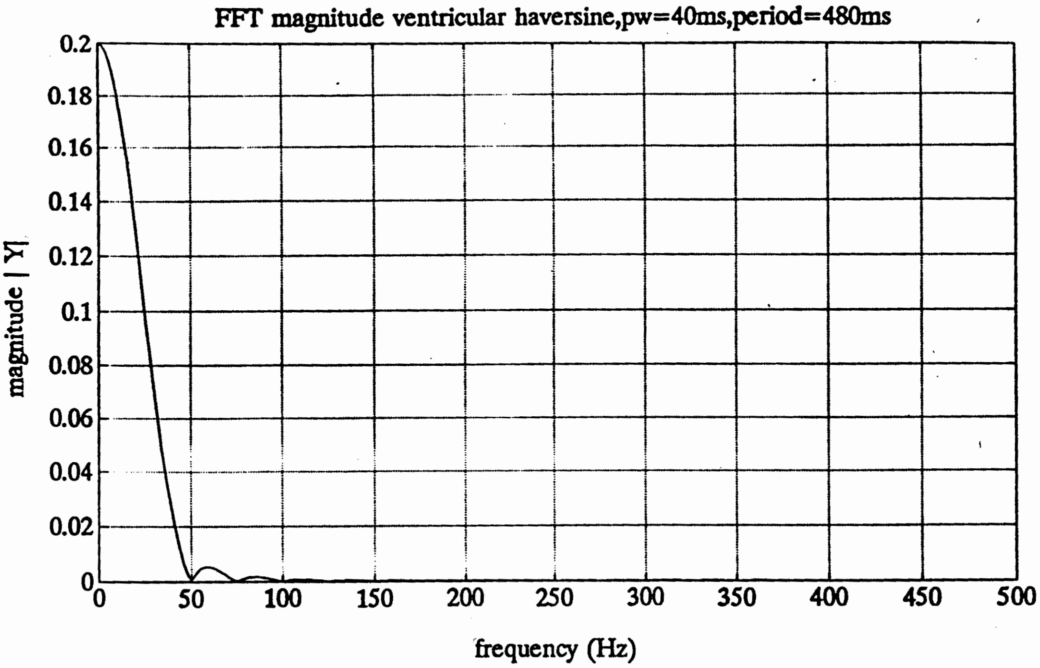


Figure 8. Ventricular signal.



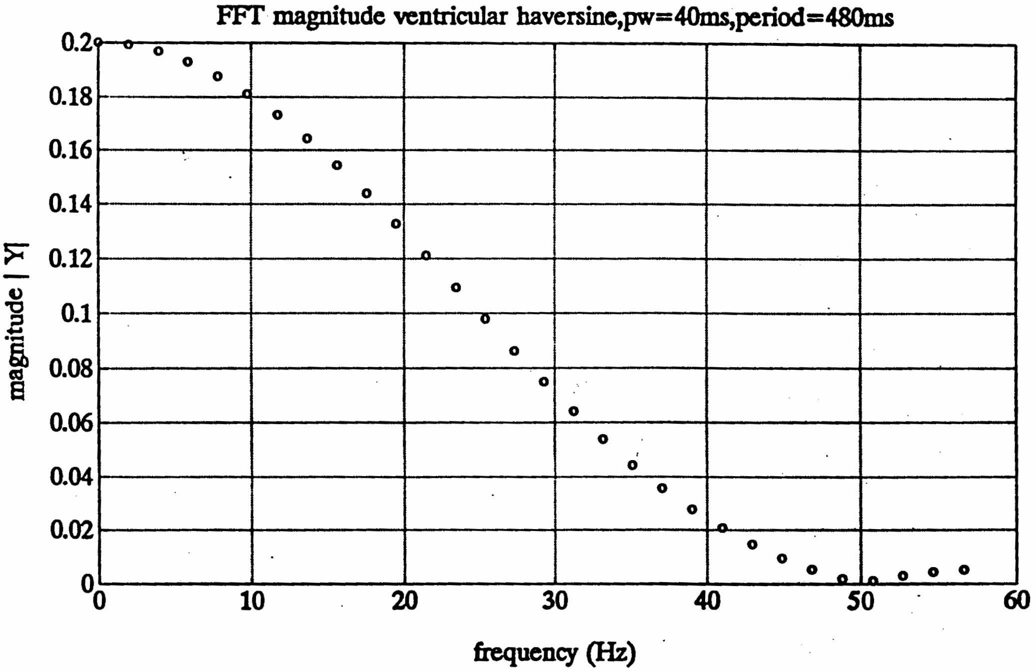


Figure 9. Ventricular spectrum analysis.

ATRIAL/VENTRICULAR REPRESENTATION

For practical purposes, it was necessary to simulate the combined atrial/ventricular action. The atrial contracts to empty the blood into the ventricular. After a time interval delay, the ventricular contracts to empty blood into the arterial system. Both the atrial and the ventricular signals are represented in the simulation by with haversine signals.

Atrial/Ventricular Waveform

Figure 10 shows that the amplitude of the atrial is 5 mV and the amplitude of the ventricular is 10 mV. The pulse width of atrial is 15 msec, and the pulse width of the ventricular is 40 msec. The atrial interval is 480 msec, and the ventricular interval is 480 msec. The atrial-ventricular delay is equal to 100 msec.

As before, y(t) = h(t) * P(t), P(t) is a square wave, and the duty cycle can be adjusted to meet wave characteristic requirements for the simulation.

The delay interval is computed from tav = AV delay interval.

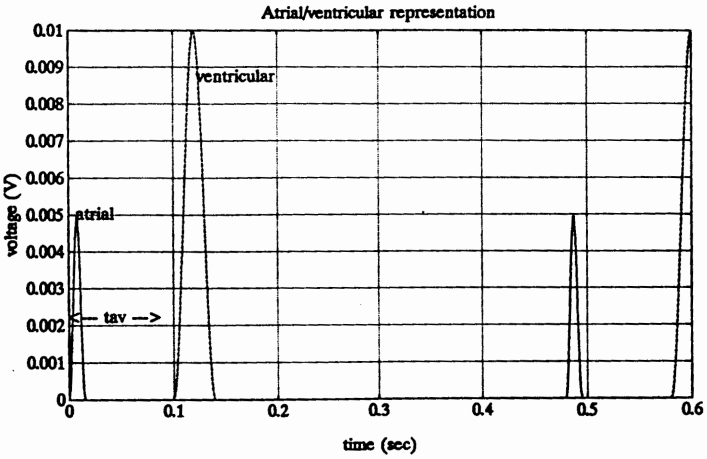


Figure 10. Atrial/ventricular signal.

SOFTWARE

This section contains the section of MATLAB code that simulates the atrial pulse (pwa), the ventricular pulse (pwv), the duty cycle, and then produces a ventricular haversine with a period of 480 msec and a pw of 40 msec. To achieve an even number of duty cycles, an atrial period of 480 msec was chosen and a ventricular period of 960 msec was chosen.

The FFT is calculated at the sampling frequency = 1000 Hz, and 1024 points FFT.

Again, f(n) = Td * f(n*Td). So, the result of the magnitude spectrum must be multiplied by the sampling period.

```
clear
t = 0:.001:.48;           % sampling at 1msec (1000 Hz)
pwa = 0.015;              % atrial pulse width = 15 msec
pwv = 0.040;              % ventricular pulse width = 40 msec
ampv = 0.010;             % V amplitude = 10 mV
ampa = 0.005;             % A amplitude = 5 mV
per1 = 0.48;              % period, type 1 = 480 msec
per2 = 0.96;              % period, type 2 = 960 msec
dutyv1 = 100/12;          % 100/12% duty cycle
dutyv2 = 100/24;          % 100/24% duty cycle
dutya1 = 3.125;           % 3.125% duty cycle
dutya2 = 1.5625;          % 1.5625% duty cycle
n = 1024;                 % number of point
fs = 1000;                % sampling rate (Hz)

%------- Ventricular: Haversine,period=480ms,pw=40ms -----%
ff = fs/2*(0:n/2)/(n/2);  % frequency range (Hz)
temp1 = ((ampv/2)*(1 - cos(2*pi*t/pwv)));
temp2 = ((1+square(2*pi*t/per1, dutyv1))/2);
hav1 = temp1 .* temp2;
havf1 = fft(hav1,n);      % FFT of haversine
magv1 = abs(havf1);       % magnitude of spectrum
magv1((n/2+2):n)=[];
magv1(2:n/2)=1*magv1(2:n/2);
temp1=[];
temp2=[];
plot(hav1),
title(’Ventricular haversine,pw=40ms,period=480ms’), ..
xlabel(’time (ms)’), ylabel(’voltage (V)’)
grid
hav1=[];
```

```
plot(ff(1:200),magv1(1:200)),
title('FFT magnitude ventricular,pw=40ms,period=480ms'), ..
xlabel('frequency (Hz)'), ylabel('|Y|')
grid
magv1=[];

%------ Ventricular: haversine,period=960ms,pw=40ms------%
temp3 = ((ampv/2)*(1- cos(2*pi*t/pwv)));
temp4 = ((1+square(2*pi*t/per2, dutyv2))/2);
hav2  = temp3 .* temp4;
havf2 = fft(hav2,n);
magv2 = abs(havf2);
magv2((n/2+2):n)=[];
magv2(2:n/2)=1*magv2(2:n/2);
temp3=[];
temp4=[];
plot(hav2),
title('Ventricular haversine,pw=40ms,period=960ms'), ..
xlabel('time (ms)'), ylabel('voltage (V)')
grid
hav2=[];
plot(ff(1:200),magv2(1:200)),
title('FFT magnitude ventricular haversine,pw=40ms,period=960ms'), ..
xlabel('frequency (Hz)'), ylabel('|Y|')
grid
magv2=[];

%------Atrial: haversine,period=480ms,pw=15ms------%
temp5 = ((ampa/2)*(1- cos(2*pi*t/pwa)));
temp6 = ((1+square(2*pi*t/per1, dutya1))/2);
haa1  = temp5 .* temp6;
haaf1 = fft(haa1,n);
maga1 = abs(haaf1);
maga1((n/2+2):n)=[];
maga1(2:n/2)=1*maga1(2:n/2);
temp5=[];
temp6=[];
plot(haa1),
title('Atrial haversine,pw=15ms,period=480ms'), ..
xlabel('time (ms)'), ylabel('voltage (V)')
grid
plot(ff(1:200),maga1(1:200)),
title('FFT magnitude atrial haversine,pw=15ms,period=480ms'), ..
xlabel('frequency (Hz)'), ylabel('|Y|')
grid
maga1=[];

%------Atrial: haversine,period=960ms,pw=15ms------%
temp7 = ((ampa/2)*(1- cos(2*pi*t/pwa)));
temp8 = ((1+square(2*pi*t/per2, dutya2))/2);
haa2 = temp7 .* temp8;
```

```
haaf2 = fft(haa2,n);
maga2 = abs(haaf2);
maga2((n/2+2):n)=[];
maga2(2:n/2)=1*maga2(2:n/2);
temp7=[];
temp8=[];
plot(haa2),
title('Atrial haversine,pw=15ms,period=960ms'), ..
xlabel('time (ms)'), ylabel('voltage (V)')
grid
haa2=[];
plot(ff(1:200),maga2(1:200)),
title('FFT magnitude atrial haversine,pw=15ms,period=960ms'), ..
xlabel('frequency (Hz)'), ylabel('|Y|')
grid
maga2=[];

%-----Atrial/ventricular representation, period = 480 msec----%
temp9 = ((ampv/2)*(1-cos (2* pi *(t-0.1) /pwv)));
temp10 = ((1 + square (2* pi (t - 0.1)/per 1, dutyv1))/2);
hav = tamp9 .* temp10;
temp9 = []; temp10 = [];
plot (t, haa1, t, hav)
title ('Atrial/Ventricular representation')
xlabel ('time (sec)'), ylabel ('voltage (V)')
grid
haa1 = []; hav = [];
```

CHAPTER IV

MYOPOTENTIAL NOISE

This chapter describes the natural occurrence of myopotential noise, the sensitivity range for detection of myopotential noise, and the conflict between myopotential noise and ventricular output. Finally, code for creation of laboratory simulated myopotential noise is presented.

UNIFORMLY DISTRIBUTED NOISE

Simulated myopotential noise represents a uniformly distributed random noise which is generated by skeletal muscle tissue. The myopotential noise has a frequency spectrum extending from 70 to 1000 Hz. The amplitude varies from 2 to 5 mV. Simulated Exponential noise represents the depolarization effects of a pacing pulse as seen at the active cardiac lead. The amplitude is very large, ˜1 volt.

Myopotential noise results from random signals and can frequently be observed on ECGs. For the purpose of this work, myopotential noises can be assumed to be transient bursts of uniformly distributed noise that typically has a frequency spectrum extending from 70 to 1000 Hz and amplitudes in the 2 to 5 mV range.

When unwanted signals such as myopotentials are sensed, the pulse generator is often inappropriately inhibited; oversensing myopotential noise is one of the more common failings of unipolar pacing. Sometimes over sensing of myopotential noise occurs with bipolar configurations as well.

A unipolar lead configuration has one conducting wire and an electrode. The pulse generator uses body fluids for its return pathway (Figure 11). A bipolar lead has two conducting wires inside its insulation. The electrical signal travels down one wire to an electrode, passes through the myocardium, causing the heart to depolarize and contract, and returns by the second electrode (Figure 12).

Pacemakers designed for atrial application with a sensitivity of 0.5 to 1 mV are always influenced by myopotential noise.

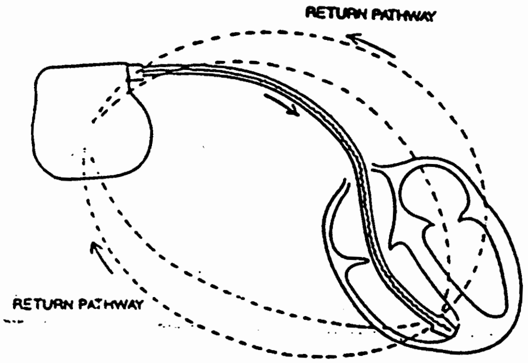


Figure 11. Unipolar lead system.

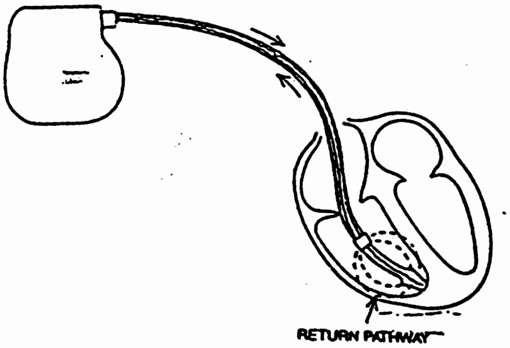


Figure 12. Bipolar lead system.

Figure 13 shows the sensitivity curve for sensing an R wave. The amplitude of the myopotential is in the 1 to 2.5 mV range and the frequency is in the 70 to 1000 Hz range. Figure 14 shows the simulated ventricular output with the myopotential noise which inhibits the ventricular output because the ventricular lead senses the muscle activity which interferes with the atrial signal. Figure 15 shows a tape record of the myopotential signals.

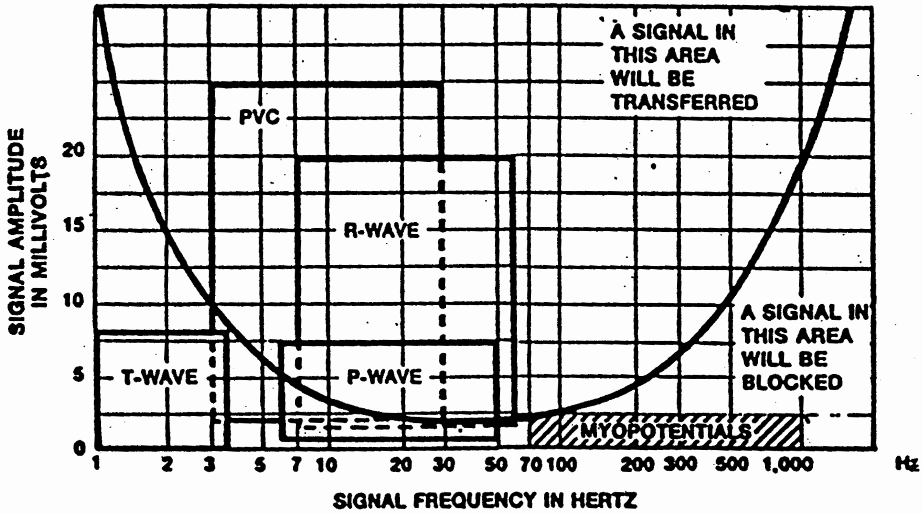


Figure 13. Sensitivity curve for sensing R waves.

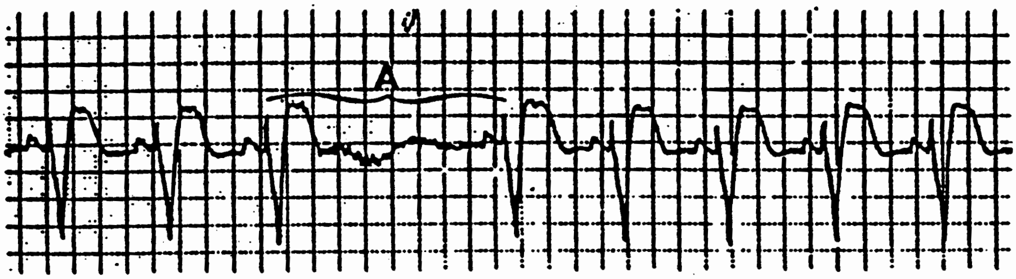


Figure 14. An atrial pacing with myopotential interference. During the interference, the ventricular lead senses muscle activity and inhibits ventricular output.

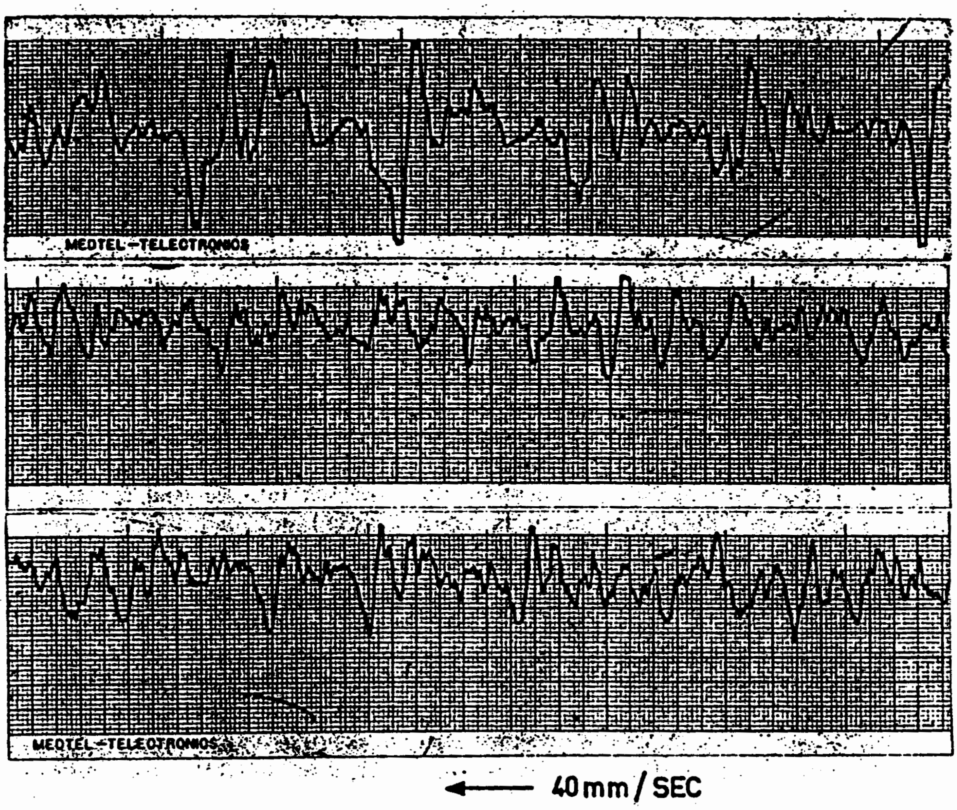


Figure 15. Examples of tape recorded myoelectric signals.

For the simulation, myopotential noise is generated by sending uniformly distributed random noise to through a bandpass filter with a pass band from 70 to 1000 Hz. Figure 16 shows the uniformly distributed random noise with amplitudes in the 1 to 5 mV range. Figure 17 shows the bandpass filter, a Chebyshev type I set to order 8, where ripple is equal to 0.1 dB in the pass band. Figure 18 shows the myopotential noise waveform. Figure 19 shows the frequency spectrum of myopotential noise created by filtering with the bandpass filter, as described above.

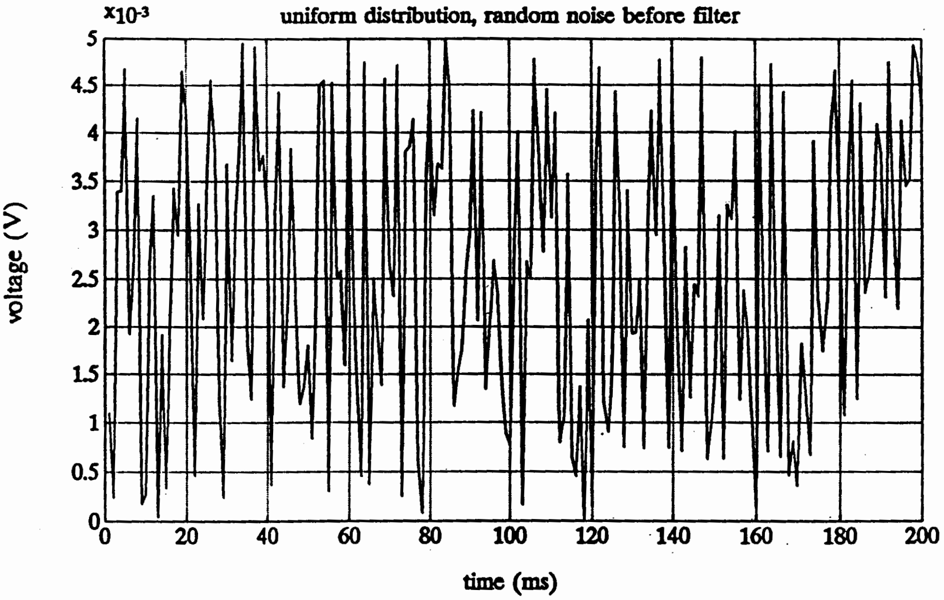


Figure 16. Uniformly distributed random noise.

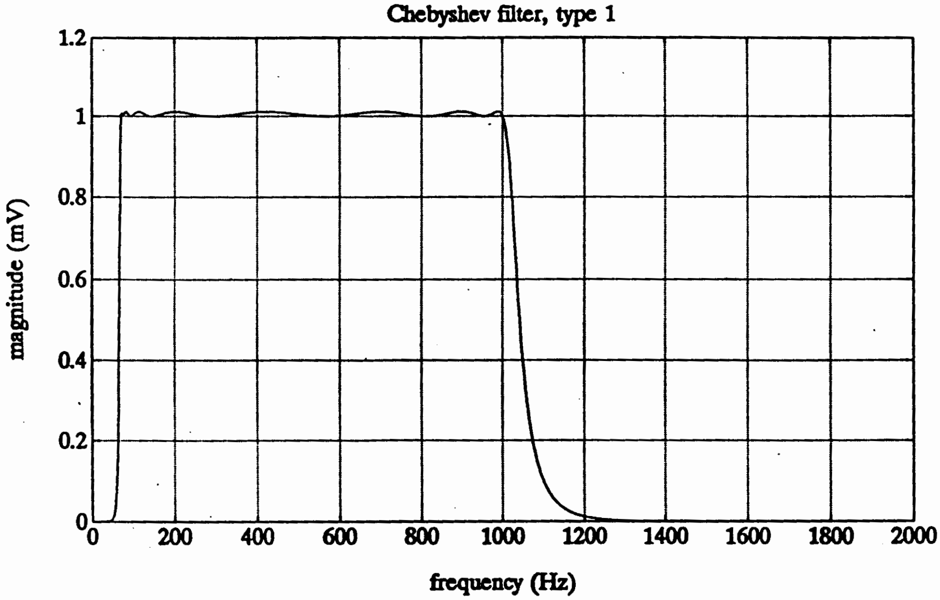


Figure 17. Chebyshev type I, bandpass filter order 8th, pass band: 70Hz to 1000Hz.

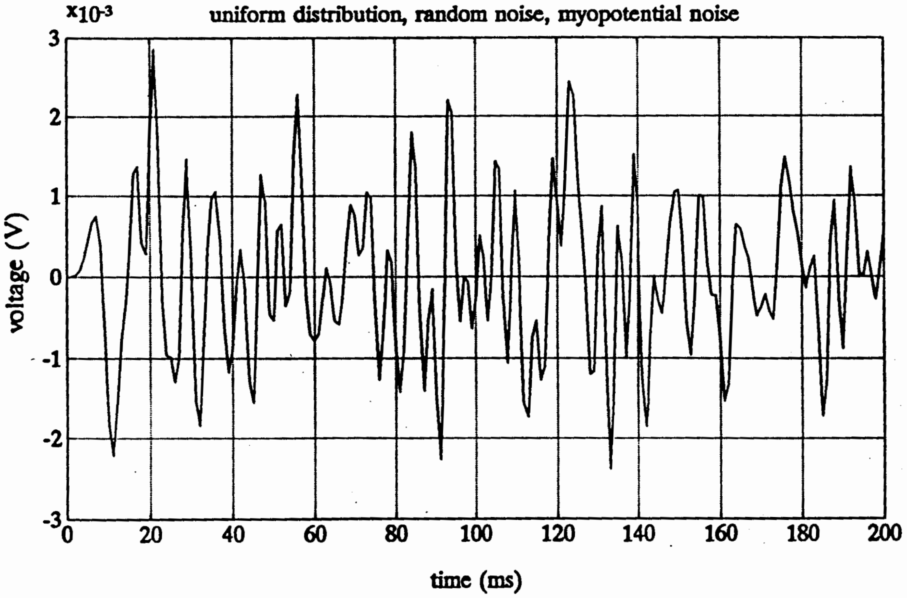


Figure 18. Myopotential noise.

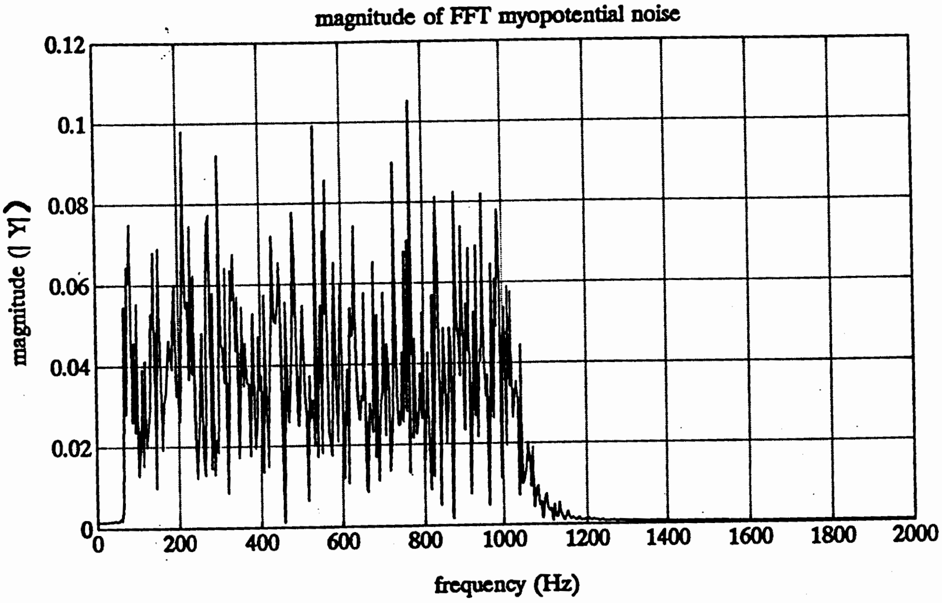


Figure 19. Spectrum of myopotential noise.

SOFTWARE

The following MATLAB code was used to simulate myopotential noise. The code creates a uniformly distributed random noise. The signal amplitude is 5 mV, and the sampling frequency is 2500 Hz. This signal is filtered by a bandpass filter. The filter is a Chebyshev type I. Ripple is at pass band .1 db, order is 8th, and the pass band is from 70 to 1000 Hz.

```
clear
t = 0:.0004:1;
rand('uniform')             % uniformly distributed random noise
y = 0.005*rand(t);          % noise, standard deviation = .005
fs = 2500;                  % sampling rate
n = 512;                    % number of point
ff = fs/(2*n) * (0:n-1);
ripple = .1;                % allowable ripple, in decibels
N = 8;                      % filter order
passband = [.056 .8];       % passband specification
[Bc,Ac] = cheby1(N, ripple, passband);
hc = freqz(Bc,Ac,n);        % frequency response
h = abs(hc);                % magnitude
z = filter(Bc,Ac,y);        % filter
y2 = fft(z,n);              % FFT of myopotential noise
m = length(y2);             % length of myopotential noise
fm = fs/2*(0:n/2)/(n/2);    % frequency range (Hz)
magy2 = abs(y2);            % magnitude of FFT myopotential
magy2((n/2+2):n)=[];
magy2(2:n/2)=1*magy2(2:n/2);
plot(y(1:200)),
title('uniformly distributed, random noise before filter')
xlabel('time (ms)'), ylabel('standard deviation')
grid
y=[];
plot(ff,h), title('Chebyshev filter, type 1')
xlabel('frequency (Hz)'), ylabel('magnitude (mV)')
grid
h=[];
plot(z(1:200)),
title('uniformly distributed, random noise, myopotential noise')
xlabel('time (ms)'), ylabel('standard deviation')
grid
z=[];
plot(fm,magy2), title('magnitude of FFT myopotential noise')
xlabel('frequency (Hz)'), ylabel('magnitude |Y|')
grid
```

CHAPTER V

EXPONENTIAL NOISE

This chapter defines and describes the "pulse interval." The chapter then describes the division of a pacing pulse into 3 parts, the conflict between exponential noise and the pacemaker's ability to register the heart's response to a pacing pulse, the possible causes of exponential noise, and the reasons a bandpass filter can not remove exponential noise. Finally, the code used to simulate exponential noise is presented.

PACE PULSE

A pacemaker delivers a small electrical pulses during an appropriate millisecond interval to produce a desired heart rate. A typical pulse interval which results in a pulse rate of 72 pulses per minute (ppm) is 833 msec. The time periodic between pulses of electrical energy, or the distance between two pacings, is the pulse interval.

The output pulse of a pacemaker has a typical shape and time duration, depending on the type of circuitry. Figure 20 shows a typical artifact magnified on an oscilloscope.

Pulse width is the time during which electrical energy is being delivered to the heart as measured from the leading edge to the trailing edge of the pace pulse.

The voltage amplitude of the output pulse and the impedance of the lead pacing system are related to electrical current flow. The measuring method differs from one manufacture to another.

Figure 21 shows the pulse width and the voltage amplitude of a pacing pulse on an oscilloscope (LeCroy 9400A Dual 175 MHz oscilloscope).

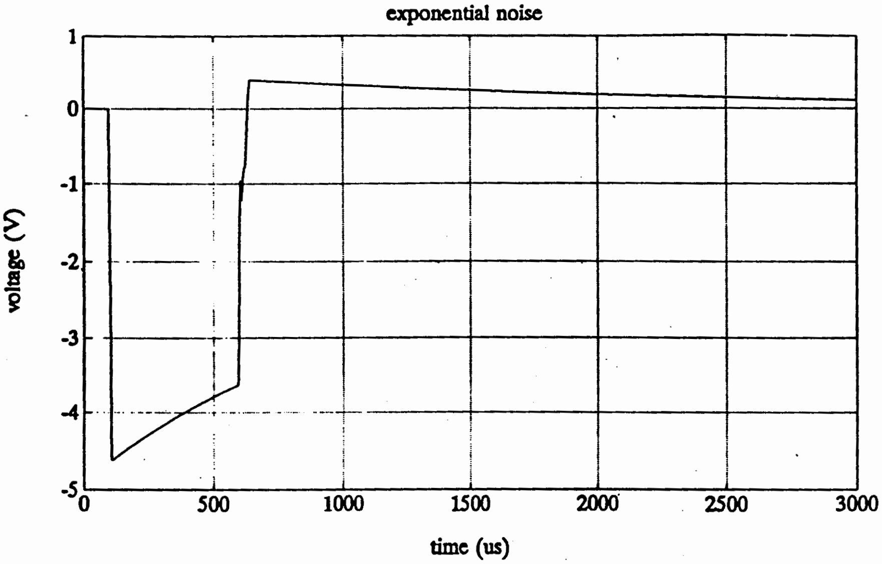


Figure 20. The pacing artifact.

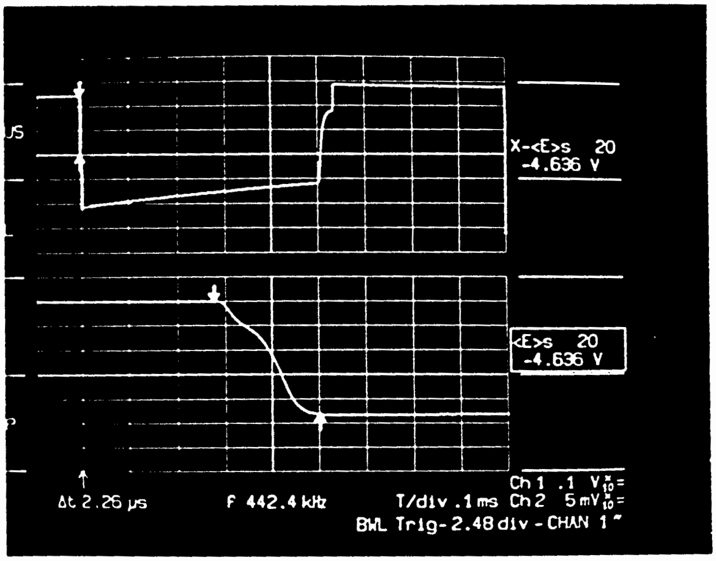


Figure 21. Pulse width = 530 S Amplitude = -4.8 V, LeCroy 9400A Dual 175 Mhz scope.

Normal pacemakers allow pulse width and voltage amplitude to be programmed to satisfy the requirements for each patient. In the simulation model, pulse width and voltage amplitude can be manipulated by changing the initial settings of the corresponding variables.

The pacing pulse shown in Figure 21 can be divided into three parts: exponential #1; exponential #2; exponential #3 (Figure 22). Exponential #3 is considered exponential noise.

Figure 21 describes the ventricular pacing pulse of the pacemaker. This pacemeker is one of the products of the MicroSystems Engineering company.

After the trailing edge of the pacing pulse, the pulse does not return immediately to ground level; rather, exponential signal decay after the trailing edge demonstrates that additional noises are produced by a pacemaker. This trailing edge noise is called exponential noise.

The amplitude of the exponential noise is very large (˜ 1 volt) compared to the voltage amplitude of the heart beat (10mV). The overlap of exponential noise on the QRS signal which identifies the heart beat makes it is difficult for a pacemaker to register the response of a heart immediately after a pacing pulse. Usually, a pacemaker has to wait a certain time until the voltage amplitude of the exponential noise decreases to a low enough level that the QRS is clear of the exponential noise. Only then the pacemaker can sense the heart beat clearly. At that time the pacemaker can read the QRS and respond by sending the next pace pulse or by suppressing a pace pulse. The important thing is how to design a digital filter to remove the exponential noise, and this problem will be solved in later chapters.

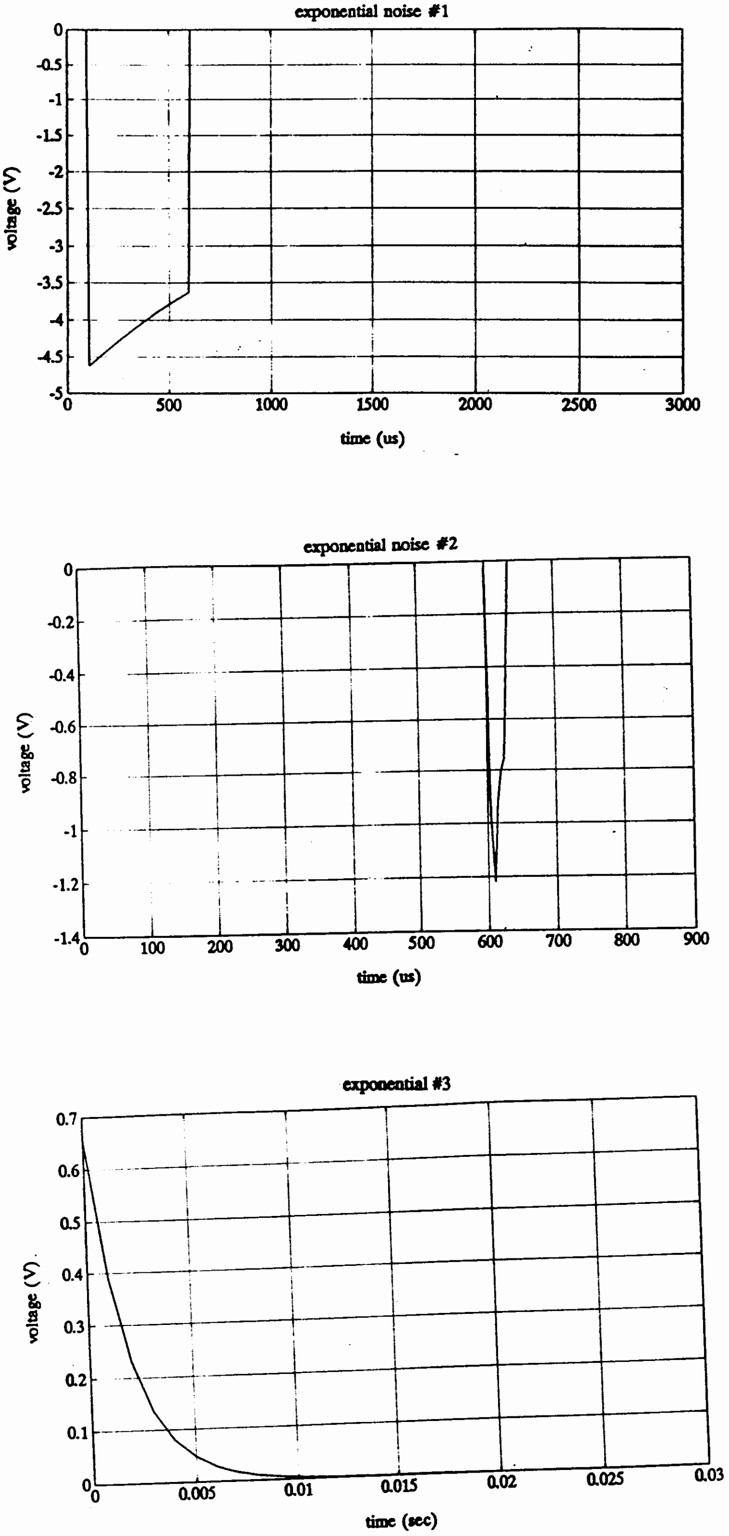


Figure 22. Detail of the pace pulse.

Exponential noise results from a number of causes; however, the main cause is the contact of the surface lead with the muscle tissue of the body. This contact establishes capacitance between the lead and the muscle tissue. So, the amplitude and the time constant of the exponential (which is also a function of time) varies from patient to patient, as well as from moment to moment. To minimize noise, manufacturers have designed many different lead configurations that reduce the surface area contact. Professor Dr. Max Schaldach, the author of "Electrotherapy of the Heart," described the electro/myocardium interface very clearly. He also places emphasis on selection of the electrode materials.

Spectrum of Exponential Noise

The spectrum of exponential noise is shown in Figure 23. At the point of generation in the simulation, the exponential noise spectrum is continuous. The pace pulse is considered a non-periodic signal at this sample point because of the assumption that the haversine happens immediately after the pace pulse. The non-periodic signal has a continuous spectrum. Sometimes the pace pulse is considered a periodic signal when the pacemaker works without sensing a response.

A pacemaker allows the heart to beat by itself if the heart can. The pacemaker will save energy during dormant times. The pacemaker will take over only when a heart cannot supply enough blood to the body.

Figure 23 shows the frequency spectrum of the exponential noise, at 0Hz frequency the dc level is read 1.6mV. The ventricular dc level is 0.2 mV and the atrial dc level is .0375mV. The ratio between the exponential noise and the ventricular signal is 8:1, between the exponential noise and the atrial signal is 42:1.

Because the amplitude of the exponential noise is much higher than the amplitude of the haversine, there is no way to remove the exponential noise by using bandpass filters. Another difficulty is that the frequency spectrum of the exponential noise overlays the frequency spectrum of the haversine.

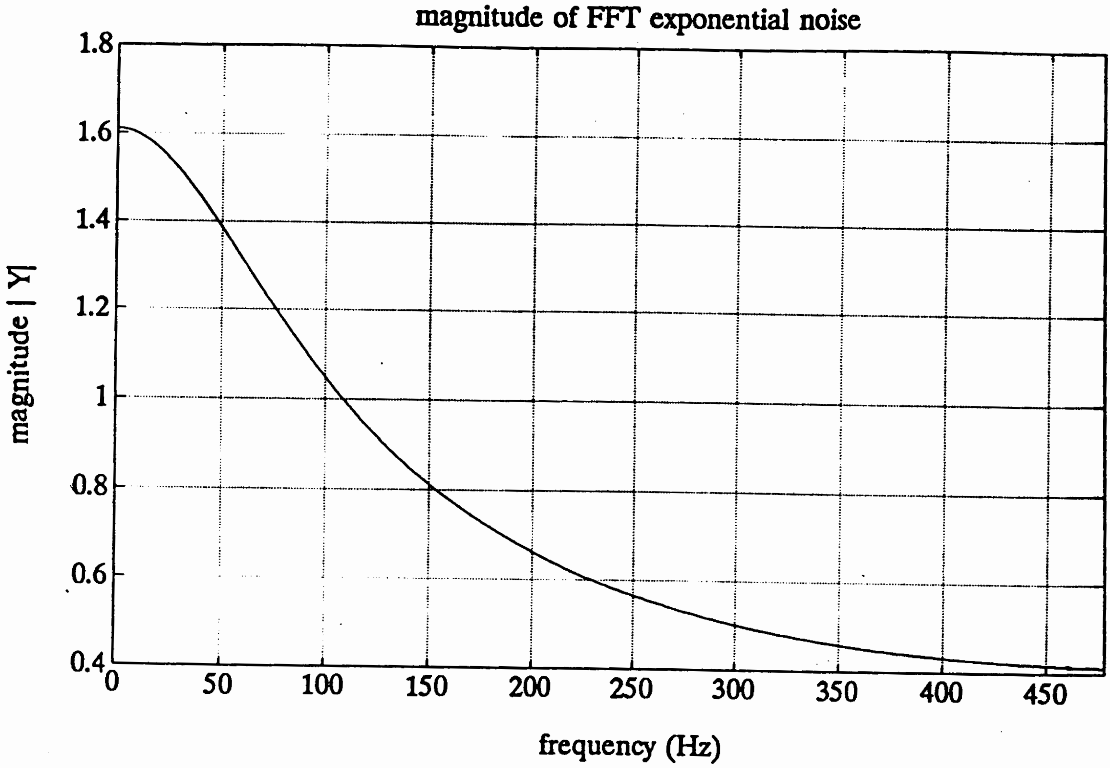


Figure 23. Spectrum of the exponential noise.

SOFTWARE

The following software listing is the MATLAB code for generating the exponential noise used in the simulation. The FFT is calculated at a sampling frequency of 1000 Hz and 512 points.

```
clear
step 1=.1;
t  = 0:.001:.7;          % time interval of exponential#1
n  = 512;                % number of point
fs = 1000;               % sampling rate
ff = fs/2 * (0:n/2)/(n/2); % frequency range
```

```
aexp3 =  0.38912;          % amplitude of exponential #3
bexp3 = -524.395452;   % time constant of exponential #3
%----------------Exponential noise -----------------------%
temp3 = (1+sign(t-step1))/2;
exp3  = (aexp3 * exp(bexp3*(t-step1))) .* temp3;
temp3 = [];
plot(t(1:300),exp3(1:300))
title('exponential noise #3')
xlabel('time (us)'), ylabel('voltage (V)')
grid
expf  = fft(exp3,n);                    % FFT of exponential noise
exp3  = [];
magexp= abs(expf);                      % magnitude of FFT
magexp(((n/2)+2):n)=[];
magexp(2:n/2)=1*magexp(2:n/2);
plot(ff,magexp)
title('magnitude of FFT exponential noise'), ..
xlabel('frequency (Hz)'), ylabel('magnitude |Y|')
grid
magexp = [];
```

CHAPTER VI

INPUT SIGNAL

This chapter describes the test input signal and provides a code sample that combines haversine, exponential, and myopotential signals to create the test input.

The signal used as input to the test filters consists of the haversine signal, exponential noise, and myopotential noise. Figure 24 shows a combination of these signals. The pace pulse is chosen such that the ventricular pace pulse has a pulse width equal to 40 msec, a period equal to 480 msec, and an amplitude equal to 10 mV. The haversine signal is very difficult to observe in Figure 24. At t=.02sec, the presence of haversine signal is seen as a tiny amplitude of the signal.

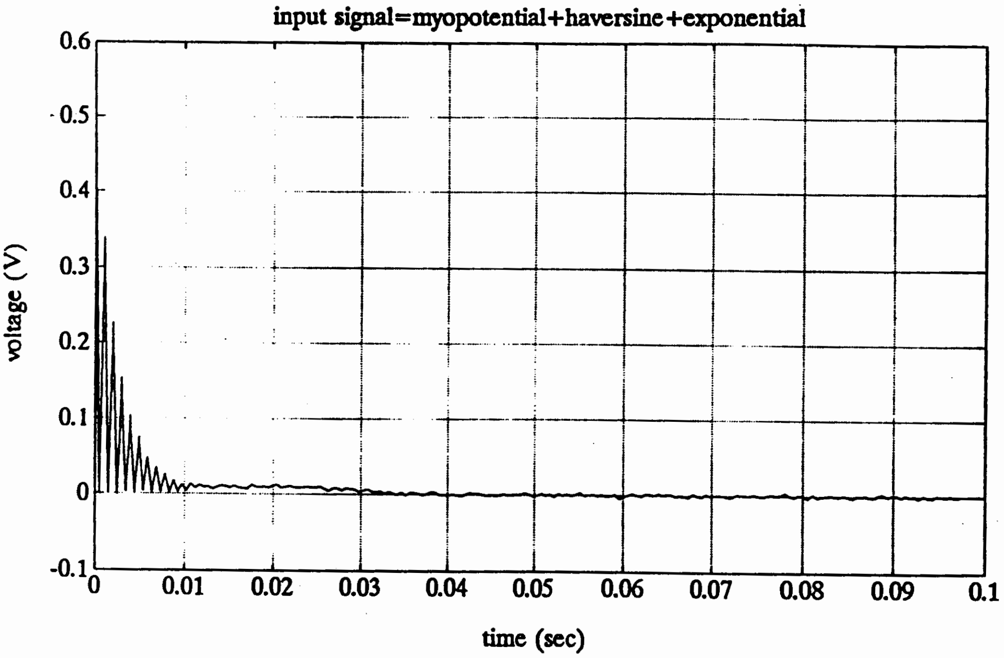


Figure 24. Haversine+exponential+myopotential.

SOFTWARE

The following software listing is the MATLAB code which provides a combination of exponential, haversine and myopotential signals for the simulation. This signal is then sent to the amplifier.

```
clear
fs = 2500;                  % sampling rate
step = 1/fs;
t = 0:step:.48;             % sampling at 1msec (1000 Hz)
pwv = 0.040;                % ventricular pulse width = 40 msec
amp = 0.01;                 % amplitude = 10 mV
per1 = 0.48;                % period, type 1 = 480 msec
dutyv1 = 100/12;            % 100/12% duty cycle
a3 = .5;                    % amplitude of exponential #3
b3 = -100;                  % time constant of exponential #3

%----- Ventricular: haversine,period=480ms------%
temp1 = ((amp/2)*(1-cos(2*pi*t/pwv)));
temp2 = ((1+square(2*pi*t/per1, dutyv1))/2);
hav1 = temp1 .* temp2;
temp1=[]; temp2=[];

%----- Exponential noise -----------------------%
exp3 = a3 * exp(b3*(t));

%---- Myopotential noise -----------------------%
rand('uniform')             % uniform distribution random noise
y = 0.005*rand(t);          % noise, standard deviation = .005
ripple = .1;                % allowable ripple, in decibels
N = 8;                      % filter order
passband = [(2*70)/fs  (2*1000)/fs]; % passband specification
[Bc,Ac] = cheby1(N, ripple, passband);
myo = filter(Bc,Ac,y);            % filter
y=[]; Bc=[]; Ac=[];

%-------------- Input signal -------------------%
s_in = exp3 + hav1 + myo;
exp3=[]; hav1=[]; myo=[];
plot(t,s_in)
title('input signal=noise+haversine+exponential noise')
xlabel('time (sec)'), ylabel('voltage (V)')
grid
```

CHAPTER VII

AMPLIFIER

This chapter describes the need for a signal amplifier and provides a code sample which simulates the signal amplification done by a normal pacemaker.

Because the haversine signal is so small, an amplifier is used to make the haversine large enough to view after filtering takes place. The maximum gain of commercially available amplifiers is approximately 400. This number is not a fixed number. It varies from one manufacture to another. For the purposes of the simulation, the gain can be manipulated.

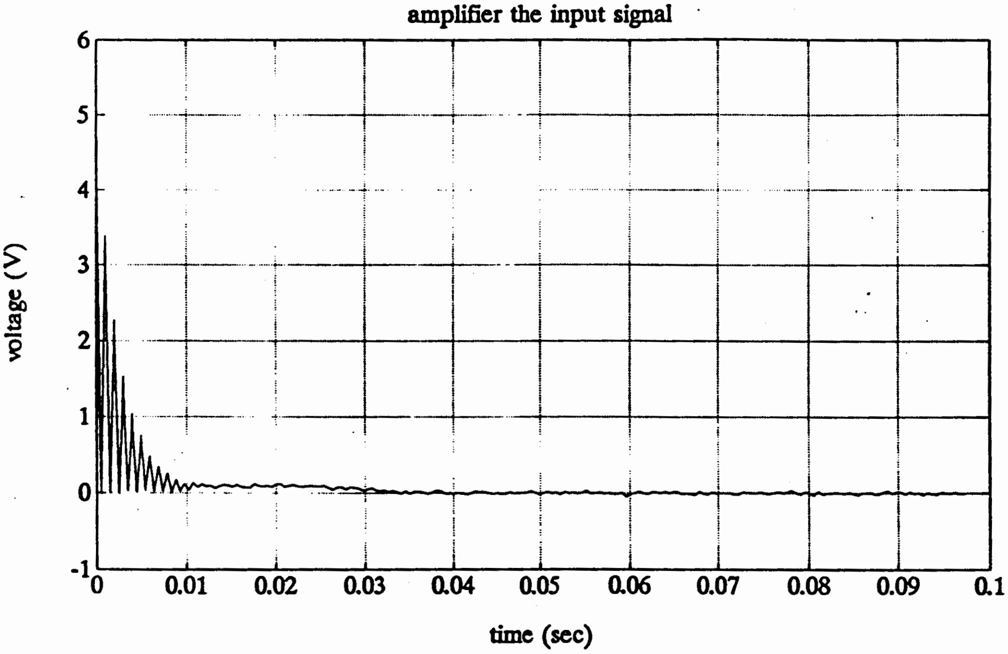


Figure 25. Amplifier the input signal.

SOFTWARE

The following software listing presents the simulated amplifier used in the test of the proposed filter. For the purposes of the simulation, assume the input signal is s_in and the amplifier gain is set to 10.

```
clear
gain = 10;                    % gain of amplifier
% Amplifier the input signal (s_in) %
s_in = gain * s_in;
plot(t,s_in)
title('amplifier the input signal')
xlabel('time (sec)'), ylabel('voltage (V)')
grid
```

CHAPTER VIII

A/D CONVERTER

This chapter describes an analog to digital converter, the sample and hold function, and presents the code listing for the sample and hold functionality. The chapter then describes the quantization process and the introduction of random noise into the quantized signal. Finally, the code which represents the quantization process is presented.

Most pacemakers handle an analog signal. In order to manipulate the pacemaker's signals with digital filters, an analog to digital converter (A/D converter) was used. The A/D converter is a physical device that converts an input voltage amplitude into a binary code representing a quantized amplitude value closest to the amplitude of the input. Because the conversion is not instantaneous, a high performance A/D typically includes a sample and hold function to compensate for the bottleneck caused by processing delays.

SAMPLE AND HOLD

The sample and hold function is designed to sample an analog signal as nearly instantaneously as possible and to hold the sample value as nearly constant as possible until the next sample is taken. The sample value is held for quantization by the A/D converter. In the test case, the signal is sampling and holding at 2048 Hz = 2^{11}. Figure 26 shows the result of the sample and hold.

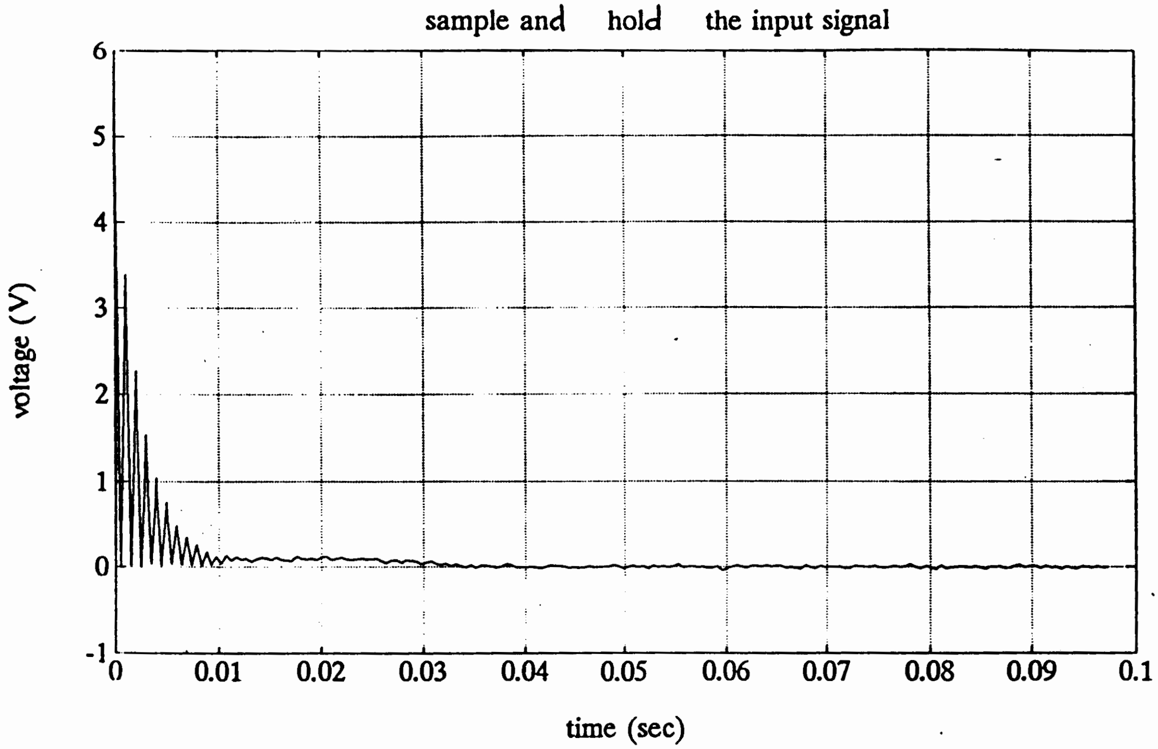


Figure 26. Sample and hold.

Software

The following listing represents the simulated sample and hold function prepares the signal for the A/D converter. The signal is sampled at a frequency of 2048 Hz, and it holds at the same frequency.

```
clear
fs = 2048;                    % sampling rate
step = 1/fs;
t = 0:step:.48;               % sampling at 2048 Hz

%---------- sample and hold ----------------%
holdtime = step;
holdsample = ceil(holdtime/step);
m = length(s_in);
s_hold = [];
```

```
t_hold = [];
s_hold(1) = s_in(1);
t_hold(1) = t(1);
k = 1;
num = 1;
while (k <= (m-1))
    k = k + 1;
    num = (k/holdsample) - fix(k/holdsample);
    if(num > 0)
            s_hold(k) = s_hold(k-1);
            t_hold(k) = t(k);
    end

    if(num <= 0)
            s_hold(k) = s_in(k);
            t_hold(k) = t(k);
    end
end
s_in=[]; t=[]; holdtime=0; holdsample=0; m=0; k=0; num=0;

plot(t_hold(1:200),s_hold(1:200))
title('sample and hold the input signal')
xlabel('time (sec)'), ylabel('voltage (V)')
grid
```

QUANTIZATION

A quantizer is a nonlinear system that transforms the input sample into one of a finite set of prescribed values. The quantization steps are usually uniform in signal processing.

Let X = input signal

X_B = quantized input signal

B = bits resolution

VFS = voltage full scale

delta = step size of the quantizer

delta $= \mathrm{VFS}/(2^B - 1)$

If the above is true, then the following expression represents the quantization done in the simulation. X_B=delta * round(X * (2^B-1)/VFS)

Because of the loss of precision due to the round-off function, the quantizer signal gains some random noise.

In this case, the signal is quantized at an 8 bit resolution. The input signal is above voltage full scale (VFS) and does not return to the output data. Figure 27 shows the relationship between the quantizer input signal and a VFS input signal of 10 V at an 8 bit resolution. Figure 28 shows the result of the input signal after going through the quantization stage.

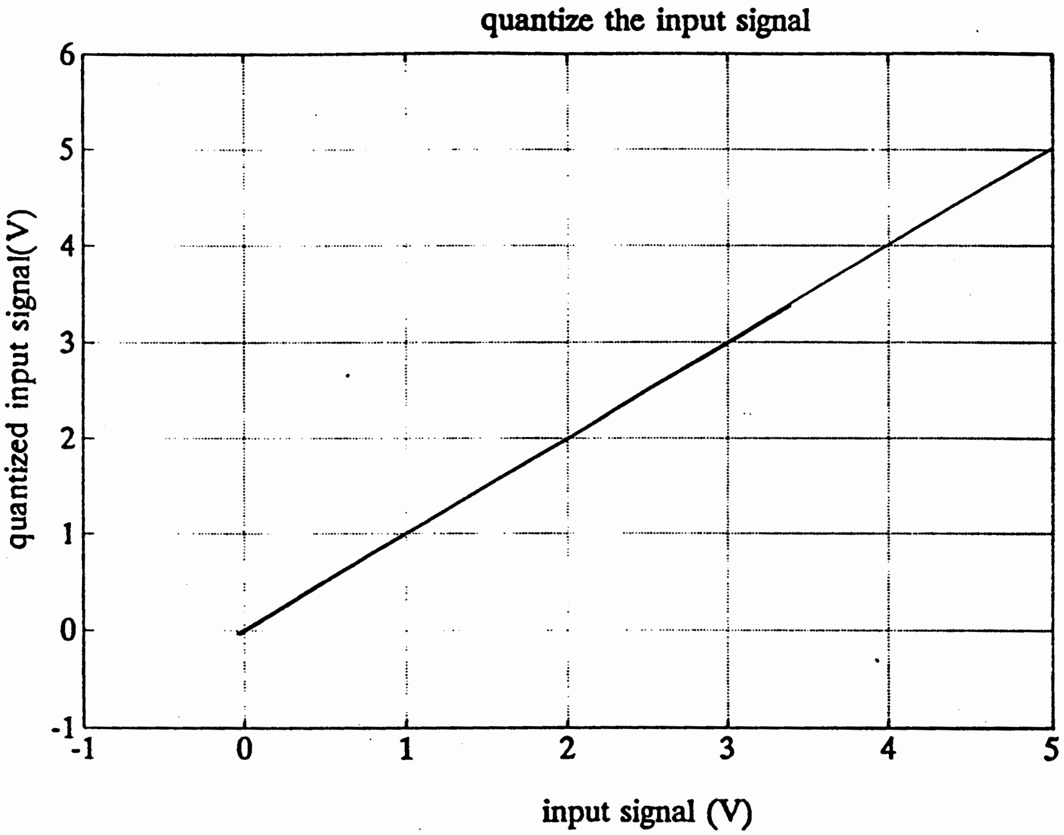


Figure 27. VFS=10, 8 bits resolution.

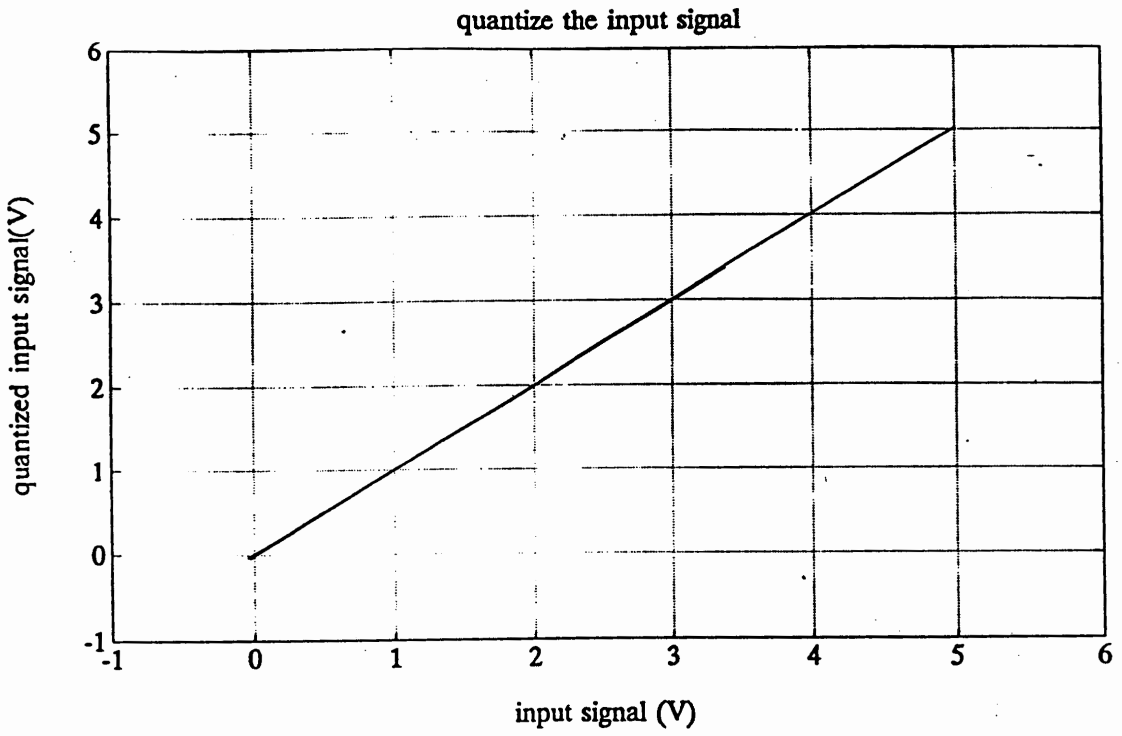


Figure 28. After quantizer, signal gains some random noise.

Software

The following code listing represents the quantization function of the simulation. After the signal is quantized, it is ready to move through the filters for removal of exponential and myopotential noise.

```
clear

disp('------- Quantization -------------');
VFS=0; bits=0; maxcount=0; delta=0;
VFS = input('Enter volts full scale (V) [VFS] ==>');
bits= input('Enter number of bits solution [bits] ==>');
maxcount = (2^bits)-1;   % number of quantizer points
delta = VFS/maxcount;    % voltage resolution at quantizer
l = 0;
l = length(s_hold);
q = 0;
```

```
s_quan=[];
t_quan=[];
s_inq=[];
while (q <= (l-1))
    q=q+1;
    num1 = abs(s_hold(q));
    num2 = sign(s_hold(q));
    s_inq(q) = s_hold(q);
    if (num1 > VFS)
           s_quan(q) = num2 * VFS;
           t_quan(q) = t_hold(q);
    end
    if (num1 <= VFS)
      s_quan(q) = num2 * delta * round((maxcount*num1)/VFS);
      t_quan(q) = t_hold(q);
    end
end
l=0; q=0; num1=0; num2=0; s_hold=[]; t_hold=[];

plot(s_inq,s_quan)
title('quantize the input signal')
xlabel('input signal (V)'), ylabel('quantized input signal(V)')
grid
s_inq=[];

plot(t_quan(1:200),s_quan(1:200))
title('quantize the input signal')
xlabel('time (sec)'), ylabel('quantize input signal(V)')
grid
```

CHAPTER IX

DIGITAL FILTER

This chapter describes the need for and inadequacy of digital filters, the instability of inverse digital filters, the use of a stable psuedo-inverse filter to remove the presence of the exponential noise, the effects of the filter on the test signal, and the use of a lowpass digital filter to minimize myopotential noise.

Since the purpose of this thesis is to show how to detect a haversine signal immediately following a pace pulse, the ability of the proposed digital filters to remove or minimize exponential noise and myopotential noise must be demonstrated. To this end, two filters are described here, the inverse digital filter, and the lowpass digital filter. When both filters have been applied to the signal which has been prepared by the simulation code described in previous chapters, the result should be output which contains only the haversine signal.

INVERSE DIGITAL FILTER

The input to the inverse digital filter is the combined signal containing the non-periodic haversine signal, non-periodic exponential noise, and myopotential random noise. The spectrum of the haversine is overlapped by the spectrum of and amplitude of the exponential, which is several orders of magnitude larger. So, classical filters like the Chebyshev, the Butterworth, and the Elliptic are not useful.

Based on the characteristics of the exponential noise, an inverse filter was designed to filter out only the exponential noise. The parameters of the exponential noise signal (amplitude and time constant) are a function of time and this makes the inverse filter desirable because it is more sensitive to noise. Design of a usable inverse filter is difficult because they are often unstable. A pseudoinverse filter combines characteristics of the inverse filter with characteristics of more stable designs to create a usable and stabilized version of the inverse filter.

Some properties of inverse system:

H(z) - transfer function of the system
H_i(z) - inverse transfer function

$$H\_i(z) = 1 / H(z)$$

To meet the definitional characteristics of inverse filters, the region of convergence of H(z) and H_i(z) must overlap. Poles of H_i(z) are zeros of H(z). If the region of convergence of H_i(z) includes the unit circle, then the H_i(z) is stable.

Suppose, the exponential signal is described as:

$$h(t) = \frac{A}{2} e^{-b.t} \left(1 + \cos\left(\frac{\pi.t}{Ts}\right)\right)$$

$$1) \Longrightarrow H(z) = \frac{z^2}{z^2 - a^2}$$

$$2) \Longrightarrow H\_i(z) = \frac{z^2 - a^2}{z^2}$$

$$a = e^{-bTs}$$

Then the envelope of h(t) is an exponential decay. This is a second order system of the exponential. Since the H_i(z) has only zeros, this filter may be called FIR (finite impulse response), all-zero, non recursive, or moving average(MA). It follows that the system has a finite duration impulse response. Therefore, the system is stable.

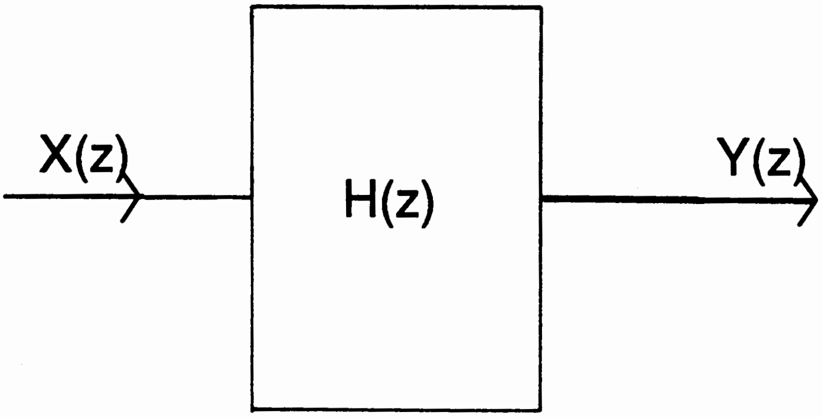
Since the H_i(z) is a polynomial with only negative powers of z, the system is causal. However, if the zeros are outside the unit circle, the system is in non-minimum phase.

Analysis of the above (1)&(2) yields:

$$Y(z) = H(z).H\_i(z) = 1$$

In time domain, $y(t) = \delta(t)$ impulse response

Summary:



$H(Z) = Y(Z) / X(Z)$

$\Longrightarrow Y(Z) = X(Z) \,.\, H(Z)$

let $H(Z) = 1 / X(Z)$

$\Longrightarrow Y(Z) = 1 \quad \Longrightarrow y(t) = \delta(t)$

After the signal goes through the inverse filter, the output is the haversine, the myo-potential, and the impulse response. Figure 29 illustrates the perfect inverse filter, the exponential is completely removed.

Figures 30 and 31 show the different magnitudes of an inverse filter of 2nd order and an inverse filter of 1st order when zero locations change.

By changing the time constant of the exponential noise, the behavior of the inverse filter changes as shown in Tables I, II, III, and IV.

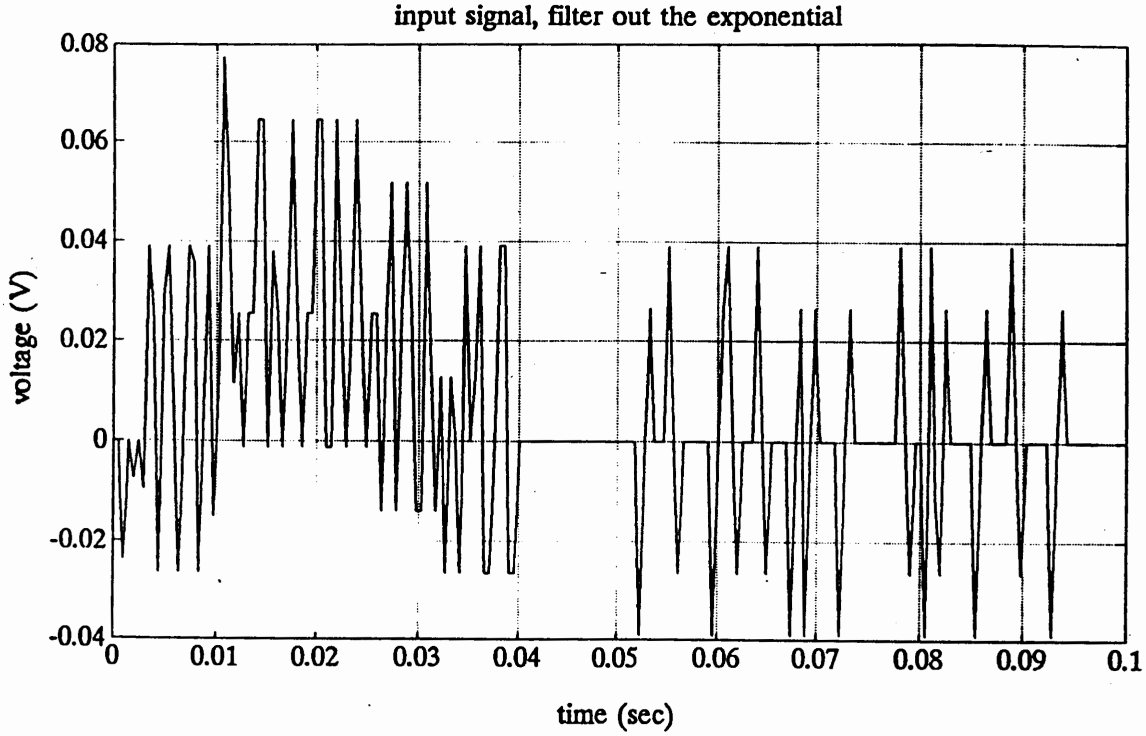


Figure 29. Inverse filter removes the exponential.

Tables I and II show the behavior of 2nd order inverse filter. By varying the a and b constants from the ideal exponential signal, Table I emphasizes the filtered results of the exponential signal and Table II emphasizes the filtered results for the combination of exponential and haversine signal. The difference between Table I and II is the haversine signal and the impulse response. From Table I, at t = 0 msec, the presence of the large amplitude of the filtered signal determines the presence of the impulse response function. At. 0%, a&b, the amplitude of the filtered signal approaches zero after 0 msec. This represents the perfect inverse filter. Increasing the percentage of the a and b coefficients causes the amplitude of the filtered signal to ring after 0 msec. This represents the exponential signal is still present after being filtered. Figure 32, 33, and 34, show three special cases describing Table II: Figure 32 shows the filtered signal at 0% a&b; 33

shows the signal at 2% a&b; and 34 at 5% a&b. The haversine in all cases is still clearly observed.

Tables III and IV show the behavior of the 1st order inverse filter. The presentation is similar to Tables I and II. Figures 35, 36 and 37 show three special cases describing Table IV that are similar to Figures 32, 33, and 34.

Tables V and VI show the sensitivity of the input signal for the second order inverse filter by changing the location of the zeros of the inverse filter. Table VI emphasizes the filtered results of the exponential signal. It describes the starting position of the zeros at 0.1, and when the zeros move closer to the ideal location (e^{-bT}), the amplitude of the filtered signal decreases after 0 msec. But, when the zeros pass through the ideal location, the amplitude of the filter signal is negative, indicating the instability of the inverse filter. Figures 38, 39, and 40 show three special cases describing Table V: Figure 38 shows the filtered signal at zero = 0.7, Figure 39 shows the filtered signal at zero = 0.8, and Figure 40 shows the filtered signal at zero = 0.9. At zero = 0.8 the haversine signal is clearly observed. Figures 41, 42, and 43 show three special cases describing Table VIII that are similar to Figures 38, 39, and 40.

Tables VII and VIII display the sensitivity of the input signal for a 1st order inverse filter. The comparison procedure is similar to that of Table V and VI. Figure 39 shows the filtered signal at zero = 0.8, and Figure 40 shows the filterd signal at zero = 0.9. At zero = 0.8 the haversine signal is clearly observed.

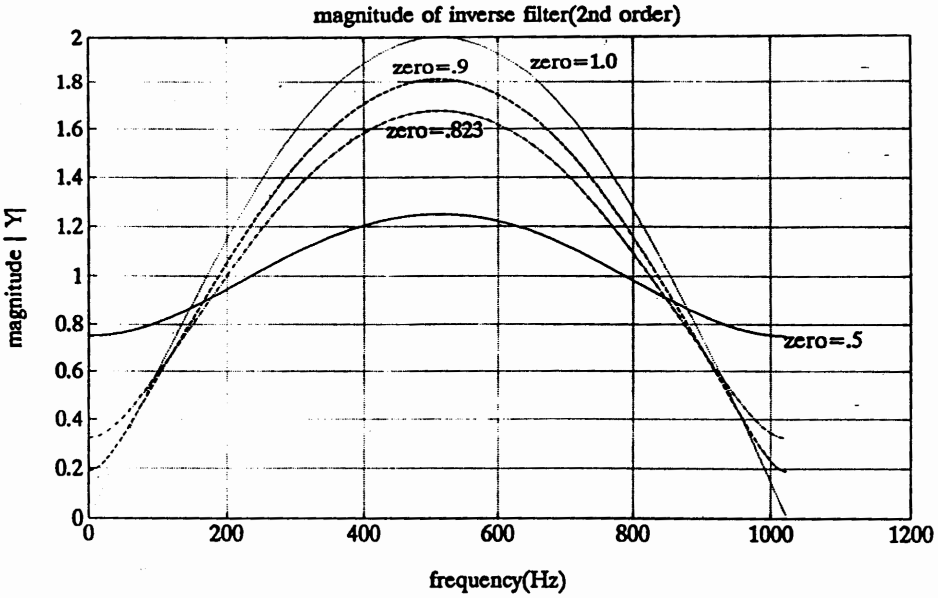


Figure 30. Magnitude of inverse filter (2nd order) at different zero location.

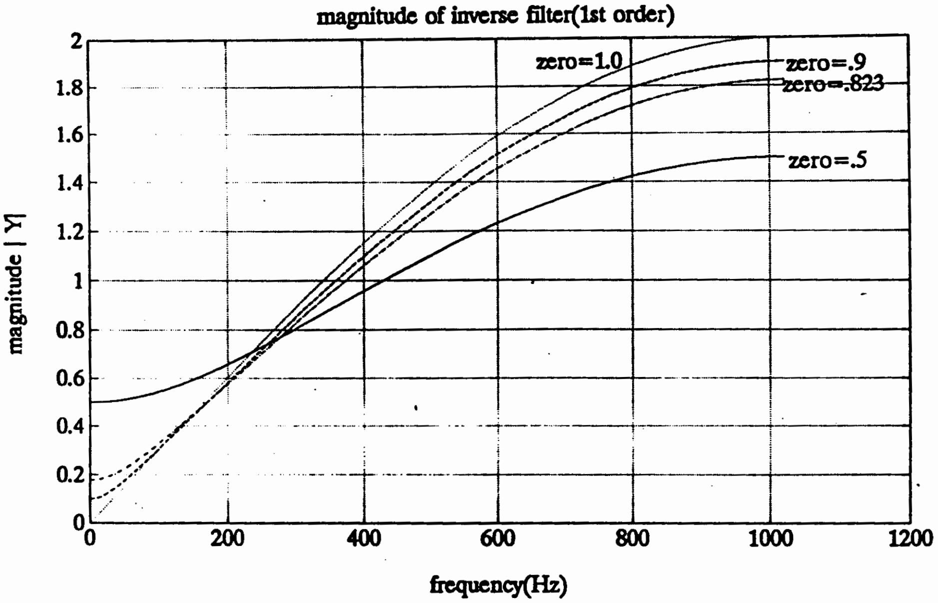


Figure 31. Magnitude of inverse filter (1st order) at different zero location.

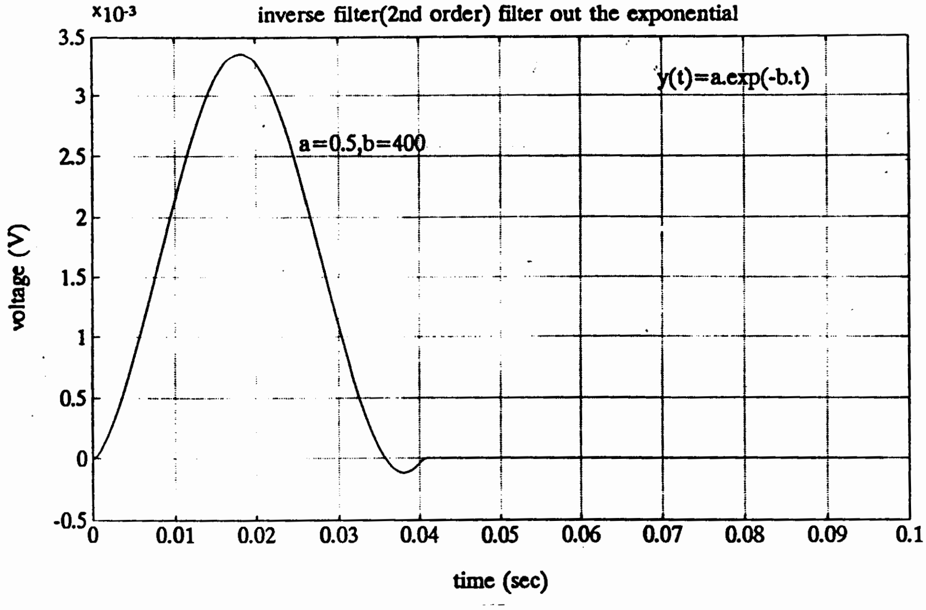


Figure 32. Fixed inverse filter (2nd order) coefficients, 0% a&b.

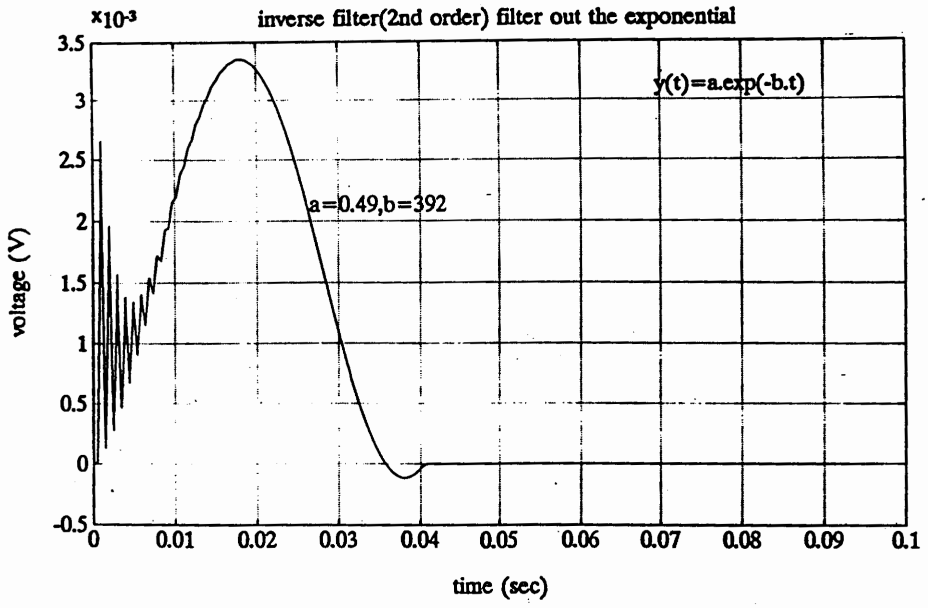


Figure 33. Fixed inverse filter (2nd order) coefficients, 2% a&b.

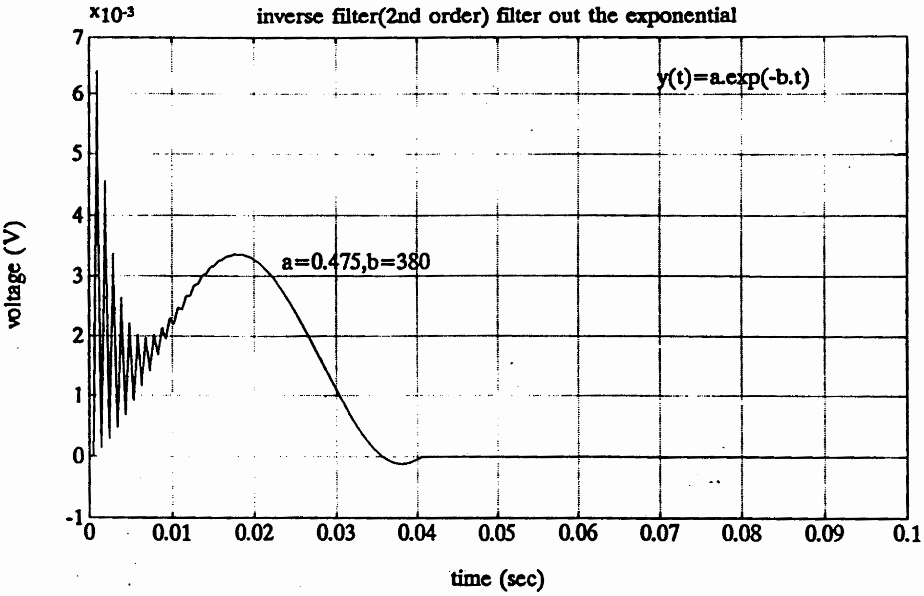


Figure 34. Fixed inverse filter (2nd order) coefficients, 5% a&b.

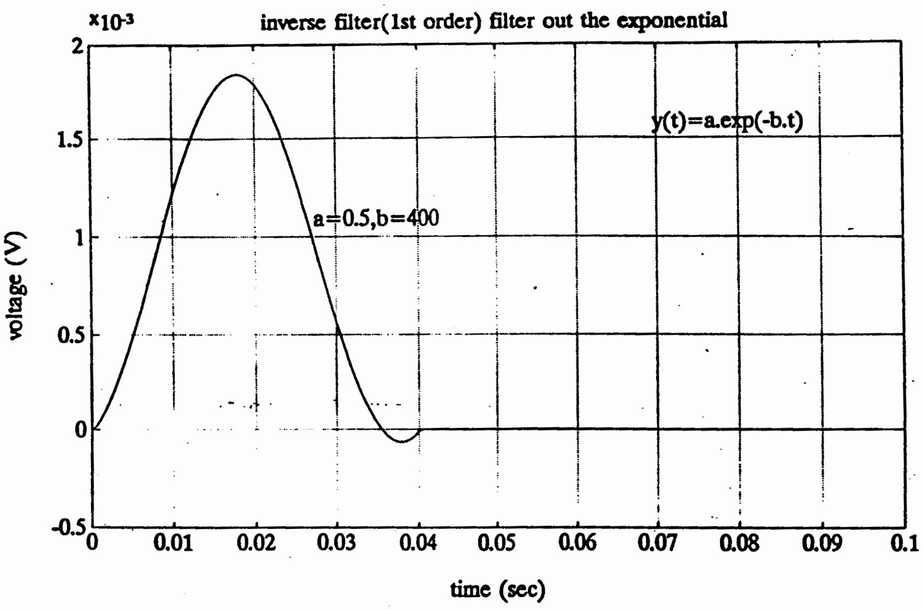


Figure 35. Fixed inverse filter (1st order) coefficients, 0% a&b.

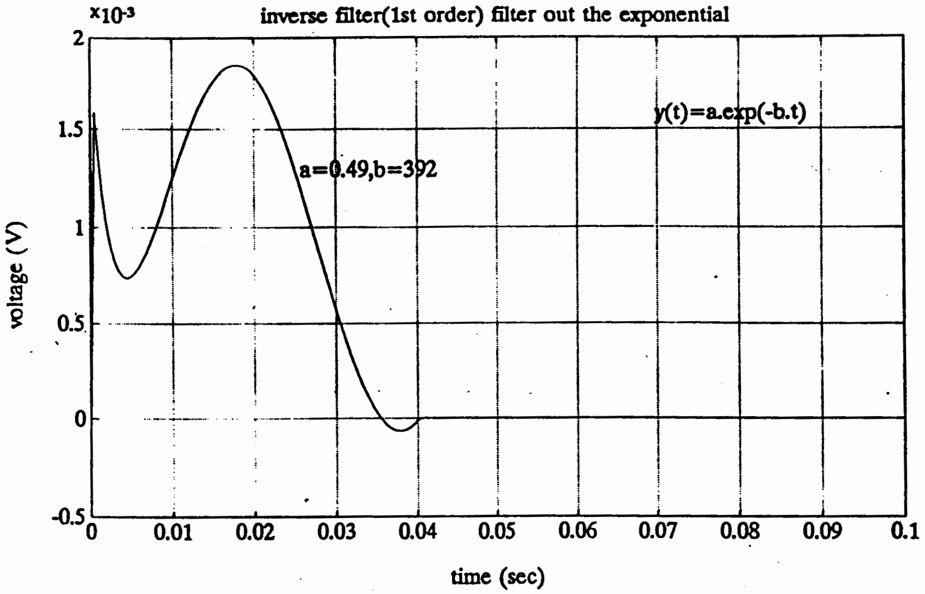


Figure 36. Fixed inverse filter (1st order) coefficients, 2% a&b.

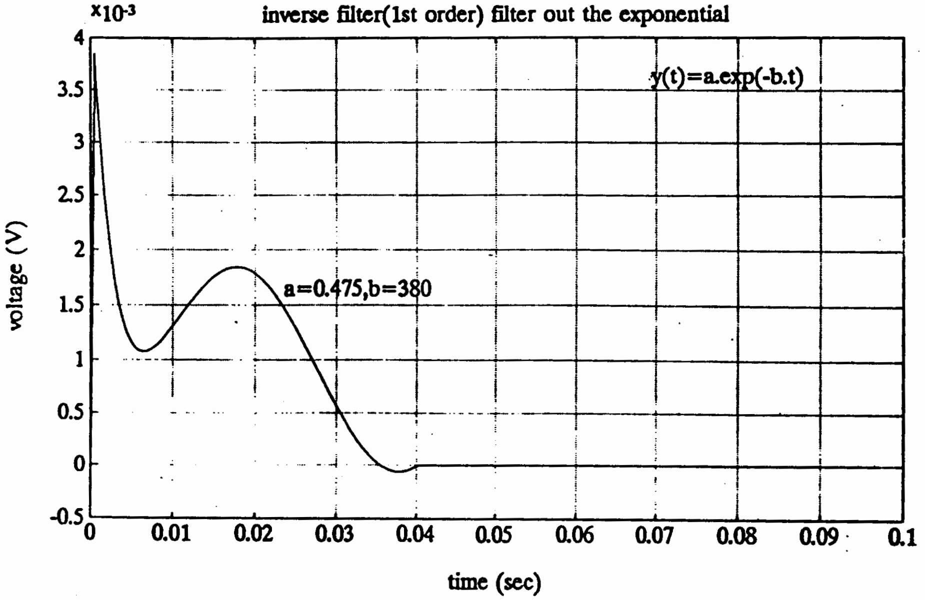


Figure 37. Fixed inverse filter (1st order) coefficients, 5% a&b.

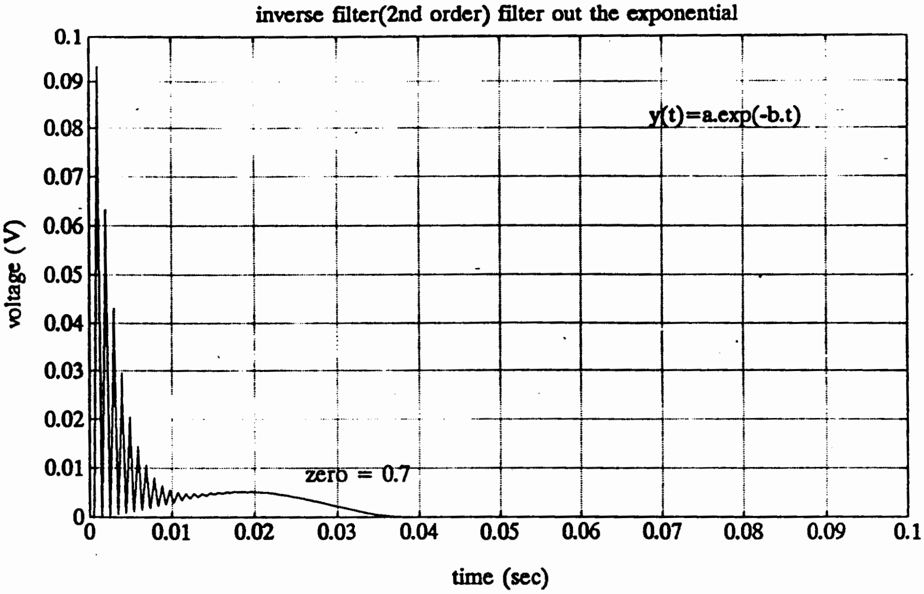


Figure 38. Change zero location (2nd order inverse filter), zero = 0.7.

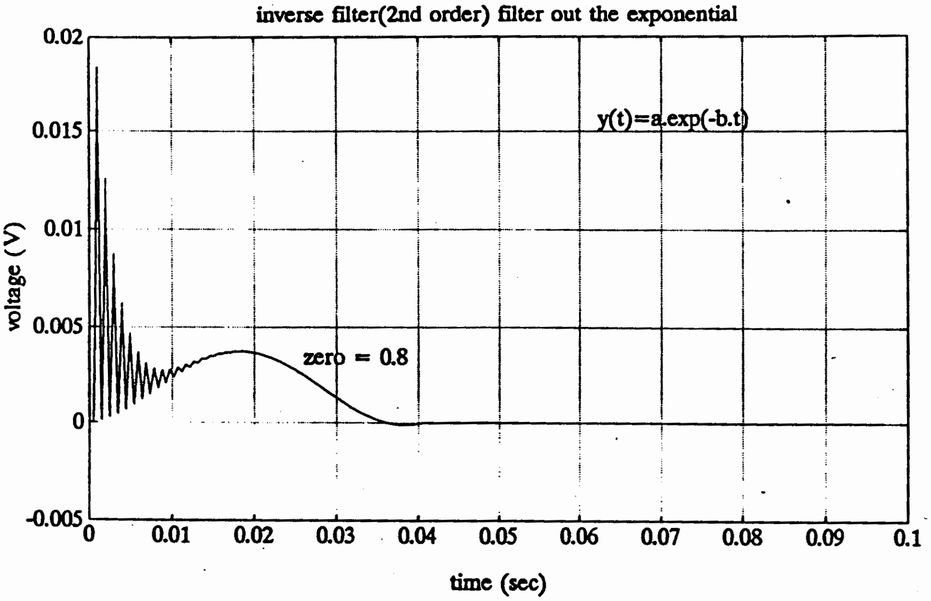


Figure 39. Change zero location (2nd order inverse filter), zero = 0.8.

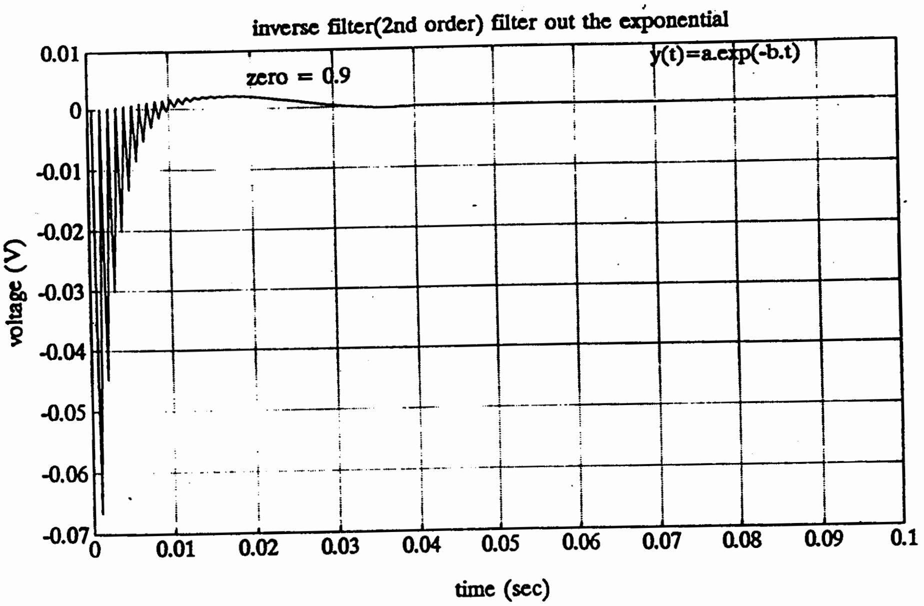


Figure 40. Change zero location (2nd order inverse filter), zero = 0.9.

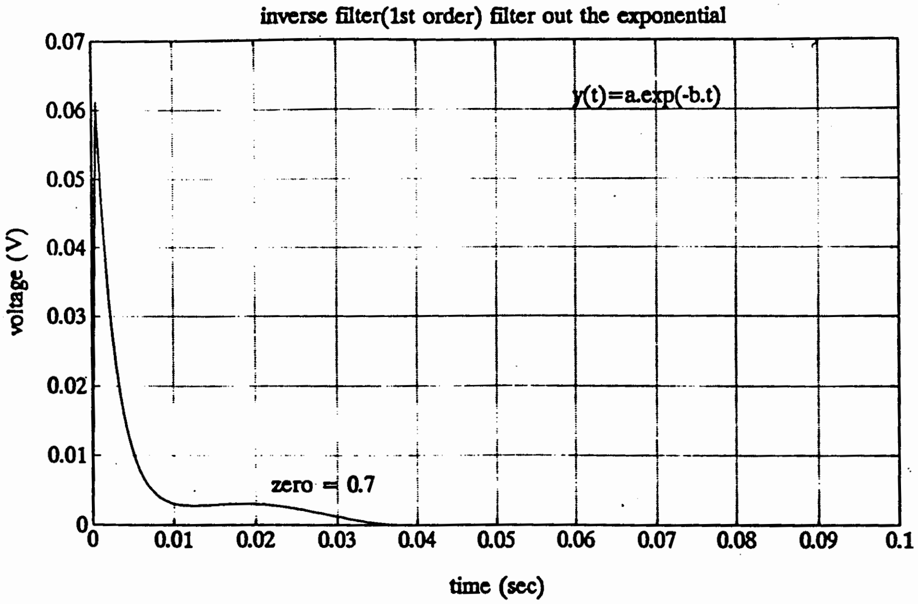


Figure 41. Change zero location (1st order inverse filter), zero = 0.7.

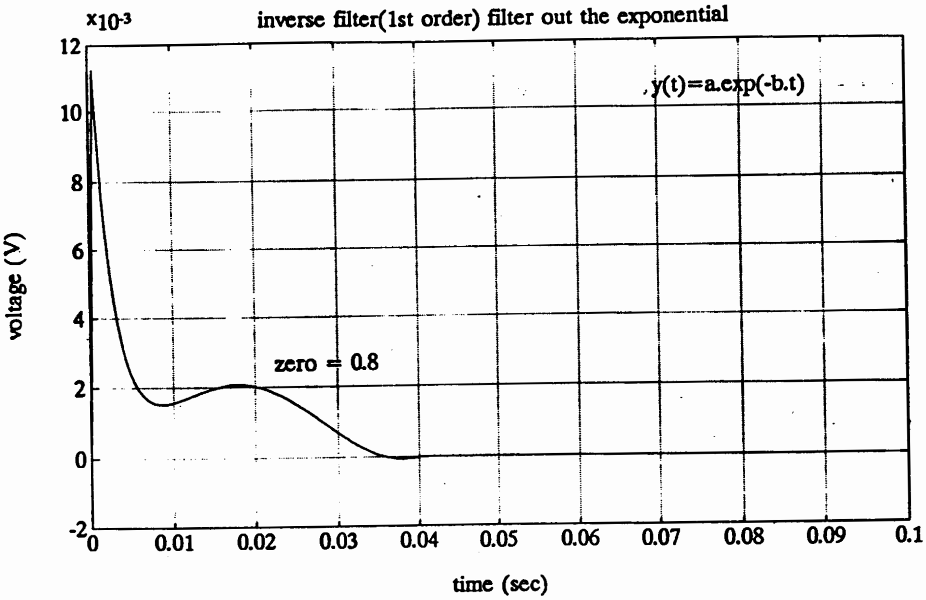


Figure 42. Change zero location (1st order inverse filter), zero = 0.8.

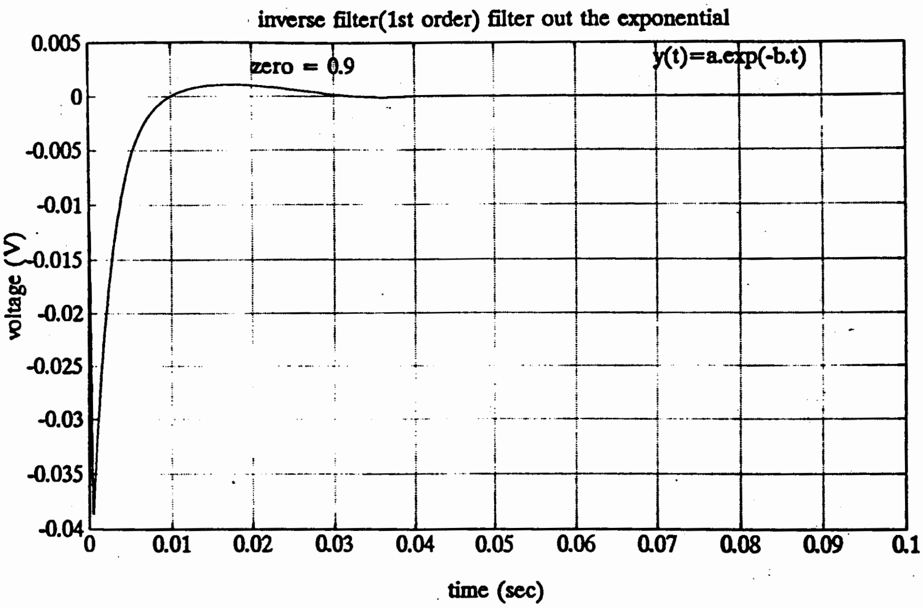


Figure 43. Change zero location (1st order inverse filter), zero = 0.9.

TABLE I

INVERSE FILTER (2ND ORDER) BEHAVIOR, WHERE INPUT SIGNAL = EXPONENTIAL ONLY: AT 0%, B = -400(1/SEC), A=0.5V IN A*EXP(-BT)

time msec	0% mV	.25% mV	.5% mV	.75% mV	1% mV	2% mV
0.000	500.000	498.750	497.500	496.250	495.000	490.000
0.488	0.000	0.000	0.000	0.000	0.000	0.000
0.977	-0.000	0.330	0.658	0.985	1.311	2.600
1.465	0.000	0.000	0.000	0.000	0.000	0.000
1.953	-0.000	0.223	0.446	0.669	0.890	1.773
2.441	0.000	0.000	0.000	0.000	0.000	0.000
2.930	-0.000	0.151	0.302	0.454	0.605	1.209
3.418	0.000	0.000	0.000	0.000	0.000	0.000
3.906	-0.000	0.102	0.205	0.308	0.411	0.825
4.395	0.000	0.000	0.000	0.000	0.000	0.000
4.883	0.000	0.069	0.139	0.209	0.279	0.562
5.371	0.000	0.000	0.000	0.000	0.000	0.000
5.859	-0.000	0.047	0.094	0.142	0.190	0.384
6.348	0.000	0.000	0.000	0.000	0.000	0.000
6.836	-0.000	0.032	0.064	0.096	0.129	0.262
7.324	0.000	0.000	0.000	0.000	0.000	0.000
7.813	0.000	0.022	0.043	0.065	0.087	0.178
8.301	0.000	0.000	0.000	0.000	0.000	0.000
8.789	-0.000	0.015	0.029	0.044	0.059	0.122
9.277	0.000	0.000	0.000	0.000	0.000	0.000
9.766	-0.000	0.010	0.020	0.030	0.040	0.083
10.254	0.000	0.000	0.000	0.000	0.000	0.000
10.742	-0.000	0.007	0.013	0.020	0.027	0.057
11.230	0.000	0.000	0.000	0.000	0.000	0.000
11.719	0.000	0.005	0.009	0.014	0.019	0.039
12.207	0.000	0.000	0.000	0.000	0.000	0.000
12.695	-0.000	0.003	0.006	0.009	0.013	0.026
13.184	0.000	0.000	0.000	0.000	0.000	0.000
13.672	0.000	0.002	0.004	0.006	0.009	0.018
14.160	0.000	0.000	0.000	0.000	0.000	0.000
14.648	-0.000	0.001	0.003	0.004	0.006	0.012
15.137	0.000	0.000	0.000	0.000	0.000	0.000
15.625	-0.000	0.001	0.002	0.003	0.004	0.008
16.113	0.000	0.000	0.000	0.000	0.000	0.000
16.602	-0.000	0.001	0.001	0.002	0.003	0.006
17.090	0.000	0.000	0.000	0.000	0.000	0.000
17.578	-0.000	0.000	0.001	0.001	0.002	0.004
18.066	0.000	0.000	0.000	0.000	0.000	0.000
18.555	-0.000	0.000	0.001	0.001	0.001	0.003

TABLE I

INVERSE FILTER (2ND ORDER) BEHAVIOR, WHERE INPUT SIGNAL = EXPONENTIAL ONLY: AT 0%, B = -400(1/SEC), A=0.5V IN A*EXP(-BT) (continued)

time msec	0% mV	.25% mV	.5% mV	.75% mV	1% mV	2% mV
19.043	0.000	0.000	0.000	0.000	0.000	0.000
19.531	-0.000	0.000	0.000	0.001	0.001	0.002
20.020	0.000	0.000	0.000	0.000	0.000	0.000
20.508	-0.000	0.000	0.000	0.000	0.001	0.001
20.996	0.000	0.000	0.000	0.000	0.000	0.000
21.484	-0.000	0.000	0.000	0.000	0.000	0.001
21.973	0.000	0.000	0.000	0.000	0.000	0.000
22.461	-0.000	0.000	0.000	0.000	0.000	0.001
22.949	0.000	0.000	0.000	0.000	0.000	0.000

TABLE I

INVERSE FILTER (2ND ORDER) BEHAVIOR, WHERE INPUT SIGNAL = EXPONENTIAL ONLY: AT 0%, B = -400(1/SEC), A=0.5V IN A*EXP(-BT) (continued)

time msec	3% mV	4% mV	5% mV	6% mV	7% mV	8% mV
0.000	485.000	480.000	475.000	470.000	465.000	460.000
0.488	0.000	0.000	0.000	0.000	0.000	0.000
0.977	3.868	5.115	6.339	7.542	8.722	9.880
1.465	0.000	0.000	0.000	0.000	0.000	0.000
1.953	2.648	3.515	4.374	5.224	6.065	6.897
2.441	0.000	0.000	0.000	0.000	0.000	0.000
2.930	1.813	2.416	3.018	3.618	4.218	4.815
3.418	0.000	0.000	0.000	0.000	0.000	0.000
3.906	1.241	1.660	2.082	2.506	2.933	3.362
4.395	0.000	0.000	0.000	0.000	0.000	0.000
4.883	0.850	1.141	1.437	1.736	2.040	2.347
5.371	0.000	0.000	0.000	0.000	0.000	0.000
5.859	0.582	0.784	0.991	1.203	1.418	1.638
6.348	0.000	0.000	0.000	0.000	0.000	0.000
6.836	0.398	0.539	0.684	0.833	0.986	1.144
7.324	0.000	0.000	0.000	0.000	0.000	0.000
7.813	0.273	0.371	0.472	0.577	0.686	0.798
8.301	0.000	0.000	0.000	0.000	0.000	0.000
8.789	0.187	0.255	0.326	0.400	0.477	0.557
9.277	0.000	0.000	0.000	0.000	0.000	0.000
9.766	0.128	0.175	0.225	0.277	0.332	0.389
10.254	0.000	0.000	0.000	0.000	0.000	0.000
10.742	0.087	0.120	0.155	0.192	0.231	0.272
11.230	0.000	0.000	0.000	0.000	0.000	0.000
11.719	0.060	0.083	0.107	0.133	0.160	0.190
12.207	0.000	0.000	0.000	0.000	0.000	0.000
12.695	0.041	0.057	0.074	0.092	0.112	0.132
13.184	0.000	0.000	0.000	0.000	0.000	0.000
13.672	0.028	0.039	0.051	0.064	0.078	0.092
14.160	0.000	0.000	0.000	0.000	0.000	0.000
14.648	0.019	0.027	0.035	0.044	0.054	0.065
15.137	0.000	0.000	0.000	0.000	0.000	0.000
15.625	0.013	0.018	0.024	0.031	0.038	0.045
16.113	0.000	0.000	0.000	0.000	0.000	0.000
16.602	0.009	0.013	0.017	0.021	0.026	0.031
17.090	0.000	0.000	0.000	0.000	0.000	0.000
17.578	0.006	0.009	0.012	0.015	0.018	0.022
18.066	0.000	0.000	0.000	0.000	0.000	0.000

TABLE I

INVERSE FILTER (2ND ORDER) BEHAVIOR, WHERE INPUT SIGNAL = EXPONENTIAL ONLY: AT 0%, B = -400(1/SEC), A=0.5V IN A*EXP(-BT) (continued)

time msec	3% mV	4% mV	5% mV	6% mV	7% mV	8% mV
18.555	0.004	0.006	0.008	0.010	0.013	0.015
19.043	0.000	0.000	0.000	0.000	0.000	0.000
19.531	0.003	0.004	0.005	0.007	0.009	0.011
20.020	0.000	0.000	0.000	0.000	0.000	0.000
20.508	0.002	0.003	0.004	0.005	0.006	0.007
20.996	0.000	0.000	0.000	0.000	0.000	0.000
21.484	0.001	0.002	0.003	0.003	0.004	0.005
21.973	0.000	0.000	0.000	0.000	0.000	0.000
22.461	0.001	0.001	0.002	0.002	0.003	0.004
22.949	0.000	0.000	0.000	0.000	0.000	0.000
23.438	0.001	0.001	0.001	0.002	0.002	0.003
23.926	0.000	0.000	0.000	0.000	0.000	0.000
24.414	0.000	0.001	0.001	0.001	0.001	0.002
24.902	0.000	0.000	0.000	0.000	0.000	0.000
25.391	0.000	0.000	0.001	0.001	0.001	0.001
25.879	0.000	0.000	0.000	0.000	0.000	0.000
26.367	0.000	0.000	0.000	0.001	0.001	0.001
26.855	0.000	0.000	0.000	0.000	0.000	0.000

TABLE I

INVERSE FILTER (2ND ORDER) BEHAVIOR, WHERE INPUT SIGNAL = EXPONENTIAL ONLY: AT 0%, B = -400(1/SEC), A=0.5V IN A*EXP(-BT) (continued)

time msec	9% mV	10% mV	11% mV	12% mV	13% mV	14% mV	15% mV
0.00	455.0	450.0	445.0	440.0	435.0	430.0	425.0
0.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.98	11.02	12.13	13.22	14.29	15.33	16.36	17.35
1.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.95	7.72	8.53	9.34	10.13	10.92	11.69	12.45
2.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.93	5.41	6.00	6.60	7.18	7.77	8.35	8.93
3.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.91	3.79	4.23	4.60	5.09	5.53	5.97	6.41
4.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.88	2.66	2.97	3.30	3.61	3.94	4.27	4.60
5.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.86	1.86	2.10	2.32	2.56	2.80	3.05	3.30
6.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.84	1.31	1.47	1.64	1.82	2.00	2.18	2.37
7.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7.81	0.92	1.04	1.16	1.29	1.42	1.56	1.70
8.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8.79	0.64	0.73	0.82	0.91	1.01	1.11	1.22
9.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.77	0.45	0.51	0.58	0.65	0.72	0.80	0.87
10.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10.74	0.32	0.36	0.41	0.46	0.51	0.57	0.63
11.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11.72	0.22	0.25	0.29	0.33	0.37	0.40	0.45
12.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12.70	0.16	0.18	0.20	0.23	0.26	0.30	0.32
13.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13.67	0.11	0.13	0.14	0.16	0.16	0.20	0.23
14.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.65	0.08	0.09	0.10	0.12	0.13	0.15	0.17
15.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15.62	0.05	0.06	0.07	0.08	0.09	0.11	0.12
16.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16.60	0.04	0.04	0.05	0.06	0.07	0.08	0.09
17.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17.58	0.03	0.03	0.04	0.04	0.05	0.06	0.06

TABLE I

INVERSE FILTER (2ND ORDER) BEHAVIOR, WHERE INPUT SIGNAL = EXPONENTIAL ONLY: AT 0%, B = -400(1/SEC), A=0.5V IN A*EXP(-BT) (continued)

time msec	9% mV	10% mV	11% mV	12% mV	13% mV	14% mV	15% mV
18.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18.56	0.02	0.02	0.03	0.03	0.03	0.04	0.04
19.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19.53	0.01	0.02	0.02	0.02	0.02	0.03	0.03
20.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20.51	0.01	0.01	0.01	0.02	0.02	0.02	0.02
21.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21.97	0.01	0.01	0.01	0.01	0.01	0.01	0.02
22.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22.95	0.00	0.01	0.01	0.01	0.01	0.01	0.01
23.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23.93	0.00	0.00	0.00	0.01	0.01	0.01	0.01
24.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24.90	0.00	0.00	0.00	0.00	0.00	0.01	0.01
25.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TABLE II

INVERSE FILTER BEHAVIOR (2ND ORDER) RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE

time msec	0% mV	.25% mV	.50% mV	.75% mV	1% mV	2% mV
0.000	500.000	498.750	497.500	496.250	495.00	490.00
0.488	0.015	0.015	0.015	0.015	0.015	0.015
0.977	0.059	0.388	0.717	1.044	1.370	2.659
1.465	0.122	0.122	0.122	0.122	0.122	0.122
1.953	0.194	0.417	0.640	0.862	1.084	1.967
2.441	0.274	0.274	0.274	0.274	0.274	0.274
2.930	0.362	0.513	0.665	0.816	0.967	1.571
3.418	0.458	0.458	0.458	0.458	0.458	0.458
3.906	0.560	0.663	0.765	0.868	0.971	1.385
4.395	0.669	0.669	0.669	0.669	0.669	0.669
4.883	0.783	0.852	0.922	0.992	1.062	1.345
5.371	0.902	0.902	0.902	0.902	0.902	0.902
5.859	1.025	1.072	1.119	1.167	1.215	1.409
6.348	1.152	1.152	1.152	1.152	1.152	1.152
6.836	1.281	1.313	1.345	1.378	1.410	1.543
7.324	1.413	1.413	1.413	1.413	1.413	1.413
7.813	1.545	1.567	1.589	1.611	1.633	1.724
8.301	1.679	1.679	1.679	1.679	1.679	1.679
8.789	1.811	1.826	1.841	1.856	1.871	1.933
9.277	1.943	1.943	1.943	1.943	1.943	1.943
9.766	2.072	2.082	2.092	2.103	2.113	2.155
10.254	2.199	2.199	2.199	2.199	2.199	2.199
10.742	2.323	2.330	2.336	2.343	2.350	2.380
11.230	2.442	2.442	2.442	2.442	2.442	2.442
11.719	2.557	2.561	2.566	2.571	2.575	2.595
12.207	2.666	2.666	2.666	2.666	2.666	2.666
12.695	2.769	2.772	2.775	2.778	2.781	2.795
13.184	2.865	2.865	2.865	2.865	2.865	2.865
13.672	2.954	2.956	2.958	2.960	2.962	2.971
14.160	3.034	3.034	3.034	3.034	3.034	3.034
14.648	3.107	3.108	3.110	3.111	3.113	3.119
15.137	3.171	3.171	3.171	3.171	3.171	3.171
15.625	3.225	3.226	3.227	3.228	3.229	3.234
16.113	3.270	3.270	3.270	3.270	3.270	3.270
16.602	3.306	3.307	3.307	3.308	3.309	3.312
17.090	3.331	3.331	3.331	3.331	3.331	3.331
17.578	3.347	3.347	3.348	3.348	3.349	3.351
18.066	3.352	3.352	3.352	3.352	3.352	3.352
18.555	3.347	3.348	3.348	3.348	3.348	3.350

TABLE II

INVERSE FILTER BEHAVIOR (2ND ORDER) RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	0% mV	.25% mV	.50% mV	.75% mV	1% mV	2% mV
19.043	3.332	3.332	3.332	3.332	3.332	3.332
19.531	3.307	3.307	3.307	3.308	3.308	3.309
20.020	3.272	3.272	3.272	3.272	3.272	3.272
20.508	3.227	3.227	3.227	3.227	3.228	3.228
20.996	3.173	3.173	3.173	3.173	3.173	3.173
21.484	3.109	3.109	3.109	3.109	3.110	3.110
21.973	3.037	3.037	3.037	3.037	3.037	3.037
22.461	2.956	2.956	2.956	2.956	2.957	2.957
22.949	2.868	2.868	2.868	2.868	2.868	2.868
23.438	2.772	2.772	2.772	2.772	2.772	2.772
23.926	2.669	2.669	2.669	2.669	2.669	2.669
24.414	2.561	2.561	2.561	2.561	2.561	2.561
24.902	2.446	2.446	2.446	2.446	2.446	2.446
25.391	2.327	2.327	2.327	2.327	2.327	2.327
25.879	2.203	2.203	2.203	2.203	2.203	2.203
26.367	2.077	2.077	2.077	2.077	2.077	2.077
26.855	1.947	1.947	1.947	1.947	1.947	1.947
27.344	1.816	1.816	1.816	1.816	1.816	1.816
27.832	1.683	1.683	1.683	1.683	1.683	1.683
28.320	1.550	1.550	1.550	1.550	1.550	1.550
28.809	1.417	1.417	1.417	1.417	1.417	1.417
29.297	1.286	1.286	1.286	1.286	1.286	1.286
29.785	1.156	1.156	1.156	1.156	1.156	1.156
30.273	1.029	1.029	1.029	1.029	1.029	1.029
30.762	0.906	0.906	0.906	0.906	0.906	0.906
31.250	0.787	0.787	0.787	0.787	0.787	0.787
31.738	0.672	0.672	0.672	0.672	0.672	0.672
32.227	0.564	0.564	0.564	0.564	0.564	0.564
32.715	0.461	0.461	0.461	0.461	0.461	0.461
33.203	0.365	0.365	0.365	0.365	0.365	0.365
33.691	0.277	0.277	0.277	0.277	0.277	0.277
34.180	0.196	0.196	0.196	0.196	0.196	0.196
34.668	0.124	0.124	0.124	0.124	0.124	0.124
35.156	0.061	0.061	0.061	0.061	0.061	0.061
35.645	0.006	0.006	0.006	0.006	0.006	0.006
36.133	-0.038	-0.038	-0.038	-0.038	-0.038	-0.038
36.621	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073
37.109	-0.099	-0.099	-0.099	-0.099	-0.099	-0.099

TABLE II

INVERSE FILTER BEHAVIOR (2ND ORDER) RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	0% mV	.25% mV	.50% mV	.75% mV	1% mV	2% mV
37.598	-0.114	-0.114	-0.114	-0.114	-0.114	-0.114
38.086	-0.119	-0.119	-0.119	-0.119	-0.119	-0.119
38.574	-0.113	-0.113	-0.113	-0.113	-0.113	-0.113
39.063	-0.098	-0.098	-0.098	-0.098	-0.098	-0.098
39.551	-0.072	-0.072	-0.072	-0.072	-0.072	-0.072
40.039	-0.037	-0.037	-0.037	-0.037	-0.037	-0.037
40.527	-0.008	-0.008	-0.008	-0.008	-0.008	-0.008
41.016	-0.000	0.000	0.000	0.000	0.000	0.000
41.504	0.000	0.000	0.000	0.000	0.000	0.000
41.992	-0.000	0.000	0.000	0.000	0.000	0.000
42.480	0.000	0.000	0.000	0.000	0.000	0.000
42.969	-0.000	0.000	0.000	0.000	0.000	0.000
43.457	0.000	0.000	0.000	0.000	0.000	0.000
43.945	-0.000	0.000	0.000	0.000	0.000	0.000
44.434	0.000	0.000	0.000	0.000	0.000	0.000
44.922	-0.000	0.000	0.000	0.000	0.000	0.000
45.410	0.000	0.000	0.000	0.000	0.000	0.000
45.898	-0.000	0.000	0.000	0.000	0.000	0.000
46.387	0.000	0.000	0.000	0.000	0.000	0.000
46.875	-0.000	0.000	0.000	0.000	0.000	0.000
47.363	0.000	0.000	0.000	0.000	0.000	0.000
47.852	-0.000	0.000	0.000	0.000	0.000	0.000
48.340	0.000	0.000	0.000	0.000	0.000	0.000
48.828	-0.000	0.000	0.000	0.000	0.000	0.000
49.316	0.000	0.000	0.000	0.000	0.000	0.000
49.805	-0.000	0.000	0.000	0.000	0.000	0.000
50.293	0.000	0.000	0.000	0.000	0.000	0.000
50.781	-0.000	0.000	0.000	0.000	0.000	0.000

TABLE II

INVERSE FILTER BEHAVIOR (2ND ORDER) RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	3% mV	4% mV	5% mV	6% mV	7% mV	8% mV
0.000	485.000	480.000	475.000	470.000	465.000	460.000
0.488	0.015	0.015	0.015	0.015	0.015	0.015
0.977	3.927	5.173	6.398	7.600	8.781	9.939
1.465	0.122	0.122	0.122	0.122	0.122	0.122
1.953	2.842	3.709	4.568	5.418	6.259	7.091
2.441	0.274	0.274	0.274	0.274	0.274	0.274
2.930	2.175	2.778	3.380	3.981	4.580	5.177
3.418	0.458	0.458	0.458	0.458	0.458	0.458
3.906	1.801	2.221	2.642	3.067	3.493	3.922
4.395	0.669	0.669	0.669	0.669	0.669	0.669
4.883	1.633	1.924	2.220	2.519	2.822	3.130
5.371	0.902	0.902	0.902	0.902	0.902	0.902
5.859	1.607	1.810	2.016	2.228	2.443	2.663
6.348	1.152	1.152	1.152	1.152	1.152	1.152
6.836	1.680	1.820	1.965	2.114	2.268	2.425
7.324	1.413	1.413	1.413	1.413	1.413	1.413
7.813	1.818	1.916	2.017	2.122	2.231	2.344
8.301	1.679	1.679	1.679	1.679	1.679	1.679
8.789	1.998	2.066	2.137	2.211	2.288	2.369
9.277	1.943	1.943	1.943	1.943	1.943	1.943
9.766	2.200	2.247	2.297	2.349	2.404	2.462
10.254	2.199	2.199	2.199	2.199	2.199	2.199
10.742	2.410	2.443	2.478	2.515	2.554	2.595
11.230	2.442	2.442	2.442	2.442	2.442	2.442
11.719	2.617	2.640	2.664	2.690	2.717	2.747
12.207	2.666	2.666	2.666	2.666	2.666	2.666
12.695	2.810	2.826	2.843	2.861	2.880	2.901
13.184	2.865	2.865	2.865	2.865	2.865	2.865
13.672	2.982	2.993	3.004	3.017	3.031	3.046
14.160	3.034	3.034	3.034	3.034	3.034	3.034
14.648	3.126	3.134	3.142	3.151	3.161	3.171
15.137	3.171	3.171	3.171	3.171	3.171	3.171
15.625	3.238	3.244	3.250	3.256	3.263	3.270
16.113	3.270	3.270	3.270	3.270	3.270	3.270
16.602	3.315	3.319	3.323	3.327	3.332	3.337
17.090	3.331	3.331	3.331	3.331	3.331	3.331
17.578	3.353	3.356	3.358	3.362	3.365	3.369
18.066	3.352	3.352	3.352	3.352	3.352	3.352

TABLE II

INVERSE FILTER BEHAVIOR (2ND ORDER) RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	3% mV	4% mV	5% mV	6% mV	7% mV	8% mV
18.555	3.351	3.353	3.355	3.357	3.360	3.363
19.043	3.332	3.332	3.332	3.332	3.332	3.332
19.531	3.310	3.311	3.312	3.314	3.316	3.318
20.020	3.272	3.272	3.272	3.272	3.272	3.272
20.508	3.229	3.230	3.231	3.232	3.233	3.234
20.996	3.173	3.173	3.173	3.173	3.173	3.173
21.484	3.110	3.111	3.112	3.112	3.113	3.114
21.973	3.037	3.037	3.037	3.037	3.037	3.037
22.461	2.957	2.958	2.958	2.959	2.959	2.960
22.949	2.868	2.868	2.868	2.868	2.868	2.868
23.438	2.773	2.773	2.773	2.774	2.774	2.774
23.926	2.669	2.669	2.669	2.669	2.669	2.669
24.414	2.561	2.561	2.561	2.562	2.562	2.562
24.902	2.446	2.446	2.446	2.446	2.446	2.446
25.391	2.327	2.327	2.327	2.328	2.328	2.328
25.879	2.203	2.203	2.203	2.203	2.203	2.203
26.367	2.077	2.077	2.077	2.077	2.077	2.077
26.855	1.947	1.947	1.947	1.947	1.947	1.947
27.344	1.816	1.816	1.816	1.816	1.816	1.816
27.832	1.683	1.683	1.683	1.683	1.683	1.683
28.320	1.550	1.550	1.550	1.550	1.550	1.550
28.809	1.417	1.417	1.417	1.417	1.417	1.417
29.297	1.286	1.286	1.286	1.286	1.286	1.286
29.785	1.156	1.156	1.156	1.156	1.156	1.156
30.273	1.029	1.029	1.029	1.029	1.029	1.029
30.762	0.906	0.906	0.906	0.906	0.906	0.906
31.250	0.787	0.787	0.787	0.787	0.787	0.787
31.738	0.672	0.672	0.672	0.672	0.672	0.672
32.227	0.564	0.564	0.564	0.564	0.564	0.564
32.715	0.461	0.461	0.461	0.461	0.461	0.461
33.203	0.365	0.365	0.365	0.365	0.365	0.365
33.691	0.277	0.277	0.277	0.277	0.277	0.277
34.180	0.196	0.196	0.196	0.196	0.196	0.196
34.668	0.124	0.124	0.124	0.124	0.124	0.124
35.156	0.061	0.061	0.061	0.061	0.061	0.061
35.645	0.006	0.006	0.006	0.006	0.006	0.006
36.133	-0.038	-0.038	-0.038	-0.038	-0.038	-0.038
36.621	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073

TABLE II

INVERSE FILTER BEHAVIOR (2ND ORDER) RESULTING FROM CHANGING a and b IN a*exp(-bt). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	3% mV	4% mV	5% mV	6% mV	7% mV	8% mV
37.109	-0.099	-0.099	-0.099	-0.099	-0.099	-0.099
37.598	-0.114	-0.114	-0.114	-0.114	-0.114	-0.114
38.086	-0.119	-0.119	-0.119	-0.119	-0.118	-0.118
38.574	-0.113	-0.113	-0.113	-0.113	-0.113	-0.113
39.063	-0.098	-0.098	-0.098	-0.098	-0.098	-0.098
39.551	-0.072	-0.072	-0.072	-0.072	-0.072	-0.072
40.039	-0.037	-0.037	-0.037	-0.037	-0.037	-0.037
40.527	-0.008	-0.008	-0.008	-0.008	-0.008	-0.008
41.016	0.000	0.000	0.000	0.000	0.000	0.000

TABLE II

INVERSE FILTER BEHAVIOR (2ND ORDER) RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	9% mV	10% mV	11% mV	12% mV	13% mV	14% mV	15% mV
0.00	455.0	450.0	445.0	440.0	435.0	430.0	425.0
0.49	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.98	11.08	12.19	13.28	14.35	15.39	16.41	17.41
1.47	0.12	0.12	0.12	0.12	0.12	0.12	0.12
1.95	7.91	8.73	9.53	10.33	11.11	11.88	12.64
2.44	0.27	0.27	0.27	0.27	0.27	0.27	0.27
2.93	5.77	6.37	6.96	7.55	8.13	8.72	9.30
3.42	0.46	0.46	0.46	0.46	0.46	0.46	0.46
3.91	4.35	4.76	5.22	5.66	6.09	6.53	6.97
4.40	0.67	0.67	0.67	0.67	0.67	0.67	0.67
4.88	3.44	3.76	4.07	4.40	4.72	5.05	5.38
5.37	0.90	0.90	0.90	0.90	0.90	0.90	0.90
5.86	2.89	3.12	3.35	3.59	3.83	4.07	4.32
6.35	1.15	1.15	1.15	1.15	1.15	1.15	1.15
6.84	2.59	2.75	2.92	3.10	3.28	3.46	3.65
7.32	1.41	1.41	1.41	1.41	1.41	1.41	1.41
7.81	2.46	2.58	2.71	2.83	2.97	3.10	3.24
8.30	1.68	1.68	1.68	1.68	1.68	3.68	1.68
8.79	2.45	2.54	2.63	2.73	2.82	2.92	3.03
9.28	1.94	1.94	1.94	1.94	1.94	1.94	1.94
9.77	2.52	2.59	2.65	2.72	2.79	2.87	2.95
10.25	2.20	2.20	2.20	2.20	2.20	2.20	2.20
10.74	2.64	2.68	2.73	2.78	2.84	2.89	2.95
11.23	2.44	2.44	2.44	2.44	2.44	2.44	2.44
11.72	2.78	2.81	2.84	2.88	2.92	2.96	3.01
12.21	2.67	2.67	2.67	2.67	2.67	2.67	2.67
12.70	2.92	2.95	2.97	3.00	3.03	3.06	3.09
13.18	2.87	2.87	2.86	2.87	2.87	2.87	2.87
13.67	3.06	3.08	3.10	3.12	3.14	3.16	3.16
14.16	3.03	3.03	3.03	3.03	3.03	3.03	3.03
14.65	3.18	3.20	3.21	3.22	3.24	3.26	3.27
15.14	3.17	3.17	3.17	3.17	3.17	3.17	3.17
15.63	3.28	3.29	3.30	3.31	3.32	3.33	3.35
16.11	3.27	3.27	3.27	3.27	3.27	3.27	3.27
16.60	3.34	3.35	3.36	3.36	3.37	3.38	3.39
17.09	3.33	3.33	3.33	3.33	3.33	3.33	3.33
17.58	3.37	3.38	3.38	3.39	3.39	3.40	3.41
18.07	3.35	3.35	3.35	3.35	3.35	3.35	3.35

TABLE II

INVERSE FILTER BEHAVIOR (2ND ORDER) RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	9% mV	10% mV	11% mV	12% mV	13% mV	14% mV	15% mV
18.56	3.37	3.37	3.37	3.37	3.38	3.39	3.39
19.04	3.33	3.33	3.33	3.33	3.33	3.33	3.33
19.53	3.32	3.32	3.33	3.33	3.33	3.34	3.34
20.02	3.27	3.27	3.27	3.27	3.27	3.27	3.27
20.51	3.24	3.24	3.24	3.24	3.24	3.25	3.25
21.00	3.17	3.17	3.17	3.17	3.17	3.17	3.17
21.48	3.11	3.12	3.12	3.12	3.12	3.12	3.13
21.97	3.04	3.04	3.04	3.04	3.04	3.04	3.04
22.46	2.96	2.96	2.96	2.96	2.97	2.97	2.98
22.95	2.87	2.87	2.87	2.87	2.87	2.87	2.87
23.34	2.77	2.78	2.78	2.77	2.77	2.78	2.78
23.93	2.67	2.67	2.67	2.67	2.67	2.67	2.67
24.41	2.56	2.56	2.56	2.56	2.57	2.57	2.57
24.90	2.45	2.44	2.45	2.45	2.45	2.45	2.45
25.39	2.33	2.33	2.33	2.33	2.33	2.33	2.33
25.88	2.20	2.20	2.20	2.20	2.20	2.20	2.20
26.37	2.08	2.08	2.08	2.08	2.08	2.08	2.08
26.86	1.95	1.95	1.95	1.95	1.95	1.95	1.95
27.34	1.82	1.81	1.82	1.82	1.82	1.82	1.82
27.83	1.68	1.68	1.68	1.68	1.68	1.68	1.68
28.32	1.55	1.55	1.55	1.55	1.55	1.55	1.55
28.91	1.42	1.42	1.42	1.42	1.42	1.42	1.42
29.30	1.27	1.29	1.29	1.27	1.27	1.29	1.29
29.78	1.15	1.17	1.17	1.16	1.16	1.17	1.17
30.27	1.03	1.03	1.03	1.03	1.03	1.03	1.03
30.76	0.91	0.91	0.91	0.91	0.91	0.91	0.91
31.25	0.78	0.79	0.79	0.79	0.79	0.79	0.79
31.74	0.67	0.67	0.67	0.67	0.67	0.67	0.67
32.23	0.56	0.56	0.56	0.56	0.56	0.56	0.56
32.72	0.46	0.46	0.46	0.46	0.46	0.46	0.46
33.20	0.37	0.37	0.36	0.36	0.37	0.37	0.37
33.69	0.28	0.28	0.28	0.27	0.28	0.28	0.28
34.18	0.20	0.20	0.20	0.20	0.20	0.20	0.20
34.67	0.12	0.12	0.12	0.12	0.12	0.12	0.12
35.17	0.06	0.06	0.06	0.06	0.06	0.06	0.06
35.65	0.01	0.01	0.01	0.01	0.01	0.01	0.01
36.13	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04
36.62	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07

TABLE II

INVERSE FILTER BEHAVIOR (2ND ORDER) RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	9% mV	10% mV	11% mV	12% mV	13% mV	14% mV	15% mV
37.12	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10
37.60	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11
38.09	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12
38.57	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11
39.06	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10
39.55	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07
40.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04
40.53	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
41.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
41.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TABLE III

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL ONLY

time msec	0% mV	.25% mV	.50% mV	.75% mV	1% mV	2% mV
0.000	500.000	498.750	497.500	496.250	495.000	490.000
0.488	0.000	0.200	0.400	0.598	0.796	1.578
0.977	-0.000	0.165	0.329	0.493	0.656	1.303
1.465	0.000	0.136	0.271	0.406	0.541	1.076
1.953	0.000	0.112	0.223	0.335	0.446	0.888
2.441	0.000	0.092	0.184	0.276	0.367	0.734
2.930	0.000	0.076	0.151	0.227	0.303	0.606
3.418	-0.000	0.062	0.125	0.187	0.250	0.500
3.906	0.000	0.051	0.103	0.154	0.206	0.413
4.395	0.000	0.042	0.084	0.127	0.169	0.341
4.883	0.000	0.035	0.070	0.105	0.140	0.282
5.371	0.000	0.029	0.057	0.086	0.115	0.233
5.859	0.000	0.024	0.047	0.071	0.095	0.192
6.348	0.000	0.019	0.039	0.058	0.078	0.159
6.836	-0.000	0.016	0.032	0.048	0.064	0.131
7.324	0.000	0.013	0.026	0.040	0.053	0.108
7.813	0.000	0.011	0.022	0.033	0.044	0.089
8.301	0.000	0.009	0.018	0.027	0.036	0.074
8.789	-0.000	0.007	0.015	0.022	0.030	0.061
9.277	-0.000	0.006	0.012	0.018	0.025	0.050
9.766	0.000	0.005	0.010	0.015	0.020	0.042
10.254	0.000	0.004	0.008	0.012	0.017	0.034
10.742	-0.000	0.003	0.007	0.010	0.014	0.028
11.230	0.000	0.003	0.006	0.008	0.011	0.023
11.719	0.000	0.002	0.005	0.007	0.009	0.019
12.207	-0.000	0.002	0.004	0.006	0.008	0.016
12.695	-0.000	0.002	0.003	0.005	0.006	0.013
13.184	0.000	0.001	0.003	0.004	0.005	0.011
13.672	0.000	0.001	0.002	0.003	0.004	0.009
14.160	-0.000	0.001	0.002	0.003	0.004	0.007
14.648	0.000	0.001	0.001	0.002	0.003	0.006
15.137	0.000	0.001	0.001	0.002	0.002	0.005
15.625	-0.000	0.000	0.001	0.001	0.002	0.004
16.113	0.000	0.000	0.001	0.001	0.002	0.003
16.602	-0.000	0.000	0.001	0.001	0.001	0.003
17.090	-0.000	0.000	0.001	0.001	0.001	0.002
17.578	0.000	0.000	0.000	0.001	0.001	0.002
18.066	0.000	0.000	0.000	0.001	0.001	0.002
18.555	-0.000	0.000	0.000	0.000	0.001	0.001

TABLE III

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL ONLY (continued)

time msec	0% mV	.25% mV	.50% mV	.75% mV	1% mV	2% mV
19.043	0.000	0.000	0.000	0.000	0.001	0.001
19.531	0.000	0.000	0.000	0.000	0.000	0.001
20.020	-0.000	0.000	0.000	0.000	0.000	0.001
20.508	0.000	0.000	0.000	0.000	0.000	0.001
20.996	0.000	0.000	0.000	0.000	0.000	0.001
21.484	-0.000	0.000	0.000	0.000	0.000	0.000
21.973	0.000	0.000	0.000	0.000	0.000	0.000

TABLE III

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL ONLY (continued)

time msec	3% mV	4% mV	5% mV	6% mV	7% mV	8% mV
0.000	485.000	480.000	475.000	470.000	465.000	460.000
0.488	2.344	3.097	3.834	4.557	5.265	5.959
0.977	1.940	2.567	3.185	3.793	4.391	4.979
1.465	1.605	2.128	2.646	3.157	3.662	4.160
1.953	1.328	1.764	2.198	2.627	3.053	3.476
2.441	1.099	1.463	1.825	2.187	2.546	2.904
2.930	0.909	1.213	1.516	1.820	2.123	2.426
3.418	0.752	1.005	1.260	1.515	1.771	2.027
3.906	0.622	0.833	1.046	1.261	1.476	1.694
4.395	0.515	0.691	0.869	1.049	1.231	1.415
4.883	0.426	0.573	0.722	0.873	1.027	1.183
5.371	0.353	0.475	0.600	0.727	0.856	0.988
5.859	0.292	0.394	0.498	0.605	0.714	0.826
6.348	0.241	0.326	0.414	0.503	0.595	0.690
6.836	0.200	0.271	0.344	0.419	0.496	0.576
7.324	0.165	0.224	0.285	0.349	0.414	0.482
7.813	0.137	0.186	0.237	0.290	0.345	0.402
8.301	0.113	0.154	0.197	0.242	0.288	0.336
8.789	0.094	0.128	0.164	0.201	0.240	0.281
9.277	0.077	0.106	0.136	0.167	0.200	0.235
9.766	0.064	0.088	0.113	0.139	0.167	0.196
10.254	0.053	0.073	0.094	0.116	0.139	0.164
10.742	0.044	0.060	0.078	0.096	0.116	0.137
11.230	0.036	0.050	0.065	0.080	0.097	0.114
11.719	0.030	0.041	0.054	0.067	0.081	0.096
12.207	0.025	0.034	0.045	0.056	0.067	0.080
12.695	0.021	0.029	0.037	0.046	0.056	0.067
13.184	0.017	0.024	0.031	0.039	0.047	0.056
13.672	0.014	0.020	0.026	0.032	0.039	0.047
14.160	0.012	0.016	0.021	0.027	0.033	0.039
14.648	0.010	0.013	0.018	0.022	0.027	0.033
15.137	0.008	0.011	0.015	0.018	0.023	0.027
15.625	0.007	0.009	0.012	0.015	0.019	0.023
16.113	0.005	0.008	0.010	0.013	0.016	0.019
16.602	0.005	0.006	0.008	0.011	0.013	0.016
17.090	0.004	0.005	0.007	0.009	0.011	0.013
17.578	0.003	0.004	0.006	0.007	0.009	0.011
18.066	0.003	0.004	0.005	0.006	0.008	0.009

TABLE III

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL ONLY (continued)

time msec	3% mV	4% mV	5% mV	6% mV	7% mV	8% mV
18.555	0.002	0.003	0.004	0.005	0.006	0.008
19.043	0.002	0.002	0.003	0.004	0.005	0.006
19.531	0.001	0.002	0.003	0.004	0.004	0.005
20.020	0.001	0.002	0.002	0.003	0.004	0.005
20.508	0.001	0.001	0.002	0.002	0.003	0.004
20.996	0.001	0.001	0.002	0.002	0.003	0.003
21.484	0.001	0.001	0.001	0.002	0.002	0.003
21.973	0.001	0.001	0.001	0.001	0.002	0.002
22.461	0.000	0.001	0.001	0.001	0.001	0.002
22.949	0.000	0.001	0.001	0.001	0.001	0.002
23.438	0.000	0.000	0.001	0.001	0.001	0.001
23.926	0.000	0.000	0.001	0.001	0.001	0.001
24.414	0.000	0.000	0.000	0.001	0.001	0.001
24.902	0.000	0.000	0.000	0.000	0.001	0.001
25.391	0.000	0.000	0.000	0.000	0.000	0.001
25.879	0.000	0.000	0.000	0.000	0.000	0.001
26.367	0.000	0.000	0.000	0.000	0.000	0.000

TABLE III

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL ONLY (continued)

time msec	9% mV	10% mV	11% mV	12% mV	13% mV	14% mV	15% mV
0.00	455.0	450.0	445.0	440.0	435.0	430.0	425.0
0.49	6.64	7.30	7.95	8.58	9.20	9.81	10.39
0.98	5.56	6.12	6.68	7.23	7.76	8.29	8.80
1.46	4.65	5.14	5.62	6.09	6.55	7.01	7.46
1.95	3.89	4.31	4.72	5.13	5.53	5.92	6.32
2.44	3.26	3.61	3.97	4.32	4.66	5.01	5.35
2.93	2.73	3.03	3.33	3.63	3.93	4.23	4.53
3.42	2.28	2.54	2.80	3.06	3.32	3.58	3.84
3.91	1.91	2.13	2.35	2.58	2.80	3.03	3.25
4.40	1.60	1.79	1.98	2.17	2.36	2.56	2.75
4.88	1.34	1.50	1.66	1.83	1.99	2.16	2.33
5.37	1.12	1.26	1.40	1.54	1.68	1.83	1.98
5.86	0.94	1.07	1.18	1.30	1.42	1.55	1.67
6.35	0.79	0.87	0.98	1.09	1.20	1.31	1.42
6.84	0.66	0.74	0.83	0.92	1.01	1.10	1.20
7.32	0.55	0.62	0.69	0.77	0.85	0.93	1.02
7.81	0.46	0.52	0.59	0.65	0.72	0.79	0.86
8.30	0.39	0.44	0.49	0.55	0.61	0.67	0.73
8.79	0.32	0.37	0.41	0.46	0.51	0.56	0.62
9.28	0.27	0.31	0.35	0.39	0.43	0.48	0.52
9.77	0.23	0.26	0.29	0.33	0.37	0.40	0.44
10.25	0.19	0.22	0.25	0.28	0.31	0.34	0.38
10.74	0.16	0.18	0.21	0.23	0.26	0.28	0.32
11.23	0.13	0.15	0.17	0.20	0.22	0.24	0.27
11.72	0.11	0.13	0.15	0.17	0.19	0.20	0.23
12.21	0.09	0.11	0.12	0.14	0.16	0.17	0.19
12.70	0.08	0.09	0.10	0.12	0.13	0.15	0.16
13.18	0.07	0.08	0.09	0.10	0.11	0.12	0.14
13.67	0.06	0.06	0.07	0.08	0.09	0.11	0.12
14.16	0.05	0.05	0.06	0.07	0.08	0.09	0.10
14.65	0.04	0.05	0.05	0.06	0.07	0.07	0.08
15.14	0.03	0.04	0.04	0.05	0.06	0.06	0.07
15.62	0.03	0.03	0.04	0.04	0.05	0.05	0.06
16.11	0.02	0.03	0.03	0.04	0.04	0.05	0.05
16.60	0.02	0.02	0.03	0.03	0.03	0.04	0.04
17.09	0.02	0.02	0.02	0.03	0.03	0.03	0.03
17.58	0.01	0.02	0.02	0.02	0.02	0.03	0.03
18.07	0.01	0.01	0.02	0.02	0.02	0.02	0.03

TABLE III

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL ONLY (continued)

time msec	9% mV	10% mV	11% mV	12% mV	13% mV	14% mV	15% mV
18.56	0.01	0.01	0.01	0.02	0.02	0.02	0.02
19.04	0.01	0.01	0.01	0.01	0.01	0.02	0.02
19.53	0.01	0.01	0.01	0.01	0.01	0.01	0.02
20.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
20.51	0.01	0.01	0.01	0.01	0.01	0.01	0.01
21.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01
21.48	0.00	0.00	0.01	0.01	0.01	0.01	0.01
21.97	0.00	0.00	0.00	0.00	0.01	0.01	0.01
22.46	0.00	0.00	0.00	0.00	0.00	0.01	0.01
22.95	0.00	0.00	0.00	0.00	0.00	0.00	0.01
23.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TABLE IV

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE

time msec	0% mV	.25% mV	.50% mV	.75% mV	1% mV	2% mV
0.000	500.000	498.750	497.500	496.250	495.000	490.000
0.488	0.015	0.215	0.415	0.613	0.811	1.592
0.977	0.047	0.212	0.376	0.540	0.703	1.349
1.465	0.083	0.219	0.355	0.490	0.624	1.159
1.953	0.125	0.237	0.348	0.460	0.571	1.013
2.441	0.171	0.263	0.355	0.447	0.538	0.905
2.930	0.221	0.297	0.373	0.448	0.524	0.827
3.418	0.276	0.338	0.400	0.463	0.525	0.776
3.906	0.333	0.385	0.436	0.487	0.539	0.747
4.395	0.394	0.437	0.479	0.521	0.564	0.736
4.883	0.458	0.493	0.528	0.563	0.598	0.740
5.371	0.525	0.553	0.582	0.611	0.640	0.758
5.859	0.593	0.617	0.641	0.664	0.688	0.786
6.348	0.664	0.683	0.703	0.722	0.742	0.822
6.836	0.735	0.751	0.767	0.784	0.800	0.866
7.324	0.808	0.821	0.834	0.848	0.861	0.916
7.813	0.881	0.892	0.903	0.914	0.925	0.970
8.301	0.954	0.963	0.972	0.981	0.990	1.028
8.789	1.027	1.034	1.041	1.049	1.056	1.087
9.277	1.098	1.104	1.110	1.117	1.123	1.149
9.766	1.169	1.174	1.179	1.184	1.189	1.210
10.254	1.238	1.242	1.246	1.250	1.255	1.272
10.742	1.305	1.308	1.311	1.315	1.318	1.333
11.230	1.369	1.372	1.375	1.378	1.380	1.393
11.719	1.431	1.433	1.435	1.438	1.440	1.450
12.207	1.489	1.491	1.493	1.495	1.497	1.505
12.695	1.544	1.545	1.547	1.549	1.550	1.557
13.184	1.595	1.596	1.597	1.599	1.600	1.606
13.672	1.642	1.643	1.644	1.645	1.646	1.651
14.160	1.684	1.685	1.686	1.687	1.688	1.691
14.648	1.722	1.722	1.723	1.724	1.725	1.728
15.137	1.754	1.755	1.756	1.756	1.757	1.760
15.625	1.782	1.783	1.783	1.784	1.784	1.786
16.113	1.805	1.805	1.805	1.806	1.806	1.808
16.602	1.822	1.822	1.822	1.823	1.823	1.824
17.090	1.833	1.833	1.834	1.834	1.834	1.835
17.578	1.839	1.839	1.839	1.840	1.840	1.841
18.066	1.839	1.840	1.840	1.840	1.840	1.841
18.555	1.834	1.834	1.834	1.835	1.835	1.836

TABLE IV

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	0% mV	.25% mV	.50% mV	.75% mV	1% mV	2% mV
19.043	1.823	1.823	1.824	1.824	1.824	1.824
19.531	1.807	1.807	1.807	1.807	1.807	1.808
20.020	1.785	1.785	1.786	1.786	1.786	1.786
20.508	1.758	1.758	1.758	1.759	1.759	1.759
20.996	1.726	1.726	1.726	1.726	1.726	1.727
21.484	1.689	1.689	1.689	1.689	1.689	1.690
21.973	1.647	1.647	1.647	1.648	1.648	1.648
22.461	1.601	1.601	1.601	1.601	1.601	1.601
22.949	1.551	1.551	1.551	1.551	1.551	1.551
23.438	1.496	1.496	1.496	1.496	1.496	1.497
23.926	1.438	1.438	1.438	1.438	1.439	1.439
24.414	1.377	1.377	1.377	1.377	1.377	1.377
24.902	1.313	1.313	1.313	1.313	1.313	1.313
25.391	1.247	1.247	1.247	1.247	1.247	1.247
25.879	1.178	1.178	1.178	1.178	1.178	1.178
26.367	1.108	1.108	1.108	1.108	1.108	1.108
26.855	1.036	1.036	1.036	1.036	1.036	1.036
27.344	0.963	0.963	0.963	0.963	0.963	0.963
27.832	0.890	0.890	0.890	0.890	0.890	0.890
28.320	0.817	0.817	0.817	0.817	0.817	0.817
28.809	0.745	0.745	0.745	0.745	0.745	0.745
29.297	0.673	0.673	0.673	0.673	0.673	0.673
29.785	0.602	0.602	0.602	0.602	0.602	0.603
30.273	0.534	0.534	0.534	0.534	0.534	0.534
30.762	0.467	0.467	0.467	0.467	0.467	0.467
31.250	0.403	0.403	0.403	0.403	0.403	0.403
31.738	0.341	0.341	0.341	0.341	0.341	0.341
32.227	0.283	0.283	0.283	0.283	0.283	0.283
32.715	0.228	0.228	0.228	0.228	0.228	0.228
33.203	0.177	0.177	0.177	0.177	0.177	0.177
33.691	0.131	0.131	0.131	0.131	0.131	0.131
34.180	0.089	0.089	0.089	0.089	0.089	0.089
34.668	0.051	0.051	0.051	0.051	0.051	0.051
35.156	0.019	0.019	0.019	0.019	0.019	0.019
35.645	-0.009	-0.009	-0.009	-0.009	-0.009	-0.009
36.133	-0.031	-0.031	-0.031	-0.031	-0.031	-0.031
36.621	-0.048	-0.048	-0.048	-0.048	-0.048	-0.048
37.109	-0.059	-0.059	-0.059	-0.059	-0.059	-0.059
37.598	-0.065	-0.065	-0.065	-0.065	-0.065	-0.065

TABLE IV

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	0% mV	.25% mV	.50% mV	.75% mV	1% mV	2% mV
38.086	-0.065	-0.065	-0.065	-0.065	-0.065	-0.065
38.574	-0.060	-0.060	-0.060	-0.060	-0.060	-0.060
39.063	-0.049	-0.049	-0.049	-0.049	-0.049	-0.049
39.551	-0.032	-0.032	-0.032	-0.032	-0.032	-0.032
40.039	-0.010	-0.010	-0.010	-0.010	-0.010	-0.010
40.527	0.000	0.000	0.000	0.000	0.000	0.000
41.016	0.000	0.000	0.000	0.000	0.000	0.000

TABLE IV

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	3% mV	4% mV	5% mV	6% mV	7% mV	8% mV
0.000	485.000	480.000	475.000	470.000	465.000	460.000
0.488	2.359	3.111	3.849	4.572	5.280	5.973
0.977	1.986	2.614	3.232	3.840	4.437	5.025
1.465	1.689	2.212	2.729	3.240	3.745	4.243
1.953	1.453	1.890	2.323	2.752	3.178	3.601
2.441	1.270	1.634	1.997	2.358	2.717	3.075
2.930	1.131	1.434	1.738	2.041	2.345	2.648
3.418	1.028	1.281	1.535	1.790	2.046	2.303
3.906	0.956	1.167	1.380	1.594	1.810	2.027
4.395	0.909	1.085	1.263	1.444	1.626	1.810
4.883	0.885	1.031	1.180	1.332	1.485	1.641
5.371	0.877	1.000	1.124	1.252	1.381	1.513
5.859	0.885	0.987	1.092	1.198	1.307	1.419
6.348	0.905	0.990	1.077	1.167	1.259	1.354
6.836	0.935	1.006	1.079	1.154	1.232	1.312
7.324	0.973	1.032	1.093	1.157	1.222	1.289
7.813	1.018	1.067	1.118	1.171	1.226	1.283
8.301	1.067	1.108	1.151	1.195	1.242	1.290
8.789	1.120	1.154	1.190	1.228	1.267	1.307
9.277	1.176	1.204	1.234	1.266	1.299	1.333
9.766	1.233	1.257	1.282	1.308	1.336	1.365
10.254	1.291	1.311	1.332	1.354	1.377	1.402
10.742	1.349	1.365	1.383	1.401	1.421	1.442
11.230	1.405	1.419	1.434	1.449	1.466	1.483
11.719	1.461	1.472	1.484	1.497	1.511	1.526
12.207	1.514	1.523	1.534	1.545	1.556	1.569
12.695	1.564	1.572	1.581	1.590	1.600	1.611
13.184	1.612	1.618	1.626	1.633	1.642	1.651
13.672	1.656	1.661	1.667	1.674	1.681	1.688
14.160	1.696	1.700	1.705	1.711	1.717	1.723
14.648	1.731	1.735	1.739	1.744	1.749	1.754
15.137	1.762	1.766	1.769	1.773	1.777	1.782
15.625	1.789	1.791	1.794	1.798	1.801	1.805
16.113	1.810	1.812	1.815	1.817	1.820	1.824
16.602	1.826	1.828	1.830	1.832	1.835	1.837
17.090	1.837	1.838	1.840	1.842	1.844	1.846
17.578	1.842	1.843	1.845	1.846	1.848	1.850
18.066	1.842	1.843	1.844	1.846	1.847	1.849

TABLE IV

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGnAL = EXPONENTIAL + HAVERSINE (continued)

time msec	3% mV	4% mV	5% mV	6% mV	7% mV	8% mV
18.555	1.836	1.837	1.838	1.839	1.841	1.842
19.043	1.825	1.826	1.827	1.828	1.829	1.830
19.531	1.809	1.809	1.810	1.811	1.811	1.812
20.020	1.787	1.787	1.788	1.788	1.789	1.790
20.508	1.759	1.760	1.760	1.761	1.761	1.762
20.996	1.727	1.727	1.728	1.728	1.729	1.729
21.484	1.690	1.690	1.690	1.691	1.691	1.692
21.973	1.648	1.648	1.648	1.649	1.649	1.650
22.461	1.602	1.602	1.602	1.602	1.603	1.603
22.949	1.551	1.551	1.551	1.552	1.552	1.552
23.438	1.497	1.497	1.497	1.497	1.497	1.498
23.926	1.439	1.439	1.439	1.439	1.439	1.440
24.414	1.377	1.378	1.378	1.378	1.378	1.378
24.902	1.313	1.313	1.314	1.314	1.314	1.314
25.391	1.247	1.247	1.247	1.247	1.247	1.247
25.879	1.178	1.178	1.178	1.178	1.178	1.179
26.367	1.108	1.108	1.108	1.108	1.108	1.108
26.855	1.036	1.036	1.036	1.036	1.036	1.036
27.344	0.963	0.964	0.964	0.964	0.964	0.964
27.832	0.890	0.890	0.891	0.891	0.891	0.891
28.320	0.817	0.817	0.817	0.818	0.818	0.818
28.809	0.745	0.745	0.745	0.745	0.745	0.745
29.297	0.673	0.673	0.673	0.673	0.673	0.673
29.785	0.603	0.603	0.603	0.603	0.603	0.603
30.273	0.534	0.534	0.534	0.534	0.534	0.534
30.762	0.467	0.467	0.467	0.467	0.467	0.467
31.250	0.403	0.403	0.403	0.403	0.403	0.403
31.738	0.341	0.341	0.341	0.341	0.341	0.341
32.227	0.283	0.283	0.283	0.283	0.283	0.283
32.715	0.228	0.228	0.228	0.228	0.228	0.228
33.203	0.177	0.177	0.177	0.177	0.177	0.177
33.691	0.131	0.131	0.131	0.131	0.131	0.131
34.180	0.089	0.089	0.089	0.089	0.089	0.089
34.668	0.051	0.051	0.051	0.051	0.051	0.051
35.156	0.019	0.019	0.019	0.019	0.019	0.019
35.645	-0.009	-0.009	-0.009	-0.009	-0.009	-0.009
36.133	-0.031	-0.031	-0.031	-0.031	-0.031	-0.031
36.621	-0.048	-0.048	-0.048	-0.048	-0.048	-0.048

TABLE IV

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	3% mV	4% mV	5% mV	6% mV	7% mV	8% mV
37.109	-0.059	-0.059	-0.059	-0.059	-0.059	-0.059
37.598	-0.065	-0.065	-0.065	-0.065	-0.065	-0.065
38.086	-0.065	-0.065	-0.065	-0.065	-0.065	-0.065
38.574	-0.060	-0.060	-0.060	-0.060	-0.060	-0.060
39.063	-0.049	-0.049	-0.049	-0.049	-0.049	-0.049
39.551	-0.032	-0.032	-0.032	-0.032	-0.032	-0.032
40.039	-0.010	-0.010	-0.010	-0.010	-0.010	-0.010
40.527	0.000	0.000	0.000	0.000	0.000	0.000
41.016	0.000	0.000	0.000	0.000	0.000	0.000

TABLE IV

INVERSE FILTER (1st order) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	9% mV	10% mV	11% mV	12% mV	13% mV	14% mV	15% mV
0.00	455.0	450.0	445.0	440.0	435.0	430.0	425.0
0.49	6.65	7.32	7.96	8.60	9.22	9.82	10.41
0.98	5.60	6.17	6.73	7.27	7.81	8.34	8.85
1.47	4.73	5.22	5.69	6.17	6.63	7.09	7.54
1.95	4.02	4.43	4.84	5.25	5.65	6.05	6.44
2.44	3.43	3.78	4.14	4.49	4.83	5.18	5.52
2.93	2.95	3.25	3.56	3.85	4.17	4.46	4.75
3.42	2.56	2.82	3.08	3.34	3.59	3.86	4.11
3.91	2.25	2.47	2.69	2.91	3.13	3.36	3.59
4.40	2.00	2.18	2.37	2.57	2.76	2.95	3.15
4.88	1.80	1.96	2.12	2.29	2.45	2.62	2.79
5.37	1.65	1.78	1.92	2.06	2.21	2.35	2.50
5.86	1.53	1.65	1.77	1.89	2.01	2.14	2.27
6.35	1.45	1.55	1.65	1.76	1.86	1.97	2.08
6.84	1.39	1.48	1.56	1.65	1.75	1.84	1.94
7.32	1.36	1.43	1.51	1.58	1.66	1.74	1.82
7.81	1.34	1.40	1.47	1.53	1.60	1.67	1.74
8.30	1.34	1.39	1.45	1.50	1.56	1.62	1.68
8.79	1.35	1.39	1.44	1.49	1.54	1.59	1.64
9.28	1.37	1.40	1.45	1.48	1.53	1.58	1.62
9.77	1.40	1.43	1.46	1.50	1.53	1.57	1.61
10.25	1.43	1.46	1.48	1.51	1.55	1.58	1.61
10.74	1.46	1.49	1.51	1.54	1.56	1.59	1.62
11.23	1.50	1.52	1.54	1.57	1.59	1.61	1.64
11.72	1.54	1.56	1.57	1.60	1.61	1.64	1.66
12.21	1.58	1.60	1.61	1.63	1.64	1.66	1.68
12.70	1.62	1.63	1.65	1.67	1.67	1.69	1.71
13.18	1.66	1.67	1.68	1.70	1.71	1.72	1.73
13.67	1.70	1.71	1.71	1.72	1.74	1.75	1.76
14.16	1.73	1.74	1.75	1.75	1.76	1.77	1.78
14.65	1.76	1.77	1.77	1.78	1.79	1.80	1.81
15.14	1.79	1.79	1.80	1.80	1.81	1.82	1.83
15.63	1.81	1.81	1.82	1.82	1.83	1.84	1.84
16.11	1.83	1.83	1.84	1.84	1.86	1.85	1.86
16.60	1.84	1.84	1.85	1.85	1.86	1.86	1.87
17.10	1.85	1.85	1.86	1.86	1.86	1.87	1.87
17.58	1.85	1.86	1.87	1.86	1.86	1.87	1.87
18.07	1.85	1.85	1.86	1.86	1.86	1.86	1.87

TABLE IV

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	9% mV	10% mV	11% mV	12% mV	13% mV	14% mV	15% mV
18.56	1.84	1.86	1.85	1.85	1.85	1.85	1.86
19.04	1.83	1.83	1.83	1.84	1.84	1.84	1.84
19.53	1.81	1.82	1.82	1.82	1.82	1.82	1.82
20.02	1.79	1.79	1.79	1.79	1.80	1.80	1.80
20.51	1.76	1.76	1.76	1.77	1.77	1.77	1.77
21.00	1.73	1.73	1.73	1.73	1.73	1.74	1.74
21.48	1.69	1.69	1.69	1.69	1.70	1.70	1.70
21.97	1.65	1.65	1.65	1.65	1.65	1.65	1.65
22.46	1.60	1.60	1.60	1.61	1.61	1.61	1.61
22.95	1.55	1.55	1.55	1.55	1.55	1.56	1.56
23.44	1.50	1.50	1.50	1.50	1.50	1.50	1.50
23.93	1.44	1.44	1.44	1.44	1.44	1.44	1.44
24.41	1.38	1.38	1.40	1.38	1.38	1.38	1.38
24.90	1.31	1.31	1.31	1.32	1.32	1.32	1.32
25.39	1.25	1.25	1.25	1.25	1.25	1.25	1.25
25.88	1.18	1.18	1.18	1.18	1.18	1.18	1.18
26.37	1.11	1.11	1.11	1.11	1.11	1.11	1.11
26.86	1.04	1.04	1.04	1.04	1.04	1.04	1.04
27.34	0.96	0.96	0.96	0.96	0.96	0.96	0.96
27.83	0.89	0.89	0.89	0.89	0.89	0.89	0.89
28.32	0.82	0.82	0.82	0.82	0.82	0.82	0.82
28.81	0.75	0.75	0.72	0.75	0.75	0.75	0.75
29.30	0.67	0.67	0.67	0.67	0.67	0.67	0.67
29.79	0.60	0.60	0.60	0.60	0.60	0.60	0.60
30.27	0.53	0.53	0.53	0.53	0.53	0.53	0.53
30.76	0.47	0.47	0.47	0.47	0.47	0.47	0.47
31.25	0.40	0.40	0.40	0.40	0.40	0.40	0.40
31.74	0.38	0.34	0.34	0.34	0.34	0.34	0.34
32.23	0.28	0.28	0.28	0.28	0.28	0.28	0.28
32.72	0.23	0.23	0.23	0.23	0.23	0.23	0.23
33.20	0.18	0.17	0.18	0.18	0.18	0.18	0.18
33.70	0.13	0.13	0.13	0.13	0.13	0.13	0.13
34.18	0.09	0.09	0.09	0.09	0.01	0.09	0.09
34.67	0.05	0.05	0.05	0.05	0.05	0.05	0.05
35.16	0.02	0.02	0.02	0.02	0.02	0.02	0.02
35.65	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
36.13	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
36.21	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05

TABLE IV

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING A AND B IN A*EXP(-BT). INPUT SIGNAL = EXPONENTIAL + HAVERSINE (continued)

time msec	9% mV	10% mV	11% mV	12% mV	13% mV	14% mV	15% mV
37.11	-0.06	-0.06	-0.06	-0.06	-0.06	-0.06	-0.06
37.60	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07
38.09	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07
38.57	-0.06	-0.06	-0.06	-0.06	-0.06	-0.06	-0.06
39.06	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
39.55	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
40.04	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
40.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00
41.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TABLE V

INVERSE FILTER (2ND ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL + HAVERSINE

time msec	z=.1 mV	z=.2 mV	z=.3 mV	z=.4 mV	z=.5 mV
0.000	500.000	500.000	500.000	500.000	500.000
0.488	0.015	0.015	0.015	0.015	0.015
0.977	333.376	318.376	293.376	258.376	213.376
1.465	0.132	0.131	0.130	0.129	0.128
1.953	225.766	215.615	198.696	175.010	144.556
2.441	0.362	0.358	0.351	0.342	0.330
2.930	153.121	146.247	134.789	118.749	98.125
3.418	0.700	0.689	0.671	0.645	0.613
3.906	104.164	99.501	91.731	80.852	66.865
4.395	1.138	1.117	1.081	1.032	0.969
4.883	71.258	68.086	62.800	55.400	45.886
5.371	1.665	1.631	1.573	1.493	1.390
5.859	49.233	47.063	43.448	38.386	31.877
6.348	2.269	2.219	2.135	2.018	1.867
6.836	34.584	33.085	30.587	27.090	22.594
7.324	2.937	2.868	2.754	2.594	2.388
7.813	24.933	23.881	22.127	19.671	16.513
8.301	3.652	3.563	3.415	3.208	2.941
8.789	18.666	17.908	16.644	14.874	12.598
9.277	4.397	4.286	4.102	3.845	3.513
9.766	14.685	14.117	13.171	11.847	10.144
10.254	5.155	5.022	4.800	4.490	4.091
10.742	12.238	11.792	11.048	10.007	8.669
11.230	5.908	5.752	5.492	5.129	4.661
11.719	10.815	10.443	9.824	8.956	7.842
12.207	6.639	6.460	6.162	5.745	5.209
12.695	10.061	9.732	9.186	8.420	7.435
13.184	7.330	7.130	6.795	6.326	5.723
13.672	9.733	9.428	8.920	8.208	7.292
14.160	7.966	7.744	7.374	6.856	6.190
14.648	9.663	9.368	8.876	8.188	7.303
15.137	8.530	8.289	7.887	7.324	6.601
15.625	9.733	9.440	8.952	8.268	7.390
16.113	9.011	8.752	8.322	7.719	6.944
16.602	9.859	9.564	9.073	8.385	7.500
17.090	9.396	9.123	8.668	8.031	7.212

TABLE V

INVERSE FILTER (2ND ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL + HAVERSINE (continued)

time msec	z=.1 mV	z=.2 mV	z=.3 mV	z=.4 mV	z=.5 mV
17.578	9.985	9.686	9.188	8.491	7.595
18.066	9.676	9.392	8.917	8.253	7.399
18.555	10.070	9.767	9.263	8.557	7.650
19.043	9.846	9.553	9.064	8.380	7.501
19.531	10.087	9.782	9.273	8.561	7.646
20.020	9.901	9.602	9.105	8.409	7.514
20.508	10.019	9.713	9.204	8.491	7.574
20.996	9.839	9.539	9.039	8.339	7.439
21.484	9.856	9.552	9.046	8.338	7.427
21.973	9.662	9.364	8.867	8.172	7.277
22.461	9.594	9.295	8.798	8.101	7.204
22.949	9.375	9.083	8.594	7.911	7.033
23.438	9.234	8.943	8.459	7.780	6.908
23.926	8.984	8.700	8.227	7.563	6.711
24.414	8.781	8.501	8.034	7.381	6.541
24.902	8.499	8.226	7.772	7.137	6.320
25.391	8.243	7.977	7.533	6.912	6.113
25.879	7.929	7.672	7.242	6.641	5.868
26.367	7.631	7.381	6.964	6.381	5.631
26.855	7.290	7.050	6.649	6.088	5.367
27.344	6.958	6.727	6.341	5.801	5.107
27.832	6.596	6.375	6.007	5.491	4.827
28.320	6.240	6.029	5.677	5.184	4.551
28.809	5.864	5.663	5.330	4.863	4.263
29.297	5.492	5.303	4.987	4.546	3.978
29.785	5.109	4.931	4.635	4.220	3.686
30.273	4.733	4.566	4.288	3.899	3.399
30.762	4.351	4.196	3.938	3.576	3.111
31.250	3.979	3.835	3.595	3.260	2.829
31.738	3.608	3.476	3.255	2.947	2.551
32.227	3.248	3.127	2.926	2.644	2.281
32.715	2.895	2.786	2.603	2.348	2.019
33.203	2.557	2.458	2.294	2.064	1.768
33.691	2.231	2.143	1.997	1.791	1.528
34.180	1.923	1.845	1.716	1.534	1.301
34.668	1.631	1.563	1.450	1.292	1.088
35.156	1.360	1.301	1.204	1.067	0.892
35.645	1.109	1.059	0.976	0.861	0.712

TABLE V

INVERSE FILTER (2ND ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL + HAVERSINE (continued)

time msec	z=.1 mV	z=.2 mV	z=.3 mV	z=.4 mV	z=.5 mV
36.133	0.881	0.840	0.771	0.674	0.550
36.621	0.677	0.643	0.587	0.508	0.407
37.109	0.498	0.471	0.426	0.364	0.283
37.598	0.345	0.324	0.290	0.242	0.180
38.086	0.219	0.204	0.179	0.143	0.098
38.574	0.121	0.111	0.093	0.069	0.037
39.063	0.052	0.045	0.034	0.018	-0.002
39.551	0.011	0.007	0.001	-0.008	-0.019
40.039	-0.000	-0.002	-0.005	-0.009	-0.013
40.527	-0.000	-0.000	-0.001	-0.002	-0.003
41.016	0.000	0.000	0.000	0.000	0.000

TABLE V

INVERSE FILTER (2ND ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL + HAVERSINE

(continued)

time msec	z=.6 mV	z=.7 mV	z=.8 mV	z=.9 mV	z=1 mV
0.000	500.000	500.000	500.000	500.000	500.000
0.488	0.015	0.015	0.015	0.015	0.015
0.977	158.376	93.376	18.376	-66.624	-161.624
1.465	0.126	0.125	0.122	0.120	0.117
1.953	107.335	63.346	12.590	-44.934	-109.225
2.441	0.316	0.299	0.279	0.256	0.231
2.930	72.919	43.129	8.757	-30.199	-73.737
3.418	0.573	0.526	0.471	0.409	0.340
3.906	49.769	29.565	6.253	-20.167	-49.695
4.395	0.891	0.800	0.694	0.575	0.441
4.883	34.257	20.513	4.656	-13.316	-33.403
5.371	1.264	1.116	0.944	0.749	0.532
5.859	23.923	14.522	3.674	-8.619	-22.359
6.348	1.683	1.465	1.213	0.928	0.610
6.836	17.099	10.605	3.111	-5.381	-14.873
7.324	2.137	1.840	1.497	1.108	0.674
7.813	12.654	8.093	2.831	-3.133	-9.799
8.301	2.616	2.231	1.787	1.284	0.721
8.789	9.817	6.530	2.737	-1.561	-6.365
9.277	3.108	2.630	2.078	1.452	0.752
9.766	8.063	5.603	2.766	-0.451	-4.045
10.254	3.603	3.027	2.362	1.608	0.766
10.742	7.033	5.099	2.868	0.339	-2.487
11.230	4.089	3.413	2.633	1.749	0.761
11.719	6.479	4.869	3.011	0.905	-1.449
12.207	4.553	3.778	2.884	1.871	0.738
12.695	6.232	4.810	3.169	1.310	-0.768
13.184	4.986	4.115	3.110	1.971	0.699
13.672	6.174	4.852	3.326	1.597	-0.335
14.160	5.377	4.415	3.305	2.048	0.642
14.648	6.221	4.942	3.467	1.795	-0.073
15.137	5.716	4.671	3.465	2.098	0.571
15.625	6.316	5.047	3.583	1.923	0.069
16.113	5.997	4.878	3.586	2.122	0.486
16.602	6.419	5.141	3.666	1.995	0.127
17.090	6.212	5.029	3.665	2.118	0.390
17.578	6.500	5.205	3.712	2.019	0.127
18.066	6.356	5.123	3.700	2.087	0.285

TABLE V

INVERSE FILTER (2ND ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL + HAVERSINE (continued)

time msec	z=.6 mV	z=.7 mV	z=.8 mV	z=.9 mV	z=1 mV
18.555	6.540	5.229	3.717	2.002	0.086
19.043	6.426	5.156	3.690	2.029	0.172
19.531	6.527	5.205	3.680	1.950	0.018
20.020	6.420	5.128	3.636	1.946	0.056
20.508	6.453	5.129	3.600	1.868	-0.068
20.996	6.339	5.039	3.539	1.839	-0.061
21.484	6.314	4.998	3.480	1.759	-0.164
21.973	6.184	4.892	3.401	1.711	-0.177
22.461	6.109	4.815	3.321	1.628	-0.264
22.949	5.959	4.690	3.225	1.566	-0.289
23.438	5.841	4.581	3.127	1.479	-0.363
23.926	5.669	4.437	3.016	1.406	-0.394
24.414	5.515	4.302	2.902	1.316	-0.457
24.902	5.321	4.141	2.779	1.235	-0.490
25.391	5.137	3.983	2.652	1.143	-0.543
25.879	4.923	3.807	2.518	1.058	-0.574
26.367	4.715	3.632	2.382	0.965	-0.618
26.855	4.485	3.443	2.241	0.878	-0.645
27.344	4.258	3.255	2.098	0.787	-0.679
27.832	4.017	3.058	1.953	0.700	-0.701
28.320	3.777	2.863	1.808	0.612	-0.725
28.809	3.529	2.662	1.661	0.528	-0.740
29.297	3.284	2.463	1.517	0.444	-0.755
29.785	3.034	2.263	1.373	0.365	-0.762
30.273	2.788	2.066	1.233	0.288	-0.767
30.762	2.542	1.871	1.095	0.217	-0.766
31.250	2.303	1.680	0.962	0.148	-0.762
31.738	2.067	1.494	0.834	0.085	-0.752
32.227	1.838	1.315	0.711	0.027	-0.738
32.715	1.617	1.142	0.595	-0.026	-0.720
33.203	1.406	0.979	0.486	-0.073	-0.698
33.691	1.205	0.824	0.384	-0.114	-0.671
34.180	1.016	0.680	0.291	-0.149	-0.641
34.668	0.840	0.546	0.207	-0.177	-0.607
35.156	0.678	0.424	0.132	-0.199	-0.570
35.645	0.530	0.315	0.067	-0.214	-0.528
36.133	0.398	0.219	0.012	-0.222	-0.484
36.621	0.283	0.137	-0.032	-0.224	-0.437

TABLE V

INVERSE FILTER (2ND ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL + HAVERSINE (continued)

time msec	z=.6 mV	z=.7 mV	z=.8 mV	z=.9 mV	z=1 mV
37.109	0.185	0.068	-0.066	-0.218	-0.388
37.598	0.104	0.015	-0.088	-0.205	-0.336
38.086	0.042	-0.024	-0.100	-0.186	-0.282
38.574	-0.002	-0.048	-0.100	-0.160	-0.227
39.063	-0.027	-0.056	-0.089	-0.128	-0.170
39.551	-0.033	-0.049	-0.067	-0.089	-0.112
40.039	-0.019	-0.027	-0.035	-0.044	-0.054
40.527	-0.004	-0.006	-0.008	-0.010	-0.012
41.016	0.000	0.000	0.000	-0.000	-0.000
41.504	0.000	0.000	0.000	0.000	0.000
41.992	0.000	0.000	0.000	-0.000	-0.000

TABLE VI

INVERSE FILTER (2ND ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL ONLY

time msec	z=.1 mV	z=.2 mV	z=.3 mV	z=.4 mV	z=.5 mV
0.000	500.000	500.000	500.000	500.000	500.000
0.488	0.000	0.000	0.000	0.000	0.000
0.977	333.317	318.317	293.317	258.317	213.317
1.465	0.000	0.000	0.000	0.000	0.000
1.953	225.534	215.384	198.468	174.786	144.337
2.441	0.000	0.000	0.000	0.000	0.000
2.930	152.604	145.736	134.290	118.266	97.664
3.418	0.000	0.000	0.000	0.000	0.000
3.906	103.257	98.610	90.865	80.023	66.083
4.395	0.000	0.000	0.000	0.000	0.000
4.883	69.867	66.723	61.483	54.146	44.714
5.371	0.000	0.000	0.000	0.000	0.000
5.859	47.274	45.147	41.601	36.637	30.255
6.348	0.000	0.000	0.000	0.000	0.000
6.836	31.987	30.548	28.149	24.790	20.471
7.324	0.000	0.000	0.000	0.000	0.000
7.813	21.644	20.670	19.046	16.774	13.852
8.301	0.000	0.000	0.000	0.000	0.000
8.789	14.645	13.986	12.887	11.350	9.372
9.277	0.000	0.000	0.000	0.000	0.000
9.766	9.909	9.463	8.720	7.680	6.342
10.254	0.000	0.000	0.000	0.000	0.000
10.742	6.705	6.403	5.900	5.196	4.291
11.230	0.000	0.000	0.000	0.000	0.000
11.719	4.537	4.333	3.992	3.516	2.903
12.207	0.000	0.000	0.000	0.000	0.000
12.695	3.070	2.932	2.701	2.379	1.965
13.184	0.000	0.000	0.000	0.000	0.000
13.672	2.077	1.984	1.828	1.610	1.329
14.160	0.000	0.000	0.000	0.000	0.000
14.648	1.405	1.342	1.237	1.089	0.899
15.137	0.000	0.000	0.000	0.000	0.000
15.625	0.951	0.908	0.837	0.737	0.609
16.113	0.000	0.000	0.000	0.000	0.000
16.602	0.643	0.614	0.566	0.499	0.412
17.090	0.000	0.000	0.000	0.000	0.000
17.578	0.435	0.416	0.383	0.337	0.279
18.066	0.000	0.000	0.000	0.000	0.000
18.555	0.295	0.281	0.259	0.228	0.189

TABLE VI

INVERSE FILTER (2ND ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL ONLY

(continued)

time msec	z=.1 mV	z=.2 mV	z=.3 mV	z=.4 mV	z=.5 mV
19.043	0.000	0.000	0.000	0.000	0.000
19.531	0.199	0.190	0.175	0.154	0.128
20.020	0.000	0.000	0.000	0.000	0.000
20.508	0.135	0.129	0.119	0.105	0.086
20.996	0.000	0.000	0.000	0.000	0.000
21.484	0.091	0.087	0.080	0.071	0.058
21.973	0.000	0.000	0.000	0.000	0.000
22.461	0.062	0.059	0.054	0.048	0.040
22.949	0.000	0.000	0.000	0.000	0.000
23.438	0.042	0.040	0.037	0.032	0.027
23.926	0.000	0.000	0.000	0.000	0.000
24.414	0.028	0.027	0.025	0.022	0.018
24.902	0.000	0.000	0.000	0.000	0.000
25.391	0.019	0.018	0.017	0.015	0.012
25.879	0.000	0.000	0.000	0.000	0.000
26.367	0.013	0.012	0.011	0.010	0.008
26.855	0.000	0.000	0.000	0.000	0.000
27.344	0.009	0.008	0.008	0.007	0.006
27.832	0.000	0.000	0.000	0.000	0.000
28.320	0.006	0.006	0.005	0.005	0.004
28.809	0.000	0.000	0.000	0.000	0.000
29.297	0.004	0.004	0.004	0.003	0.003
29.785	0.000	0.000	0.000	0.000	0.000
30.273	0.003	0.003	0.002	0.002	0.002
30.762	0.000	0.000	0.000	0.000	0.000
31.250	0.002	0.002	0.002	0.001	0.001
31.738	0.000	0.000	0.000	0.000	0.000
32.227	0.001	0.001	0.001	0.001	0.001
32.715	0.000	0.000	0.000	0.000	0.000
33.203	0.001	0.001	0.001	0.001	0.001
33.691	0.000	0.000	0.000	0.000	0.000
34.180	0.001	0.001	0.001	0.000	0.000
34.668	0.000	0.000	0.000	0.000	0.000

TABLE VI

INVERSE FILTER (2ND ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL ONLY (continued)

time msec	z=.6 mV	z=.7 mV	z=.8 mV	z=.9 mV	z=1.0 mV
0.000	500.000	500.000	500.000	500.000	500.000
0.488	0.000	0.000	0.000	0.000	0.000
0.977	158.317	93.317	18.317	-66.683	-161.683
1.465	0.000	0.000	0.000	0.000	0.000
1.953	107.123	63.141	12.394	-45.120	-109.400
2.441	0.000	0.000	0.000	0.000	0.000
2.930	72.483	42.724	8.386	-30.530	-74.024
3.418	0.000	0.000	0.000	0.000	0.000
3.906	49.044	28.908	5.674	-20.657	-50.087
4.395	0.000	0.000	0.000	0.000	0.000
4.883	33.185	19.560	3.839	-13.978	-33.891
5.371	0.000	0.000	0.000	0.000	0.000
5.859	22.454	13.235	2.598	-9.458	-22.932
6.348	0.000	0.000	0.000	0.000	0.000
6.836	15.193	8.955	1.758	-6.399	-15.516
7.324	0.000	0.000	0.000	0.000	0.000
7.813	10.280	6.059	1.189	-4.330	-10.499
8.301	0.000	0.000	0.000	0.000	0.000
8.789	6.956	4.100	0.805	-2.930	-7.104
9.277	0.000	0.000	0.000	0.000	0.000
9.766	4.707	2.774	0.545	-1.982	-4.807
10.254	0.000	0.000	0.000	0.000	0.000
10.742	3.185	1.877	0.368	-1.341	-3.252
11.230	0.000	0.000	0.000	0.000	0.000
11.719	2.155	1.270	0.249	-0.908	-2.201
12.207	0.000	0.000	0.000	0.000	0.000
12.695	1.458	0.859	0.169	-0.614	-1.489
13.184	0.000	0.000	0.000	0.000	0.000
13.672	0.987	0.582	0.114	-0.416	-1.008
14.160	0.000	0.000	0.000	0.000	0.000
14.648	0.668	0.393	0.077	-0.281	-0.682
15.137	0.000	0.000	0.000	0.000	0.000
15.625	0.452	0.266	0.052	-0.190	-0.461
16.113	0.000	0.000	0.000	0.000	0.000
16.602	0.306	0.180	0.035	-0.129	-0.312
17.090	0.000	0.000	0.000	0.000	0.000
17.578	0.207	0.122	0.024	-0.087	-0.211
18.066	0.000	0.000	0.000	0.000	0.000

TABLE VI

INVERSE FILTER (2ND ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL ONLY (continued)

time msec	z=.6 mV	z=.7 mV	z=.8 mV	z=.9 mV	z=1.0 mV
18.555	0.140	0.082	0.016	-0.059	-0.143
19.043	0.000	0.000	0.000	0.000	0.000
19.531	0.095	0.056	0.011	-0.040	-0.097
20.020	0.000	0.000	0.000	0.000	0.000
20.508	0.064	0.038	0.007	-0.027	-0.065
20.996	0.000	0.000	0.000	0.000	0.000
21.484	0.043	0.026	0.005	-0.018	-0.044
21.973	0.000	0.000	0.000	0.000	0.000
22.461	0.029	0.017	0.003	-0.012	-0.030
22.949	0.000	0.000	0.000	0.000	0.000
23.438	0.020	0.012	0.002	-0.008	-0.020
23.926	0.000	0.000	0.000	0.000	0.000
24.414	0.013	0.008	0.002	-0.006	-0.014
24.902	0.000	0.000	0.000	0.000	0.000
25.391	0.009	0.005	0.001	-0.004	-0.009
25.879	0.000	0.000	0.000	0.000	0.000
26.367	0.006	0.004	0.001	-0.003	-0.006
26.855	0.000	0.000	0.000	0.000	0.000
27.344	0.004	0.002	0.000	-0.002	-0.004
27.832	0.000	0.000	0.000	0.000	0.000
28.320	0.003	0.002	0.000	-0.001	-0.003
28.809	0.000	0.000	0.000	0.000	0.000
29.297	0.002	0.001	0.000	-0.001	-0.002
29.785	0.000	0.000	0.000	0.000	0.000
30.273	0.001	0.001	0.000	-0.001	-0.001
30.762	0.000	0.000	0.000	0.000	0.000
31.250	0.001	0.001	0.000	-0.000	-0.001
31.738	0.000	0.000	0.000	0.000	0.000
32.227	0.001	0.000	0.000	-0.000	-0.001
32.715	0.000	0.000	0.000	0.000	0.000
33.203	0.000	0.000	0.000	-0.000	-0.000
33.691	0.000	0.000	0.000	0.000	0.000
34.180	0.000	0.000	0.000	-0.000	-0.000
34.668	0.000	0.000	0.000	0.000	0.000

TABLE VII

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL ONLY

time msec	z=.1 mV	z=.2 mV	z=.3 mV	z=.4 mV	z=.5 mV
0.000	500.000	500.000	500.000	500.000	500.000
0.488	361.289	311.289	261.289	211.289	161.289
0.977	297.188	256.059	214.930	173.801	132.673
1.465	244.460	210.629	176.797	142.965	109.133
1.953	201.087	173.258	145.429	117.600	89.771
2.441	165.410	142.518	119.627	96.735	73.843
2.930	136.063	117.232	98.402	79.572	60.742
3.418	111.922	96.433	80.943	65.454	49.965
3.906	92.065	79.323	66.582	53.841	41.100
4.395	75.730	65.250	54.769	44.289	33.808
4.883	62.294	53.673	45.052	36.431	27.810
5.371	51.242	44.150	37.059	29.967	22.876
5.859	42.150	36.317	30.484	24.650	18.817
6.348	34.672	29.873	25.075	20.277	15.478
6.836	28.520	24.573	20.626	16.679	12.732
7.324	23.460	20.213	16.967	13.720	10.473
7.813	19.298	16.627	13.956	11.286	8.615
8.301	15.874	13.677	11.480	9.283	7.087
8.789	13.058	11.250	9.443	7.636	5.829
9.277	10.741	9.254	7.768	6.281	4.795
9.766	8.835	7.612	6.390	5.167	3.944
10.254	7.268	6.262	5.256	4.250	3.244
10.742	5.978	5.151	4.323	3.496	2.669
11.230	4.918	4.237	3.556	2.876	2.195
11.719	4.045	3.485	2.925	2.366	1.806
12.207	3.327	2.867	2.406	1.946	1.485
12.695	2.737	2.358	1.979	1.601	1.222
13.184	2.251	1.940	1.628	1.317	1.005
13.672	1.852	1.596	1.339	1.083	0.827
14.160	1.523	1.313	1.102	0.891	0.680
14.648	1.253	1.080	0.906	0.733	0.559
15.137	1.031	0.888	0.745	0.603	0.460
15.625	0.848	0.731	0.613	0.496	0.379
16.113	0.697	0.601	0.504	0.408	0.311
16.602	0.574	0.494	0.415	0.336	0.256
17.090	0.472	0.407	0.341	0.276	0.211
17.578	0.388	0.334	0.281	0.227	0.173
18.066	0.319	0.275	0.231	0.187	0.143
18.555	0.263	0.226	0.190	0.154	0.117

TABLE VII

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL ONLY (continued)

time msec	z=.1 mV	z=.2 mV	z=.3 mV	z=.4 mV	z=.5 mV
19.043	0.216	0.186	0.156	0.126	0.096
19.531	0.178	0.153	0.129	0.104	0.079
20.020	0.146	0.126	0.106	0.085	0.065
20.508	0.120	0.104	0.087	0.070	0.054
20.996	0.099	0.085	0.072	0.058	0.044
21.484	0.081	0.070	0.059	0.048	0.036
21.973	0.067	0.058	0.048	0.039	0.030
22.461	0.055	0.047	0.040	0.032	0.025
22.949	0.045	0.039	0.033	0.026	0.020
23.438	0.037	0.032	0.027	0.022	0.017
23.926	0.031	0.026	0.022	0.018	0.014
24.414	0.025	0.022	0.018	0.015	0.011
24.902	0.021	0.018	0.015	0.012	0.009
25.391	0.017	0.015	0.012	0.010	0.008
25.879	0.014	0.012	0.010	0.008	0.006
26.367	0.012	0.010	0.008	0.007	0.005
26.855	0.009	0.008	0.007	0.006	0.004
27.344	0.008	0.007	0.006	0.005	0.003
27.832	0.006	0.006	0.005	0.004	0.003
28.320	0.005	0.005	0.004	0.003	0.002
28.809	0.004	0.004	0.003	0.003	0.002
29.297	0.004	0.003	0.003	0.002	0.002
29.785	0.003	0.003	0.002	0.002	0.001
30.273	0.002	0.002	0.002	0.001	0.001
30.762	0.002	0.002	0.001	0.001	0.001
31.250	0.002	0.001	0.001	0.001	0.001
31.738	0.001	0.001	0.001	0.001	0.001
32.227	0.001	0.001	0.001	0.001	0.000
32.715	0.001	0.001	0.001	0.001	0.000
33.203	0.001	0.001	0.001	0.000	0.000
33.691	0.001	0.001	0.000	0.000	0.000
34.180	0.001	0.000	0.000	0.000	0.000
34.668	0.000	0.000	0.000	0.000	0.000

TABLE VII

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL ONLY
(continued)

time msec	z=.6 mV	z=.7 mV	z=.8 mV	z=.9 mV	z=1.0 mV
0.000	500.000	500.000	500.000	500.000	500.000
0.488	111.289	61.289	11.289	-38.711	-88.711
0.977	91.544	50.415	9.286	-31.843	-72.972
1.465	75.302	41.470	7.638	-26.193	-60.025
1.953	61.942	34.112	6.283	-21.546	-49.375
2.441	50.952	28.060	5.168	-17.723	-40.615
2.930	41.912	23.082	4.251	-14.579	-33.409
3.418	34.476	18.986	3.497	-11.992	-27.481
3.906	28.359	15.618	2.877	-9.864	-22.606
4.395	23.327	12.847	2.366	-8.114	-18.595
4.883	19.189	10.568	1.946	-6.675	-15.296
5.371	15.784	8.693	1.601	-5.490	-12.582
5.859	12.984	7.150	1.317	-4.516	-10.350
6.348	10.680	5.882	1.083	-3.715	-8.513
6.836	8.785	4.838	0.891	-3.056	-7.003
7.324	7.226	3.980	0.733	-2.514	-5.760
7.813	5.944	3.274	0.603	-2.068	-4.738
8.301	4.890	2.693	0.496	-1.701	-3.898
8.789	4.022	2.215	0.408	-1.399	-3.206
9.277	3.309	1.822	0.336	-1.151	-2.637
9.766	2.722	1.499	0.276	-0.947	-2.169
10.254	2.239	1.233	0.227	-0.779	-1.784
10.742	1.841	1.014	0.187	-0.641	-1.468
11.230	1.515	0.834	0.154	-0.527	-1.207
11.719	1.246	0.686	0.126	-0.433	-0.993
12.207	1.025	0.564	0.104	-0.357	-0.817
12.695	0.843	0.464	0.086	-0.293	-0.672
13.184	0.694	0.382	0.070	-0.241	-0.553
13.672	0.570	0.314	0.058	-0.198	-0.455
14.160	0.469	0.258	0.048	-0.163	-0.374
14.648	0.386	0.213	0.039	-0.134	-0.308
15.137	0.318	0.175	0.032	-0.110	-0.253
15.625	0.261	0.144	0.026	-0.091	-0.208
16.113	0.215	0.118	0.022	-0.075	-0.171
16.602	0.177	0.097	0.018	-0.061	-0.141
17.090	0.145	0.080	0.015	-0.051	-0.116
17.578	0.120	0.066	0.012	-0.042	-0.095
18.066	0.098	0.054	0.010	-0.034	-0.078

TABLE VII

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL ONLY

(continued)

time msec	z=.6 mV	z=.7 mV	z=.8 mV	z=.9 mV	z=1.0 mV
18.555	0.081	0.045	0.008	-0.028	-0.064
19.043	0.067	0.037	0.007	-0.023	-0.053
19.531	0.055	0.030	0.006	-0.019	-0.044
20.020	0.045	0.025	0.005	-0.016	-0.036
20.508	0.037	0.020	0.004	-0.013	-0.030
20.996	0.030	0.017	0.003	-0.011	-0.024
21.484	0.025	0.014	0.003	-0.009	-0.020
21.973	0.021	0.011	0.002	-0.007	-0.016
22.461	0.017	0.009	0.002	-0.006	-0.014
22.949	0.014	0.008	0.001	-0.005	-0.011
23.438	0.011	0.006	0.001	-0.004	-0.009
23.926	0.009	0.005	0.001	-0.003	-0.008
24.414	0.008	0.004	0.001	-0.003	-0.006
24.902	0.006	0.004	0.001	-0.002	-0.005
25.391	0.005	0.003	0.001	-0.002	-0.004
25.879	0.004	0.002	0.000	-0.002	-0.003
26.367	0.004	0.002	0.000	-0.001	-0.003
26.855	0.003	0.002	0.000	-0.001	-0.002
27.344	0.002	0.001	0.000	-0.001	-0.002
27.832	0.002	0.001	0.000	-0.001	-0.002
28.320	0.002	0.001	0.000	-0.001	-0.001
28.809	0.001	0.001	0.000	-0.000	-0.001
29.297	0.001	0.001	0.000	-0.000	-0.001
29.785	0.001	0.000	0.000	-0.000	-0.001
30.273	0.001	0.000	0.000	-0.000	-0.001
30.762	0.001	0.000	0.000	-0.000	-0.000
31.250	0.001	0.000	0.000	-0.000	-0.000
31.738	0.000	0.000	0.000	-0.000	-0.000
32.227	0.000	0.000	0.000	-0.000	-0.000
32.715	0.000	0.000	0.000	-0.000	-0.000
33.203	0.000	0.000	0.000	-0.000	-0.000

TABLE VIII

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL + HAVERSINE

time msec	z=.1 mV	z=.2 mV	z=.3 mV	z=.4 mV	z=.5 mV
0.000	500.000	500.000	500.000	500.000	500.000
0.488	361.303	311.303	261.303	211.303	161.303
0.977	297.245	256.115	214.985	173.854	132.724
1.465	244.586	210.749	176.911	143.073	109.236
1.953	201.308	173.465	145.623	117.781	89.938
2.441	165.750	142.835	119.920	97.005	74.090
2.930	136.546	117.680	98.813	79.947	61.080
3.418	112.574	97.032	81.491	65.950	50.408
3.906	92.906	80.095	67.283	54.472	41.660
4.395	76.784	66.212	55.640	45.068	34.497
4.883	63.580	54.844	46.108	37.373	28.637
5.371	52.778	45.547	38.315	31.084	23.852
5.859	43.955	37.954	31.953	25.952	19.951
6.348	36.761	31.765	26.770	21.774	16.778
6.836	30.908	26.732	22.556	18.381	14.205
7.324	26.158	22.650	19.142	15.633	12.125
7.813	22.317	19.351	16.384	13.417	10.451
8.301	19.224	16.695	14.167	11.638	9.110
8.789	16.744	14.569	12.394	10.218	8.043
9.277	14.769	12.877	10.985	9.093	7.201
9.766	13.208	11.542	9.876	8.209	6.543
10.254	11.985	10.498	9.011	7.523	6.036
10.742	11.040	9.693	8.345	6.998	5.651
11.230	10.320	9.081	7.842	6.604	5.365
11.719	9.783	8.627	7.471	6.315	5.159
12.207	9.393	8.299	7.205	6.111	5.018
12.695	9.121	8.073	7.024	5.975	4.927
13.184	8.943	7.926	6.909	5.892	4.875
13.672	8.839	7.843	6.847	5.851	4.855
14.160	8.790	7.807	6.823	5.840	4.857
14.648	8.784	7.807	6.829	5.852	4.875
15.137	8.808	7.832	6.856	5.879	4.903
15.625	8.852	7.873	6.895	5.917	4.938
16.113	8.908	7.925	6.942	5.959	4.976
16.602	8.968	7.979	6.990	6.001	5.012
17.090	9.028	8.032	7.037	6.041	5.045
17.578	9.082	8.080	7.077	6.075	5.073
18.066	9.126	8.118	7.109	6.101	5.092
18.555	9.157	8.144	7.130	6.117	5.103

TABLE VIII

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL + HAVERSINE (continued)

time msec	z=.1 mV	z=.2 mV	z=.3 mV	z=.4 mV	z=.5 mV
19.043	9.172	8.155	7.138	6.121	5.104
19.531	9.170	8.151	7.132	6.113	5.094
20.020	9.148	8.129	7.110	6.091	5.072
20.508	9.104	8.088	7.071	6.054	5.038
20.996	9.039	8.027	7.015	6.003	4.991
21.484	8.952	7.947	6.942	5.937	4.932
21.973	8.842	7.847	6.851	5.855	4.859
22.461	8.710	7.726	6.742	5.758	4.775
22.949	8.555	7.586	6.616	5.647	4.678
23.438	8.379	7.426	6.474	5.521	4.569
23.926	8.181	7.248	6.315	5.382	4.448
24.414	7.963	7.051	6.140	5.229	4.317
24.902	7.726	6.838	5.951	5.063	4.176
25.391	7.470	6.609	5.748	4.886	4.025
25.879	7.198	6.365	5.532	4.699	3.866
26.367	6.911	6.108	5.305	4.501	3.698
26.855	6.610	5.839	5.067	4.296	3.524
27.344	6.297	5.559	4.821	4.083	3.344
27.832	5.974	5.270	4.567	3.863	3.160
28.320	5.642	4.975	4.307	3.639	2.971
28.809	5.304	4.673	4.042	3.411	2.780
29.297	4.962	4.368	3.775	3.181	2.588
29.785	4.617	4.061	3.505	2.950	2.394
30.273	4.271	3.754	3.236	2.719	2.202
30.762	3.927	3.448	2.969	2.490	2.011
31.250	3.586	3.145	2.705	2.264	1.824
31.738	3.251	2.848	2.445	2.043	1.640
32.227	2.923	2.557	2.192	1.827	1.461
32.715	2.604	2.275	1.946	1.618	1.289
33.203	2.297	2.003	1.710	1.417	1.124
33.691	2.002	1.743	1.484	1.225	0.966
34.180	1.723	1.496	1.270	1.044	0.818
34.668	1.459	1.264	1.069	0.875	0.680
35.156	1.214	1.048	0.883	0.718	0.552
35.645	0.988	0.850	0.712	0.574	0.436
36.133	0.782	0.670	0.557	0.445	0.332
36.621	0.599	0.509	0.420	0.330	0.241
37.109	0.438	0.369	0.300	0.232	0.163

TABLE VIII

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL + HAVERSINE (continued)

time msec	z=.1 mV	z=.2 mV	z=.3 mV	z=.4 mV	z=.5 mV
37.598	0.301	0.251	0.200	0.149	0.099
38.086	0.189	0.154	0.119	0.084	0.048
38.574	0.103	0.080	0.058	0.035	0.013
39.063	0.042	0.029	0.017	0.004	-0.008
39.551	0.007	0.002	-0.004	-0.009	-0.015
40.039	-0.001	-0.002	-0.004	-0.005	-0.006
40.527	0.000	0.000	0.000	0.000	0.000
41.016	0.000	0.000	0.000	0.000	0.000
41.504	0.000	0.000	0.000	0.000	0.000
41.992	0.000	0.000	0.000	0.000	0.000

TABLE VIII

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL + HAVERSINE

(continued)

time msec	z=.6 mV	z=.7 mV	z=.8 mV	z=.9 mV	z=1.0 mV
0.000	500.000	500.000	500.000	500.000	500.000
0.488	111.303	61.303	11.303	-38.697	-88.697
0.977	91.594	50.463	9.333	-31.797	-72.928
1.465	75.398	41.561	7.723	-26.114	-59.952
1.953	62.096	34.254	6.411	-21.431	-49.274
2.441	51.175	28.260	5.345	-17.570	-40.485
2.930	42.214	23.348	4.481	-14.385	-33.252
3.418	34.867	19.326	3.784	-11.757	-27.298
3.906	28.849	16.037	3.226	-9.586	-22.397
4.395	23.925	13.353	2.781	-7.790	-18.362
4.883	19.902	11.166	2.431	-6.305	-15.040
5.371	16.621	9.389	2.158	-5.074	-12.305
5.859	13.950	7.949	1.948	-4.053	-10.054
6.348	11.783	6.787	1.792	-3.204	-8.200
6.836	10.029	5.854	1.678	-2.497	-6.673
7.324	8.617	5.108	1.600	-1.908	-5.417
7.813	7.484	4.517	1.551	-1.416	-4.383
8.301	6.582	4.053	1.525	-1.004	-3.532
8.789	5.868	3.693	1.518	-0.658	-2.833
9.277	5.309	3.417	1.526	-0.366	-2.258
9.766	4.877	3.211	1.545	-0.121	-1.787
10.254	4.548	3.061	1.574	0.086	-1.401
10.742	4.303	2.956	1.609	0.262	-1.086
11.230	4.126	2.887	1.649	0.410	-0.829
11.719	4.003	2.847	1.692	0.536	-0.620
12.207	3.924	2.830	1.736	0.642	-0.452
12.695	3.878	2.829	1.781	0.732	-0.317
13.184	3.858	2.841	1.824	0.807	-0.210
13.672	3.859	2.863	1.867	0.870	-0.126
14.160	3.873	2.890	1.906	0.923	-0.061
14.648	3.897	2.920	1.942	0.965	-0.012
15.137	3.927	2.951	1.975	0.999	0.023
15.625	3.960	2.981	2.003	1.025	0.046
16.113	3.993	3.010	2.026	1.043	0.060
16.602	4.023	3.034	2.045	1.056	0.067
17.090	4.049	3.054	2.058	1.062	0.066
17.578	4.070	3.068	2.065	1.063	0.061
18.066	4.084	3.076	2.067	1.059	0.050

TABLE VIII

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL + HAVERSINE (continued)

time msec	z=.6 mV	z=.7 mV	z=.8 mV	z=.9 mV	z=1.0 mV
18.555	4.090	3.076	2.063	1.050	0.036
19.043	4.087	3.070	2.053	1.036	0.019
19.531	4.075	3.056	2.037	1.018	-0.001
20.020	4.053	3.034	2.015	0.997	-0.022
20.508	4.021	3.005	1.988	0.971	-0.045
20.996	3.979	2.967	1.955	0.943	-0.069
21.484	3.926	2.921	1.916	0.911	-0.094
21.973	3.864	2.868	1.872	0.876	-0.119
22.461	3.791	2.807	1.823	0.839	-0.144
22.949	3.708	2.739	1.770	0.800	-0.169
23.438	3.616	2.664	1.711	0.759	-0.194
23.926	3.515	2.582	1.649	0.716	-0.217
24.414	3.406	2.494	1.583	0.672	-0.240
24.902	3.288	2.401	1.514	0.626	-0.261
25.391	3.164	2.302	1.441	0.580	-0.281
25.879	3.032	2.199	1.366	0.533	-0.300
26.367	2.895	2.092	1.289	0.486	-0.317
26.855	2.753	1.982	1.210	0.439	-0.333
27.344	2.606	1.868	1.130	0.392	-0.346
27.832	2.456	1.753	1.049	0.346	-0.358
28.320	2.304	1.636	0.968	0.300	-0.367
28.809	2.149	1.518	0.887	0.256	-0.375
29.297	1.994	1.401	0.807	0.213	-0.380
29.785	1.839	1.283	0.728	0.172	-0.383
30.273	1.685	1.168	0.650	0.133	-0.384
30.762	1.533	1.054	0.575	0.096	-0.383
31.250	1.383	0.943	0.502	0.062	-0.379
31.738	1.237	0.835	0.432	0.029	-0.373
32.227	1.096	0.731	0.365	0.000	-0.365
32.715	0.960	0.631	0.302	-0.026	-0.355
33.203	0.830	0.537	0.244	-0.050	-0.343
33.691	0.707	0.448	0.189	-0.070	-0.329
34.180	0.592	0.366	0.140	-0.086	-0.313
34.668	0.485	0.290	0.095	-0.100	-0.295
35.156	0.387	0.221	0.056	-0.110	-0.275
35.645	0.298	0.160	0.022	-0.116	-0.254
36.133	0.219	0.107	-0.006	-0.118	-0.231
36.621	0.151	0.062	-0.028	-0.117	-0.207

TABLE VIII

INVERSE FILTER (1ST ORDER) BEHAVIOR RESULTING FROM CHANGING THE LOCATION OF ZEROS. INPUT = EXPONENTIAL + HAVERSINE (continued)

time msec	z=.6 mV	z=.7 mV	z=.8 mV	z=.9 mV	z=1.0 mV
37.109	0.094	0.025	-0.044	-0.112	-0.181
37.598	0.048	-0.003	-0.054	-0.104	-0.155
38.086	0.013	-0.022	-0.057	-0.092	-0.128
38.574	-0.010	-0.032	-0.055	-0.077	-0.099
39.063	-0.021	-0.033	-0.046	-0.058	-0.071
39.551	-0.020	-0.025	-0.031	-0.036	-0.042
40.039	-0.007	-0.009	-0.010	-0.011	-0.012
40.527	0.000	0.000	0.000	-0.000	-0.000
41.016	0.000	0.000	0.000	-0.000	-0.000
41.504	0.000	0.000	0.000	-0.000	-0.000

Software

The following code are listing represents the inverse filter (1st order and 2nd order). After the exponential noise is filtered out, it is ready to move through the lowpass filter for removal of myopotential noise.

```
%-------Filter #1: filter the exponential noise-------%

if (order == 1)
t1 = exp(-b3*step);
b = [1 -t1];
a = [1];
end

if (order ==2)
t1 = exp(-b3*step) * exp (-b3*step);
b = [1 0 -t1];
a = [1];
end

y = filter(b,a,s_quan);            %filter
s_quan=[];
y(1) = 0;
plot(t_quan(1:200),y(1:200))
title('input signal, filter out the exonential')
xlabel('time(sec)'), ylabel('voltage (V)')
grid
t1=0; b=[]; a=[];
```

LOWPASS DIGITAL FILTER

To minimize myopotential noise, the output signal from the inverse filter is filtered by a lowpass digital filter. Myopotential noise has a wide band spectrum from 70 to 1000 Hz (see Figure 13). A lowpass Chebyshev type I filter has a pass band of 50 Hz, or order 2, 4, 6, or 8, is used to filter the myopotential noise.

TABLE IX

LOCATION OF POLES, AND ZEROS BY ORDER

order	i	bi	ai	zeros	poles
N= 2	1	.0163	1.0	-1	.8157+j.1766
	2	.0326	-1.6315	-1	.8157-j.1766
	3	.0163	.6966		
N= 4	1	.025 e-3	1.0	-1	.9044+j.0649
	2	.1001 e-3	-3.7013	-1	.9044-j.0649
	3	.1501 e-3	5.1677	-1	.9463+j.1646
	4	.1001 e-3	-3.2244	-1	.9463-j.1646
	5	.025 e-3	.7584		
N= 6	1	.0371 e-6	1.0	-1	.9354+j.0408
	2	.2225 e-6	-5.7033	-.998-j.0016	.9354-j.0408
	3	.5563 e-6	13.5919	-.979+j.0014	.9464+j.1130
	4	.7418 e-6	-17.3241	-1.0009-j.0024	.9464-j.1130
	5	.5563 e-6	12.4547	-1.0007+j.0025	.9698+j.1585
	6	.2225 e-6	-4.7883	-1.0026+j.0001	.9698-j.1585
	7	.0371 e-6	.7691		
N= 8	1	.0055 e-8	-1.0	-1.0	.9513+j.0300
	2	.0438 e-8	-7.6962	-1.0124-j.0157	.9513-j.0300
	3	.1532 e-8	25.9629	-.9954-j.0193	.9552+j.0860
	4	.3065 e-8	-50.1425	-1.0200	.9552-j.0860
	5	.3831 e-8	60.6377	-.9822-j.0085	.9779+j.1561
	6	.3065 e-8	-47.0169	-1.0124+j.0157	.9779-j.1561

TABLE IX

LOCATION OF POLES, AND ZEROS BY ORDER
(continued)

order	i	bi	ai	zeros	poles
N= 8	7	.1532 e-8	22.8261	-.9822+j.0085	.9637+j.1302
	8	.0438 e-8	-6.3438	-.9954+j.0193	.9637-j.1302
	9	.0055 e-8	.7727		

Software

The folowing code listing represents the lowpass filter Chebyshev type I of the stimulation. After the myopotential noise is filtered out, it is ready to move through the threshold level detector.

```
%-------Filter #2: filter the myopotential noise-------%

y = filter(b,a,s_quan);                %filter
s_quan=[];
y(1) = 0;
plot(t_quan(1:200),y(1:200))
title('input signal, filter out the exonential')
xlabel('time(sec)'), ylabel('voltage (V)')
grid
t1=0; b=[]; a=[];

rp2 = .1; Wn2 = (2*50)/fs;
[Bc2,Ac2] = chebyl (Nc2, rp2, Wn2);
yf = filter(Bc2,Ac2,y);
y = [];
Nc2=0; Wn2=0; Rp2=0; Bc2=[]; Ac2=[];
plot(t_quan(1:200),yf(1:200))
title('input signal, filter out the myopotential')
xlabel('time (sec)'), ylabel('voltage (V)')
grid
```

A z-transform of a differential equation for a digital filter yields the following frequency domain or transfer function model description:

$$H(z) = \frac{[b1\ b2\ b3\ b4\ b5\ b6\ b7\ b8\ b9]}{[1\ \ a2\ a3\ a4\ a5\ a6\ a7\ a8\ a9]}$$

Table IX shows the filter coefficients, location of poles and the zeros of the lowpass filter for order 2, 4, 6, and 8. Figure 44 shows the magnitude reskponse of the lowpass digital filter with different orders 2, 4, 6, and 8. Figure 36 shows the lowpass filter's output is clear of myopotential noise.

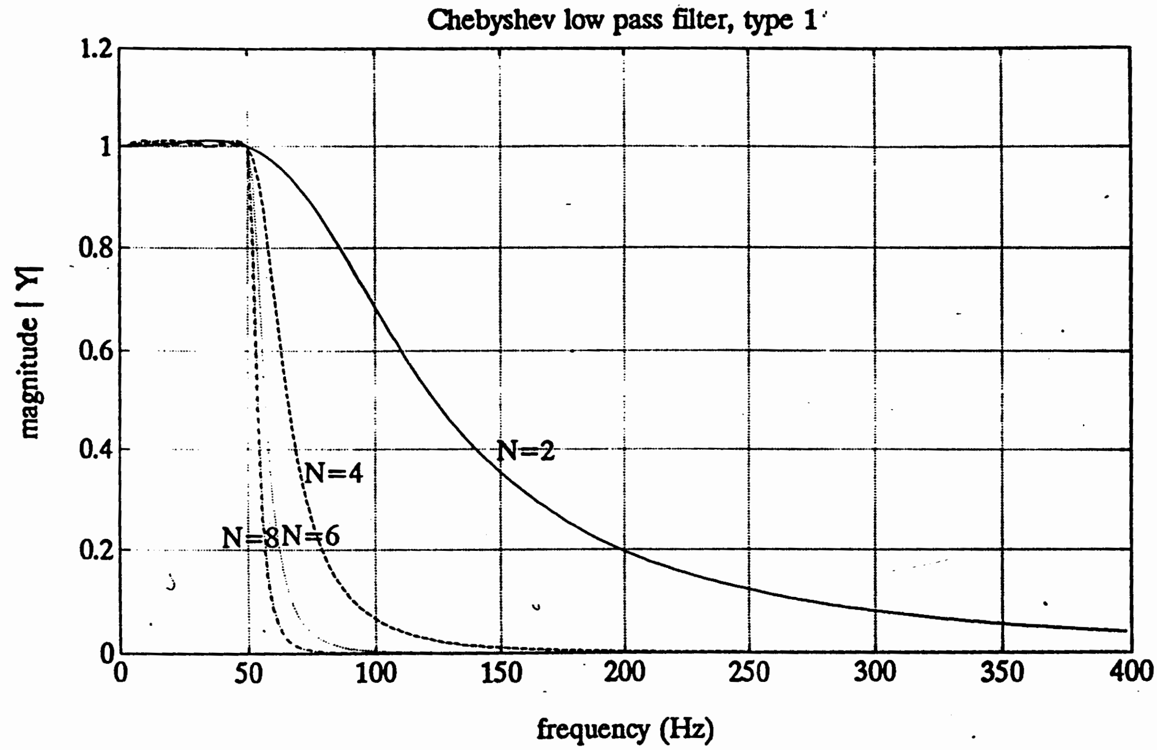


Figure 44. Magnitude of lowpass filter Chebyshev type I.

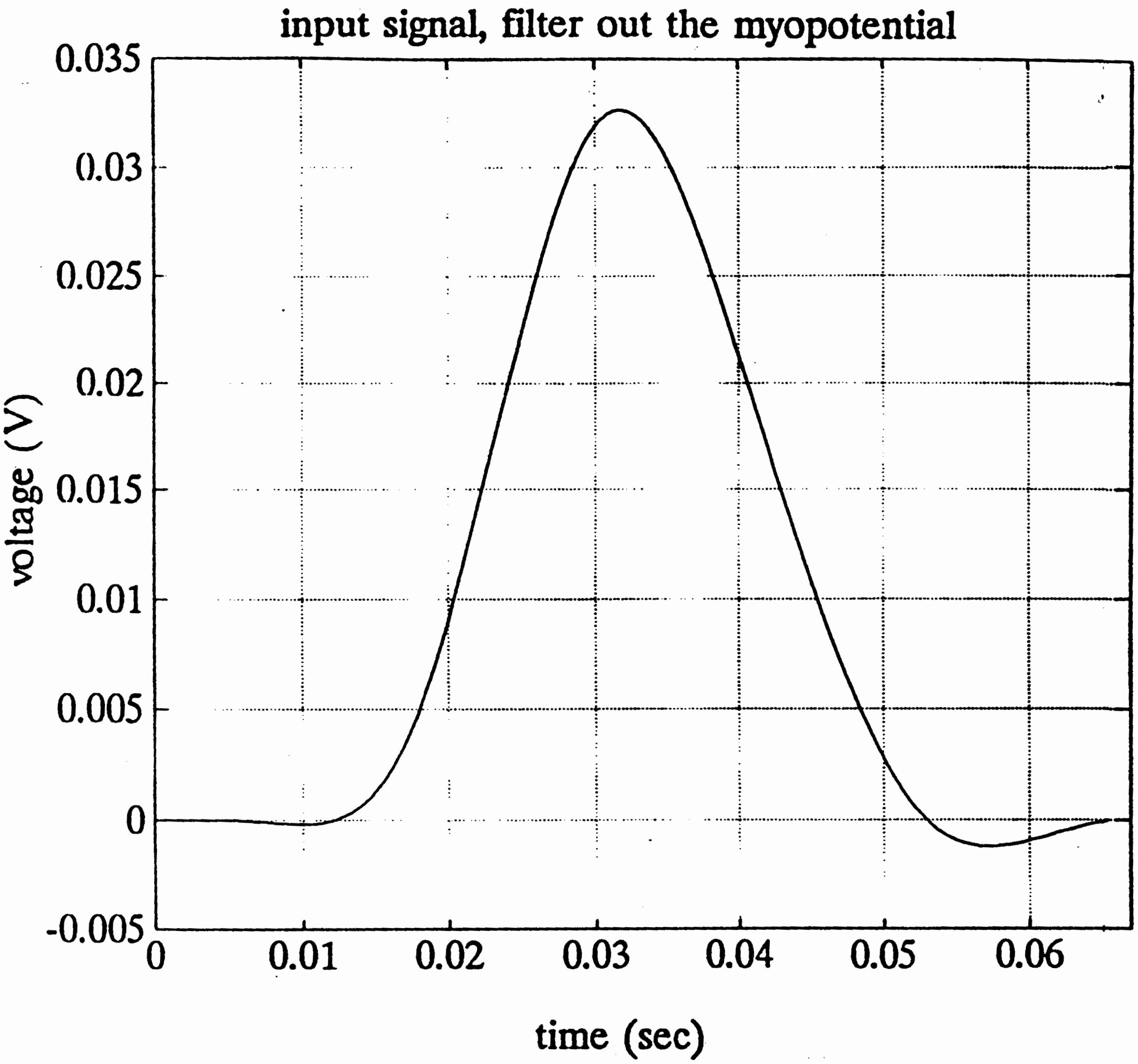


Figure 45. Lowpass filter filter out myopotential.

THRESHOLD LEVEL DETECTOR

The threshold level detector in the simulation can be set to any level. Signals that exceed this level are detected. In the simulation, this function corresponds to the pacemaker's sensor function. Figure 46 below shows the results of running the simulation as seen by the threshold level detector.

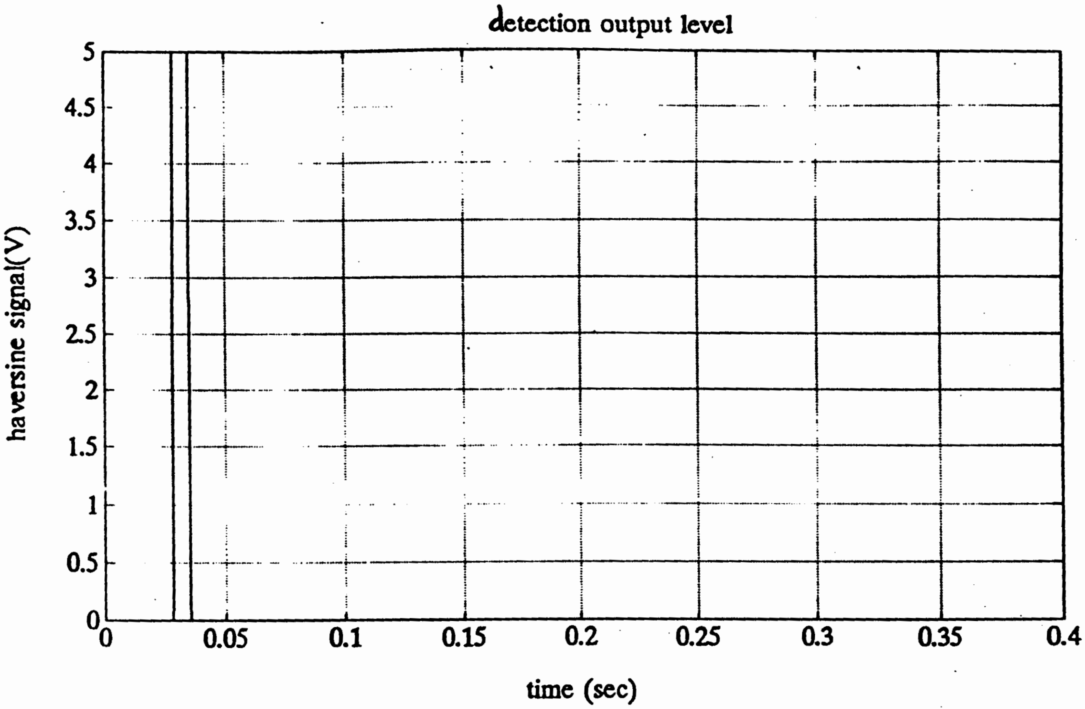


Figure 46. Detect output level.

Software

The following code lisitng represent the threshold level detector of the simulation.

```
%-----------threshold level = +/- .2V-------%

level1 = 5;
level0 = 0;
th_hold = [];
l1 = 0;
l1 = length(yf);
h = 0;
while (h <= (l1 - 1))
        h = h +1;
        if (abs(yf(h)) >= VHOLD)
                th_hold(h) = level1;
        end
        if (abs(yf(h)) < VHOLD)
                th_hold(h) = level 0;
        end
```

```
end
h=0;
yf=[];
plot(t_quan,th_hold)
title('detection output level')
xlabel('time (sec)'), ylabel('haversine signal (V)')
grid
t_quan=[]; th_hold=[]; h=0; l1=0;
```

CHAPTER X

CONCLUSIONS

This chapter presents conclusions based on the test system. The conclusions include a description of limitations suggested by test runs of the simulation.

PROCEDURE SUMMARY

Using MATLAB as supporting software, the simulation program is written for operation in a DOS environment. The program generates a haversine signal, myopotential noise (random noise), and exponential noise. All three signals are combined and sent through an amplifier stage and an A/D converter stage. The exponential noise is filter out by an inverse digital filter, and the myopotential noise is filtered out by a lowpass digital filter. The output signal is deemed "detected" if its waveform exceeds threshold level.

CONCLUSIONS

The inverse filter is designed to eliminate the effects of the exponential response following a pace pulse, such that the resultant haversine signal is recognized. First order and second order systems are used to represent the exponential signal. An inverse filter is used to filter out the exponential signal.

Tests show that the haversine signal can be clearly sensed if there is a 5% change in the time constant of the exponential. Within a 5 to 15% change of the time constant, the filtered exponential amplitude swamps out the haversine. See Tables I, II, III, and IV.

The sensitivity of the inverse filter was also studied:when using a fixed exponential time constant but changing the location of the zeros, the effect of the exponential noise on the haversine signal is minimal when zeros are located between 0.75 to 0.85 of the unit circle. See Tables V, VI, VII, and VIII.

The lowpass digital filter is used to filter out the myopotential noise. Tests showed that an order of 8 for the lowpass filter was most successful for this purpose.

REFERENCES

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Yoshio Watanabe, Tokyo March 14 - 18, 1976. "Cardiac Pacing" *Proceeding of the Vth International Symposium.*

APPENDIX A

SOFTWARE

This program is using MATLAB tool. It is written by
Merry Tran.

It includes:

1. create a haversine signal
2. create a exponential noise
3. create a myopotential noise
4. amplifier signal
5. sample and hold
6. quantization
7. filter out the exponential noise
8. filter out the myopotential noise
9. threshold

```
clear
%*******************Input information*******************%

fs = input ('Enter sampling frequency (Hz) [fs] ==>');
tf = input ('Enter max on time axis (sec) [tf]  ==>');
step = 1/fs;
t = 0:step:tf;              % time axis
n = 512;                    % number of point
ff = fs/ (2*n) * (0:n-1);   % sampling frequency (Hz)

disp('---------haversine signal------------------');
amp=0; pw=0;per=0;
amp  = input ('Enter the amplitude (V) [amp] ==>');
pw   = input ('Enter the pulse width (sec) [pw] ==>');
per  = input ('Enter the period (sec) [per] ==>');

disp('--Exponential signal : 1st & 2nd order-----');
a3=0; b3=0; order=0;
a3    = input ('Enter the amplitude (V) [a3] ==>');
b3    = input ('Enter the time constant (1/sec) [b3] ==>');
order = input ('Enter the order of system [order] ==>');

disp('-------Myopotential noise------------------');
amy=0;
amy = input ('Enter the amplitude (max=.005 V) [amy] ==>');
```

```
disp('-------Amplifier---------');
gain=0;
gain = input ('Enter the gain amplifier [gain] ==>');

disp('-------Quantization-------------');
VFS=0; bits=0; maxcount=0; delta=0;
VFS = input ('Enter volts full scale (V) [VFS] ==>');
bits= input ('Enter number of bits solution [bits] ==>');
maxcount = (2^bits)-1;  %number of quantizer points
delta = VFS/maxcount;  %voltage resolution at quantizer output


disp ('--Filter out the myopotential,Chebyshev lowpass filter--');

Nc2=0;
Nc2 = input ('Enter the order of filter [Nc2] ==>');


disp('-------Threshold-------------');
VHOLD=0;
VHOLD = input ('Enter threshold level (V) [VHOLD] ==>');


%**************Calculation*********************%

%-----------haversine signal-------------------%
duty=0;
duty = (pw/per)*100;            %duty cycle
temp1 = ((amp/2)*(1-cos(2*pi*t/pw)));
temp2 = ((1+square(2*pi*t/per, duty))/2);
hav1 = temp1 .* temp2;
temp1 = []; temp2=[];
%-----------exponential noise------------------%

if (order == 1)
	exp3 = a3 * exp (-b3*t);
end
if (order == 2)
	exp3 = ((a3/2)*exp(-b3*t)) .* (1 + cos(pi*t/step));
end
```

```
%-----------myopotential noise-----------------%

rand ('uniform')   % uniformly distributed random noise
y = amy*rand(t);   % noise, standard deviation = .005
ripple = .1;       % allowable ripple, in decibels
N = 8;                     %filter order
passband = [(2*70)/fs  (2*1000)/fs]; % passband specification
[Bc,Ac] = chebyl (N, ripple, passband);
myo = filter (Bc,Ac,y);   % filter
y=[]; Bc=[]; Ac=[];
%---- Input signal = haversine + exponential + myopotential ----%

disp('you can test filters by following menu:');
disp('1=exponential,2=haversine,3=myopotential');
disp('4=exponential+haversine,5=exp.+haversine+myo.');
no = input('enter number, [no]==>');
if(no ==1)
        s_in = exp3;
end
if(no == 2)
        s_in = hav1;
end
if (no ==3)
      s_in = myo;
end
if(no == 4)
        s_in = hav1 + exp3:
end
if(no == 5)
        s_in = exp3+hav1+myo;
end
no=0;
plot(t(1:200),s_in(1:200))
title('input signal=myopotential+haversine+exponential')
xlable('time (sec)'), ylabel('voltage (V) ')
grid

%--------------Amplifier------------------%

s_in = gain * s_in;
```

```
plot(t(1:200),s_in(1:200))
title('amplifier the input signal')
xlabel('time (sec)'), ylabel('voltage (V) ')
grid
%----------sample and hold---------------%
holdtime = step;
holdsample = ceil(holdtime/step);
m = length(s_in);
s_hold = [];
t_hold = [];
s_hold(l) = s_in(l);
t_hold(l) = t(l);

k = 1;
num = 1;
while (k <= (m-1))
        k = k + 1;
        num = (k/holdsample) - fix(k/holdsample);
        if(num > 0)
                s_hold(k) = s_hold(k-1);
                t_hold(k) = t (k);
        end
end
s_in=[]; t=[]; holdtime=0; holdsample=0; m=0; k=0; num=0;

plot(t_hold(1:200),s_hold(1:200))
title('sample and hold the input signal')
xlabel('time (sec)'),ylabel('voltage (V)')
grid

%--------quantizer the input signal--------------%

l = 0;
l = length(s_hold);
q = 0;
s_quan=[];
t_quan=[];
s_inq=[];
while (q <= (l-1))
        q=q+1;
        num1 = abs(s_hold(q));
        num2 = sign(s_hold(q));
        s_inq(q) = s_hold(q);
```

```
        if(num1 > VFS)
                s_quan(q) = num2 * VFS;
                t_quan(q) = t_hold(q);
        end
        if (num1 <= VFS)
                s_quan(q) = num2 * delta * round((maxcount*num1)/VFS;
                t_quan(q) = t_hold(q);
        end
end
1=0; q=0; num1=0; num2=0; s_hold=[]; t_hold=[];

plot(s_inq,s_quan)
title('quantize the input signal')
xlabel('input signal (V)'), ylabel('quantized input signal (V)')
grid
s_inq=[];
plot(t_quan(1:200),s_quan(1:200))
title('quantize the input signal')
xlabel('time (sec)'), ylabel('quantize input signal(V)')
grid

%-------Filter #1: filter the exponential noise-------%

if (order == 1)
t1 = exp(-b3*step);
 b = [1 -t1];
 a = [1];
end

if (order ==2)
 t1 = exp(-b3*step) * exp (-b3*step);
 b = [1 0 -t1];
 a = [1];
end

y = filter(b,a,s_quan);                    %filter
s_quan=[];
y(1) = 0;
plot(t_quan(1:200),y(1:200))
title('input signal, filter out the exonential')
xlabel('time(sec)'), ylabel('voltage (V)')
grid
t1=0; b=[]; a=[];
```

```
%-------Filter #2: filter the myopotential noise-------%

rp2 = .1; Wn2 = (2*50)/fs;
[Bc2,Ac2] = chebyl (Nc2, rp2, Wn2);
yf = filter(Bc2,Ac2,y);
y = [];
Nc2=0; Wn2=0; Rp2=0; Bc2=[]; Ac2=[];
plot(t_quan(1:200),yf(1:200))
title('input signal, filter out the myopotential')
xlabel('time (sec)'), ylabel('voltage (V)')
grid

%-----------threshold level = +/- .2V-------%

level1 = 5;
level0 = 0;
th_hold = [];
l1 = 0;
l1 = length(yf);
h = 0;
while (h <= (l1 - 1))
        h = h +1;
        if (abs(yf(h)) >= VHOLD)
                th_hold(h) = level1;
        end
        if (abs(yf(h)) < VHOLD)
                th_hold(h) = level 0;
        end

end
h=0;
yf=[];
plot(t_quan,th_hold)
title('detection output level')
xlabel('time (sec)'), ylabel('haversine signal (V)')
grid
t_quan=[]; th_hold=[]; h=0; l1=0;
```

APPENDIX B

GLOSSARY

GLOSSARY

- *amplifier,* The signal amplification stage. The amplifier increases the visibility of the haversine signal.
- *analog to digital converter (A/D converter),* The A/D converter transforms an analog signal into a binary signal.
- *Atrial representation,* Atrial contracts and produces a P wave that is simulated with the haversine waveform.
- *Bandpass filter,* A signal filter which allows only signals that fall within a preset band to pass through.
- *Bipolar configuration,* A pacemaker with two leads.
- *Cardiac Cycle.* The rhythmic contraction and expansion of the heart muscle. For the purposes of this paper, the signals which result from depolarization and repolarization.
- *Depolarization,* A muscle cell receiving a stimulus and contracting or a nerve cell receiving stimulus and transmitting the stimulus to the next nerve.
- *Digital Filter,* A signal filter designed to evaluate a binary signal, identify some component of that signal and remove interfering components.
- *Duty cycle,* The peak of the square wave used to create the haversine signal.
- *ECG,* An Electro Cardio Graph records signals from the cardiac cycle on a trace sheet.
- *Exponential noise,* Exponential signal decay after the trailing edge of a pace pulse.

- *Implanted Leads,* Electrodes which extend from the pacemaker and have been surgically attached to the trigger nodes of the heart.
- *myocardium,* Tissue of the wall of the heart to which the implanted leads are connected.
- *myopotential noise,* Myopotential noise is interfering noise generated by the contraction of skeletal muscles.
- *Pace pulse,* The electrical charge sent by the pacemaker to the heart.
- *Pulse generator,* The part of a pacemaker that actually creates the electrical pulse. Usually the pulse generator consists of a timer and a battery.
- *pulse interval,* The time periodic between pulses of electrical energy, or the distance between two pacings.
- *pulse width,*The time during which electrical energy is being delivered to the heart, it is measured from the leading edge to the trailing edge of the pace pulse.
- *QRS,* or simply an R wave, is a large signal generated during depolarization of the ventricular. This is the beginning of ventricular contraction.
- *R wave,* or simply a QRS wave, is a large signal generated during depolarization of the ventricular. This is the beginning of ventricular contraction.
- *Repolarization,* Recovery of a cell from depolarization so that it is ready to receive the next stimulus.
- *S_A node,* The Sino-Atrial is the point at which depolarization begins in the atrium.
- *S_V node,* The Sino-ventricular node is the point at which depolarization begins in a ventricular contraction.

- *Threshold detector,* The threshold detector examines the returning signal for the haversine signal.
- *Unipolar pacing,* A pacemaker with a single implanted lead which is used for both sending the pace pulse and sensing responses.
- *Ventricular representation,* The Ventricular contracts and produces a QRS wave that is simulated with the haversine waveform.