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Chapter 1

Introduction and Problem Statement

1.1 Overview

This report examines the design and implementation of various digital filter types using LabVIEW. The primary focus is on understanding the behavior of different filter prototypes, including Butterworth, Chebyshev Type I, Chebyshev Type II (Inverse Chebyshev), Elliptic, and Bessel filters. By comparing their frequency responses across different configurations (low-pass, high-pass, band-pass, and band-stop), we gain comprehensive insights into their characteristics and appropriate applications.

1.2 Objectives

The primary objectives of this report are:

- To implement various filter types using LabVIEW's filter design tools.
- To analyze and compare the frequency responses of different filter prototypes.
- To understand the trade-offs between different filter characteristics, such as passband ripple, stopband attenuation, and roll-off steepness.
- To determine the optimal filter type for specific signal processing applications.

1.3 Problem Statement

The assignment requires the design and analysis of five filter types:

- Bessel Filter

- Butterworth Filter
- Chebyshev Type I Filter
- Elliptic (Cauer) Filter
- Chebyshev Type II (Inverse Chebyshev) Filter

Each filter is to be configured in four different topologies:

- Low-pass
- High-pass
- Band-pass
- Band-stop

The filter parameters are:

- Sampling frequency (f_s): 1000 Hz
- Low cutoff frequency (f_l): 100 Hz
- High cutoff frequency (f_h): 300 Hz
- Filter order: 46
- Passband ripple (where applicable): 0.1 dB
- Stopband attenuation (where applicable): 40 dB

1.4 System Description

The analysis is performed using LabVIEW's filter design and frequency response VIs. Figure 1.1 shows the LabVIEW block diagram used to compute and display the magnitude response of a user-configured infinite-impulse-response (IIR) filter in real time.

On the left side of the diagram, a set of front-panel controls allows the user to select both the filter prototype and the filter topology. In addition, numeric inputs specify the sampling rate, cutoff frequencies (lower and upper), filter order, passband ripple, and stopband attenuation.

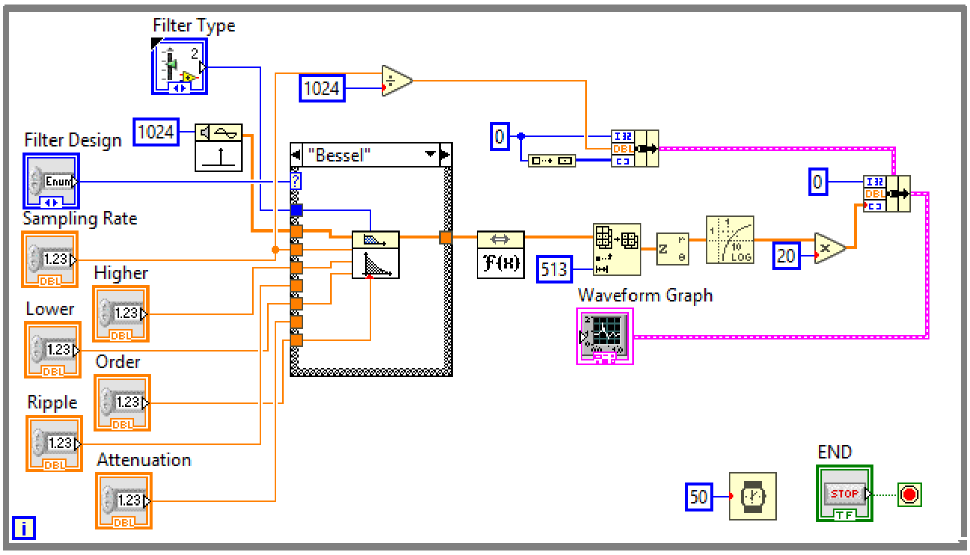

Figure 1.1: LabVIEW Block Diagram for Filter Analysis

These parameters are wired into the IIR Filter Design Express VI, which calculates the digital filter coefficients (numerator and denominator) according to the chosen approximation and design specifications.

Once the coefficients are available, they feed into the Frequency Response VI along with a constant defining the number of frequency-domain samples (513). The complex output $H(e^{j\omega})$ is then converted to magnitude, transformed to decibels via a $20{\cdot}\log_{10}$ operation, and bundled into a waveform data type. That waveform is plotted on the Waveform Graph, giving an immediate plot of magnitude (dB) versus normalized frequency. All of this logic is wrapped in a while-loop—with a 50 ms wait and a STOP button—so that any adjustment of filter parameters instantly regenerates and redraws the magnitude response.

Chapter 2

LabVIEW Implementation of Filters

2.1 Filter Virtual Instruments (VIs)

LabVIEW provides a comprehensive set of VIs for implementing different filter types. This section describes the inputs, outputs, and functionality of each filter design VI used in this assignment.

2.1.1 Bessel Filter

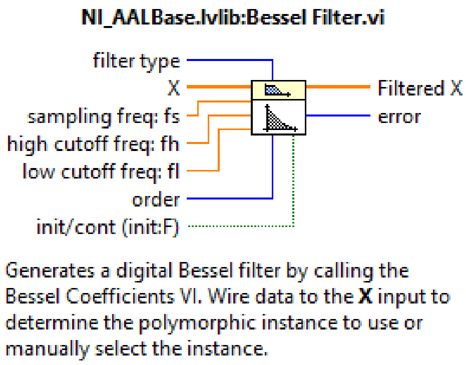

Figure 2.1: Bessel Filter VI Inputs and Outputs

The Bessel Filter VI (NI_AALBase.lvlib:Bessel Filter.vi) has the following inputs and outputs:

Inputs:

- **filter type (enum):** low-pass, high-pass, band-pass or band-stop
- **X:** the raw data waveform or array to be filtered
- **sampling freq (fs):** the signal's sampling rate (Hz)
- **high cutoff freq (fh), low cutoff freq (fl):** the corner frequencies (Hz) defining the passband or stopband

- **order:** the filter order (polynomial degree)
- **init/cont (init F):** a Boolean toggle—TRUE to (re)initialize the filter's state, FALSE to continue filtering from its last state

Outputs:

- **Filtered X:** the data after passing through the Bessel IIR filter
- **error:** standard LabVIEW error cluster

Functionality: The VI internally calls the Bessel Coefficients VI to compute the digital Bessel polynomial for the specified order and cutoffs, then applies that IIR filter to the X input.

2.1.2 Butterworth Filter

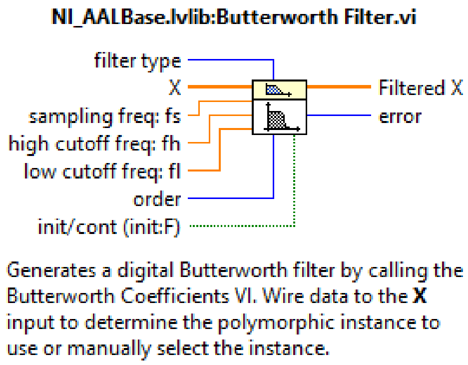

Figure 2.2: Butterworth Filter VI Inputs and Outputs

The Butterworth Filter VI (NI_AALBase.lvlib:Butterworth Filter.vi) has the same inputs and outputs as the Bessel Filter VI:

Inputs: filter type, X, sampling freq, high/low cutoff freqs, order, init/cont flag

Outputs: Filtered X, error

Functionality: Instead of Bessel, it calls the Butterworth Coefficients VI—yielding the maximally flat (in-band) response—for whatever filter type and order chosen, and then filters the data.

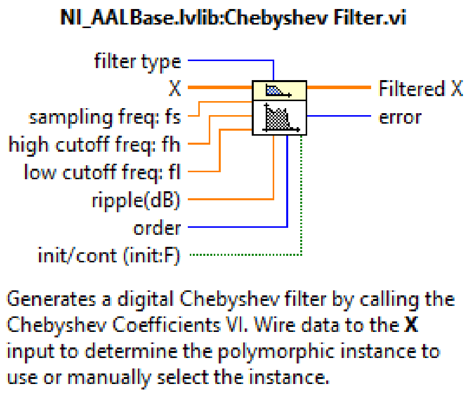

Figure 2.3: Chebyshev Type I Filter VI Inputs and Outputs

2.1.3 Chebyshev Type I Filter

The Chebyshev Type I Filter VI (NI_AALBase.lvlib:Chebyshev Filter.vi) includes all of the Butterworth inputs, plus:

Additional Input:

- **ripple (dB):** the allowable passband ripple (ε), in dB

Outputs: Filtered X, error

Functionality: Calls the Chebyshev Coefficients VI to generate an IIR filter whose magnitude response oscillates within the specified ripple in the passband (for low/high) or in each passband of a band-pass/stop design.

2.1.4 Elliptic (Cauer) Filter

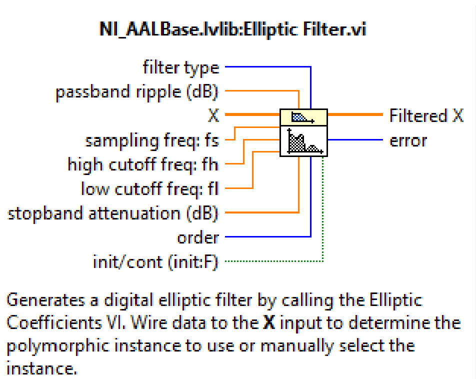

Figure 2.4: Elliptic Filter VI Inputs and Outputs

The Elliptic Filter VI (NI_AALBase.lvlib:Elliptic Filter.vi) has the following inputs and outputs:

Inputs:

- **filter type**
- **passband ripple (dB)**
- **sampling freq (fs)**
- **high cutoff freq (fh), low cutoff freq (fl)**
- **stopband attenuation (dB):** the minimum attenuation outside the passband
- **order**
- **init/cont**

Outputs: Filtered X, error

Functionality: Uses the Elliptic Coefficients VI to produce the steepest roll-off filter for a given order, with user-specified ripple in the passband and attenuation in the stopband, then filters the data.

2.1.5 Chebyshev Type II (Inverse Chebyshev) Filter

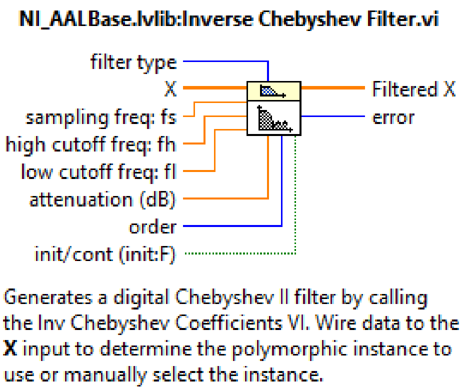

Figure 2.5: Inverse Chebyshev Filter VI Inputs and Outputs

The Inverse Chebyshev Filter VI (NI_AALBase.lvlib:Inverse Chebyshev Filter.vi) is similar to Butterworth, except the ripple control is replaced by:

Additional Input:

- **attenuation (dB):** the stopband ripple spec (ε')

Outputs: Filtered X, error

Functionality: Calls the Inverse Chebyshev Coefficients VI, yielding a filter with an equi-ripple characteristic in the stopband (rather than the passband), then applies it to X.

2.2 Filter Block Diagrams

Each filter type is implemented using a specific block diagram that configures the appropriate coefficients and applies them to process the input signal. Figures 2.6, 2.7, 2.8, 2.9, and 2.10 show the block diagrams for each filter type.

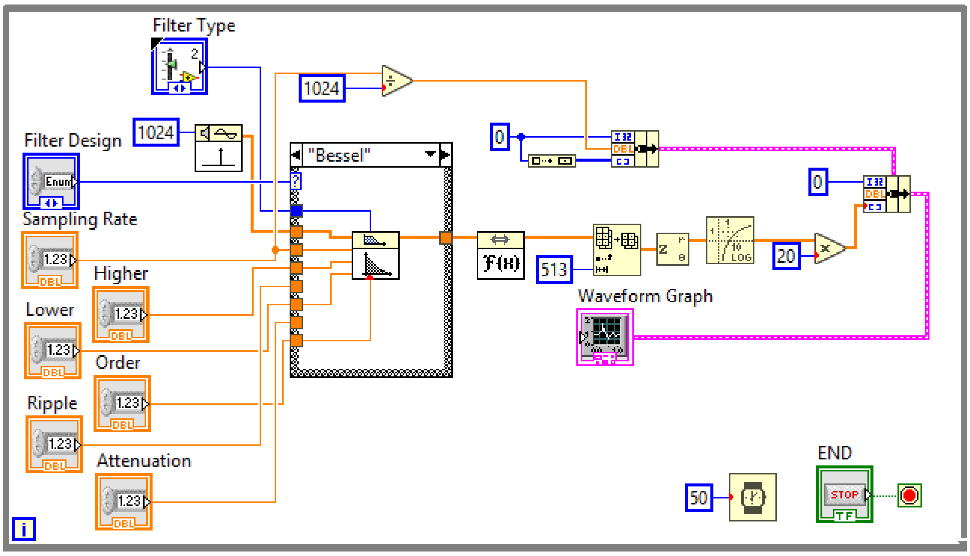

Figure 2.6: Block Diagram for Bessel Filter

In all cases, the user feeds in a signal plus design parameters, the VI computes the IIR coefficients via its respective "Coefficients" subVI, and finally the built-in filter engine applies those coefficients to produce the filtered output (Filtered X) and any error information.

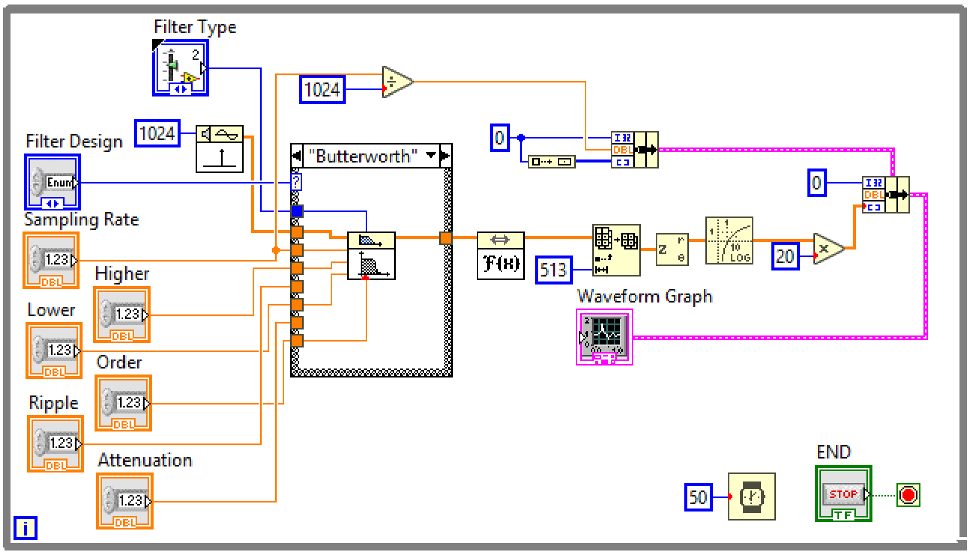

Figure 2.7: Block Diagram for Butterworth Filter

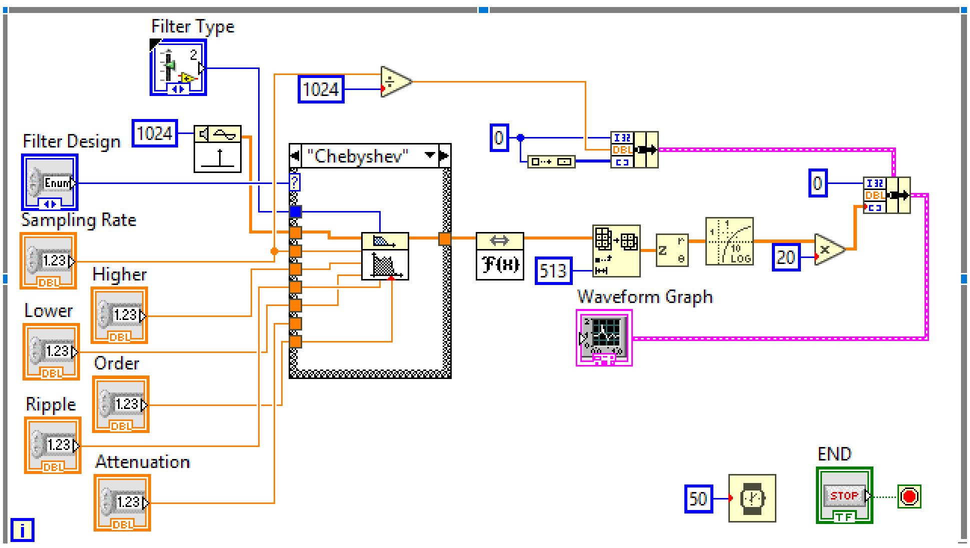

Figure 2.8: Block Diagram for Chebyshev Type I Filter

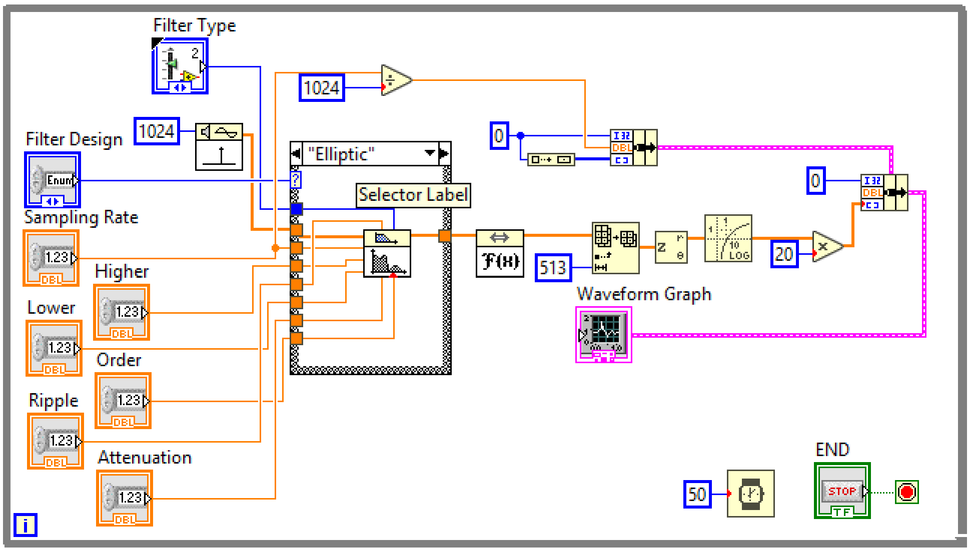

Figure 2.9: Block Diagram for Elliptic Filter

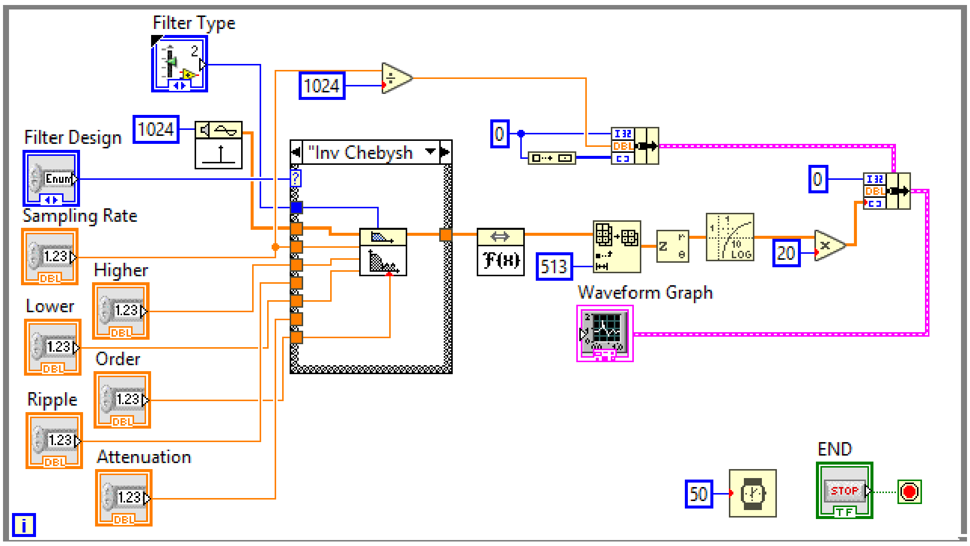

Figure 2.10: Block Diagram for Inverse Chebyshev Filter

Chapter 3

Filter Types and Characteristics

3.1 Bessel Filter

Bessel filters are characterized by their maximally flat group delay (linear phase) in the pass-band. This comes at the expense of a gradual roll-off in the transition region. The Bessel response is optimized for preserving the wave shape of filtered signals in the passband.

3.1.1 Bessel Band-pass

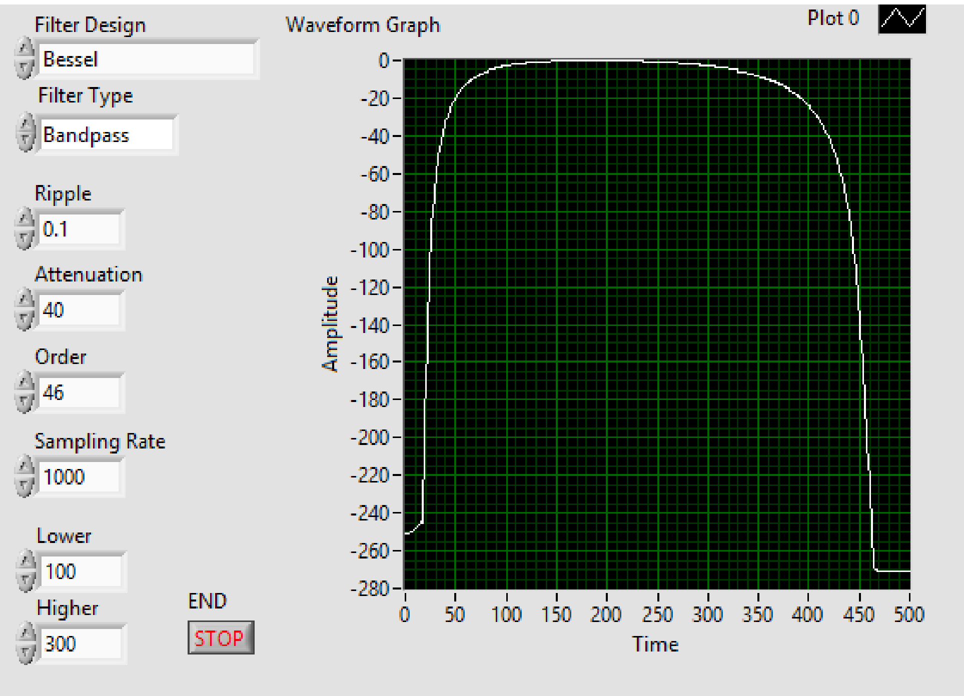

Figure 3.1: Bessel Band-pass Response

The Bessel band-pass response (Figure 3.1) shows the following characteristics:

- **Pass-band:** Between roughly 100 Hz and 300 Hz (index 50-150), the response sits essentially at 0 dB (flat top).

- **Stop-bands:** Below ∼100 Hz and above ∼300 Hz the attenuation climbs smoothly, exceeding 40 dB by ∼30 Hz/370 Hz and ultimately dropping below –200 dB at the extremes.
- **Transition slopes:** Noticeably gentle compared to Chebyshev or elliptic designs—Bessel sacrifices roll-off steepness to preserve a maximally flat group delay across the pass-band.

3.1.2 Bessel Band-stop

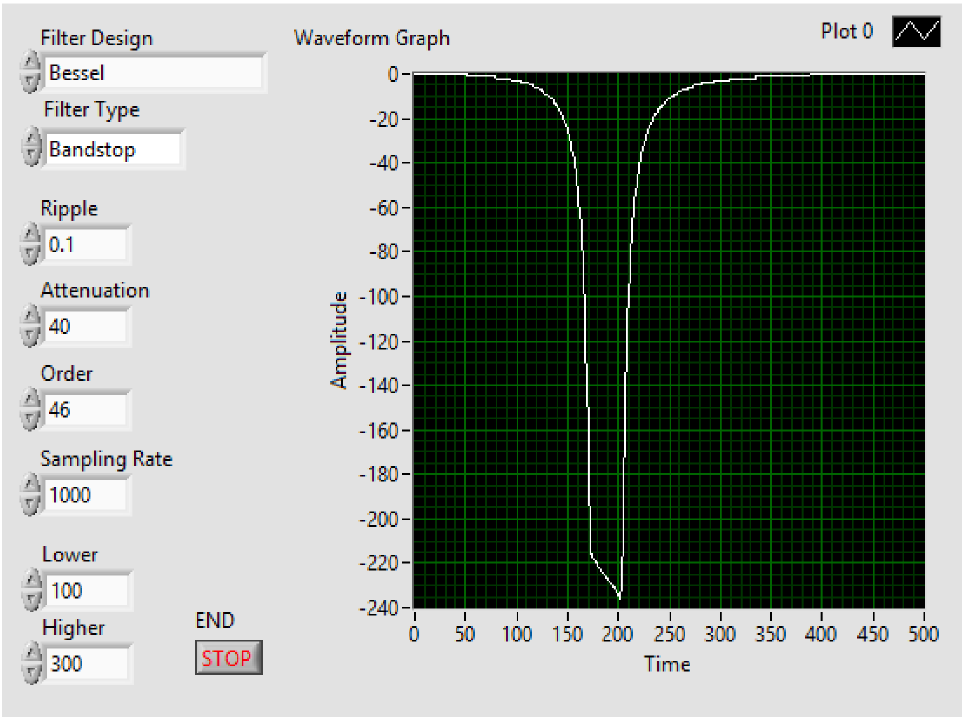

Figure 3.2: Bessel Band-stop Response

The Bessel band-stop response (Figure 3.2) exhibits:

- **Notch:** Deep attenuation (well below –200 dB) centered between 100–300 Hz (index 50–150), so frequencies in that band are almost completely suppressed.
- **Pass-bands:** Below ∼100 Hz and above ∼300 Hz the filter passes with ¡1 dB ripple, flattening out near 0 dB.
- **Skirts:** The edges of the notch roll-off gradually, again reflecting the Bessel prototype's smooth phase response rather than a razor-sharp magnitude cutoff.

3.1.3 Bessel High-pass

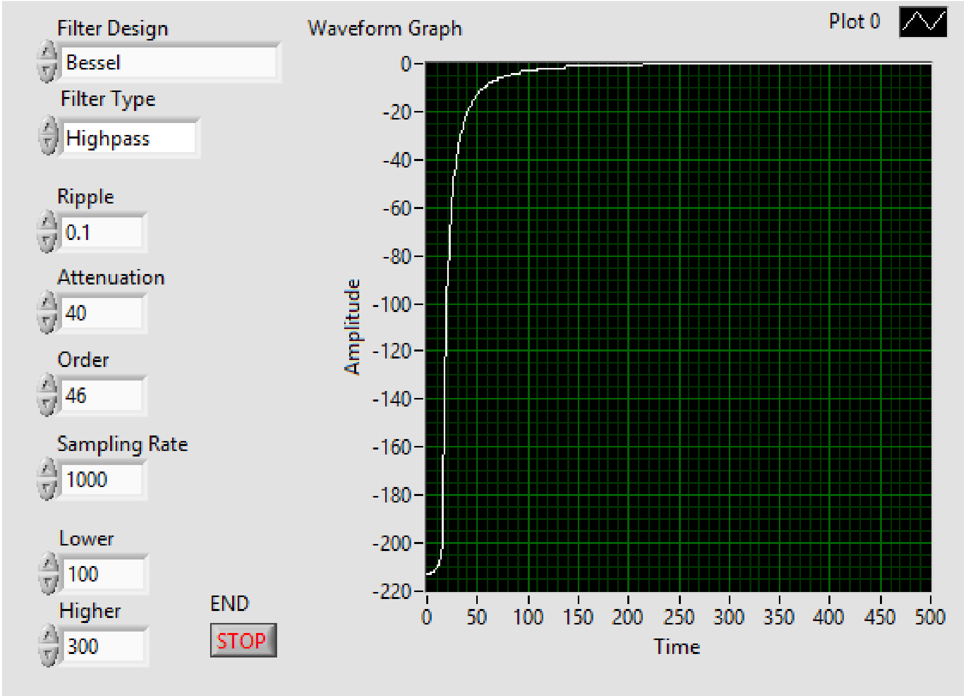

Figure 3.3: Bessel High-pass Response

The Bessel high-pass response (Figure 3.3) shows:

- **Cutoff:** The –3 dB corner occurs at ∼index 50 (≈100 Hz).
- **Stop-band:** DC and low frequencies are driven down below –200 dB, so essentially nothing passes below ∼80 Hz.
- **Pass-band:** Above ∼120 Hz the response is flat at 0 dB.
- **Slope:** A very smooth, gradual rise through the transition—ideal if you need constant group delay at the expense of a wide transition region.

3.1.4 Bessel Low-pass

The Bessel low-pass response (Figure 3.4) features:

- **Pass-band:** From DC up to index 150 (≈300 Hz) the magnitude is nearly 0 dB.
- **Transition:** The roll-off begins just after the cutoff and reaches –40 dB by ∼index 175 (≈350 Hz), eventually descending below –300 dB at high indices.

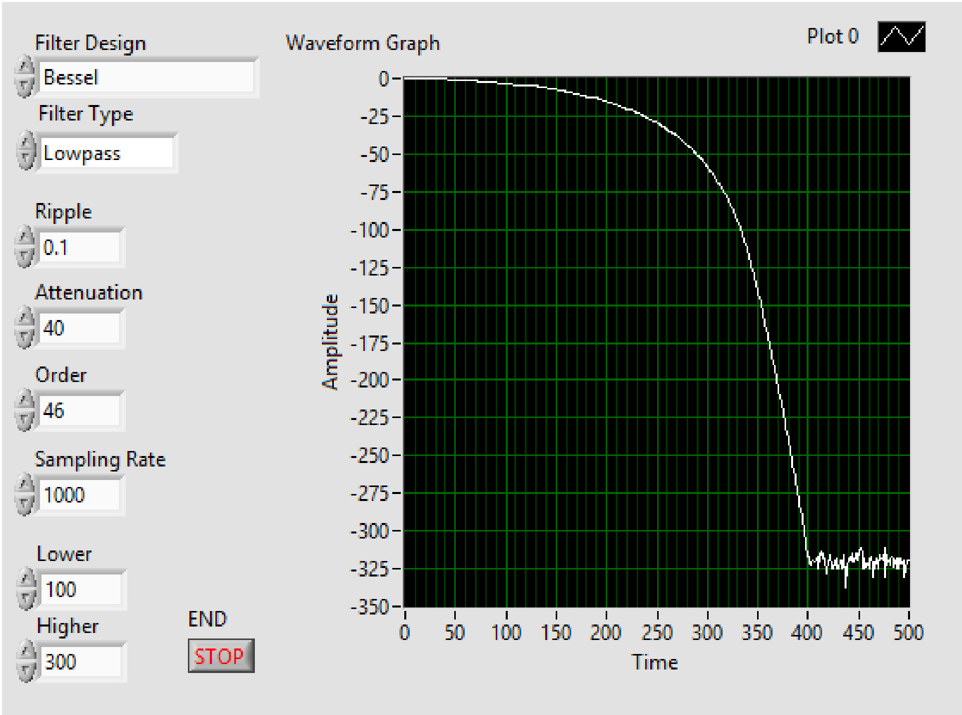

Figure 3.4: Bessel Low-pass Response

- **Behavior:** The gentle knee and flat top typify a Bessel low-pass—excellent amplitude flatness in-band and linear phase, but slower attenuation outside the pass-band.

3.2 Butterworth Filter

Butterworth filters provide a maximally flat magnitude response in the passband with no ripple. They offer a moderate roll-off in the transition region, falling between Bessel filters (slower roll-off) and Chebyshev filters (steeper roll-off).

3.2.1 Butterworth Band-pass

The Butterworth band-pass response (Figure 3.5) is perfectly flat at 0 dB between 100 Hz and 300 Hz, with a maximally smooth, monotonic skirt on either side. The –3 dB points sit almost exactly at the user-specified cutoffs, and the attenuation climbs steadily—about –40 dB just outside the pass-band edges and well below –120 dB toward DC and Nyquist. This archetypal ”no ripple, gentle roll-off” response makes Butterworth ideal when you care most about in-band flatness.

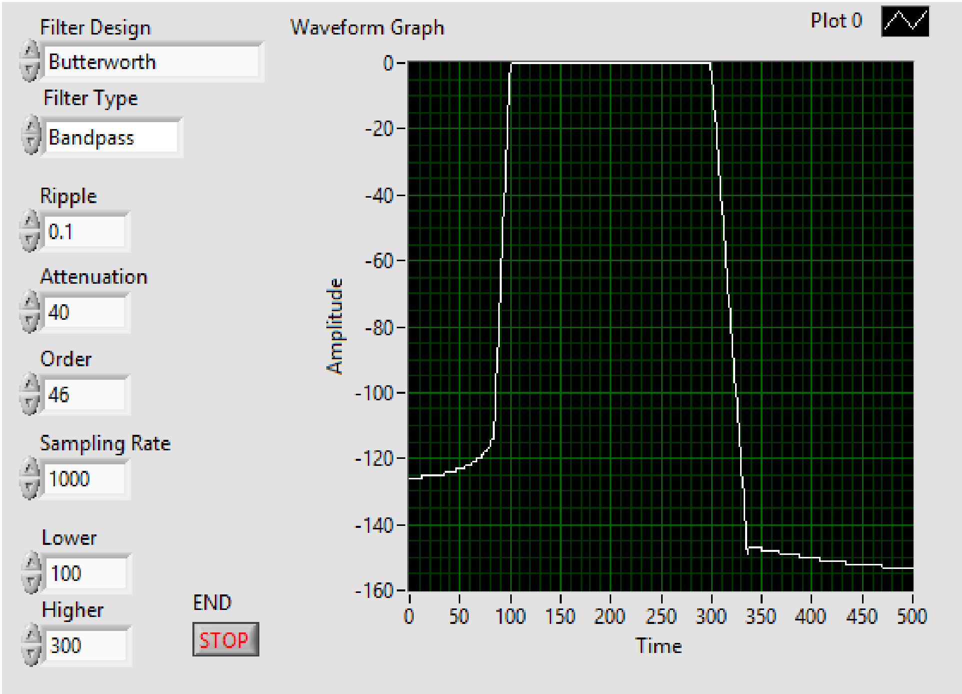

Figure 3.5: Butterworth Band-pass Response

3.2.2 Butterworth Band-stop

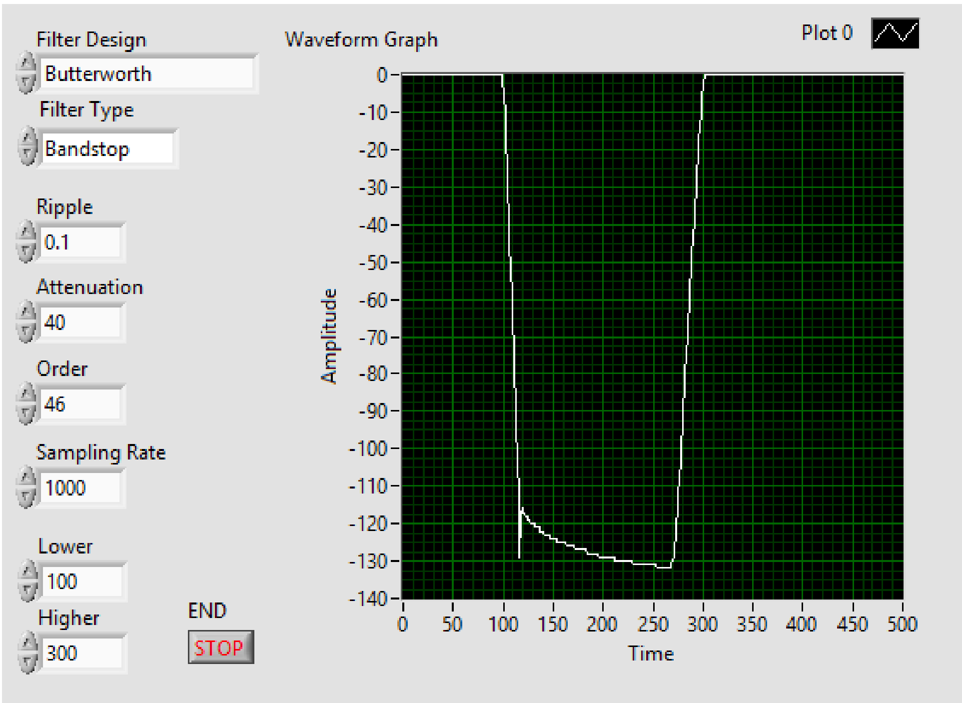

Figure 3.6: Butterworth Band-stop Response

In the band-stop view (Figure 3.6), you see a deep notch from 100 Hz to 300 Hz, the attenuation bottoming out near –125 dB at the center. Outside the notch, both low and high-frequency pass-bands return to 0 dB without any ripple. Again, the skirts into and out of the stop-band are gradual and monotonic, characteristic of the Butterworth prototype.

3.2.3 Butterworth High-pass

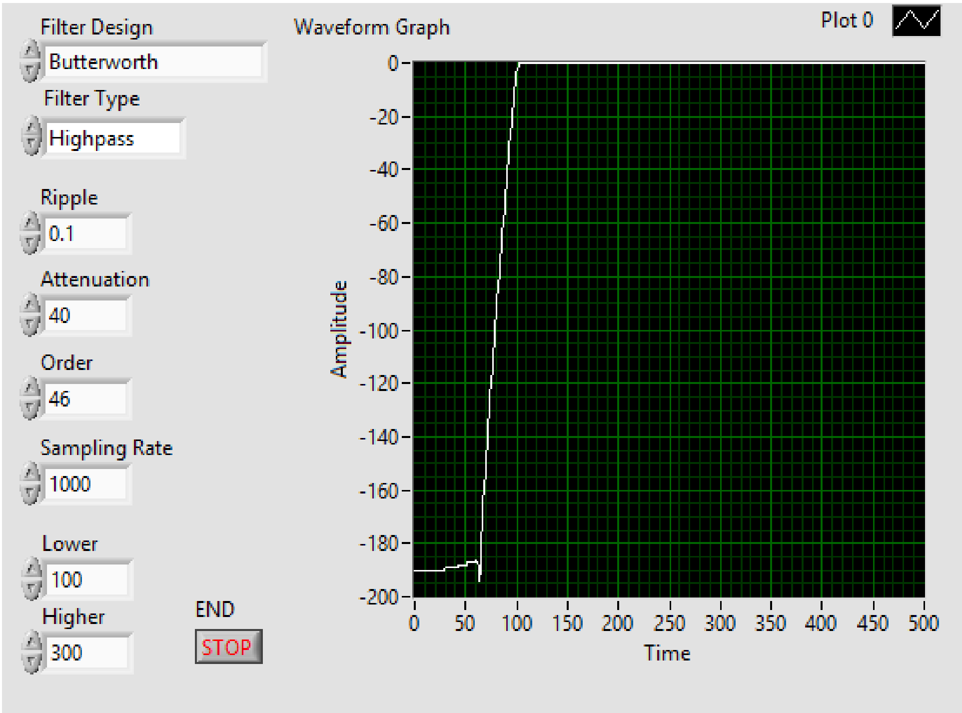

Figure 3.7: Butterworth High-pass Response

The high-pass curve (Figure 3.7) shows a –3 dB corner right at ∼100 Hz, then a flat 0 dB pass-band beyond ∼120 Hz. Below cutoff, the attenuation is monotonic, plunging past –150 dB toward DC. The transition region spans a few tens of hertz, reflecting the trade-off between flat group delay and roll-off steepness.

3.2.4 Butterworth Low-pass

The low-pass response (Figure 3.8) has an equally flat 0 dB response up to 300 Hz, with a smooth, monotonic roll-off. By ∼350 Hz it's down around –40 dB, and it continues descending toward –160 dB as you approach Nyquist. The gentle knee and lack of ripple are hallmarks of a high-order Butterworth design.

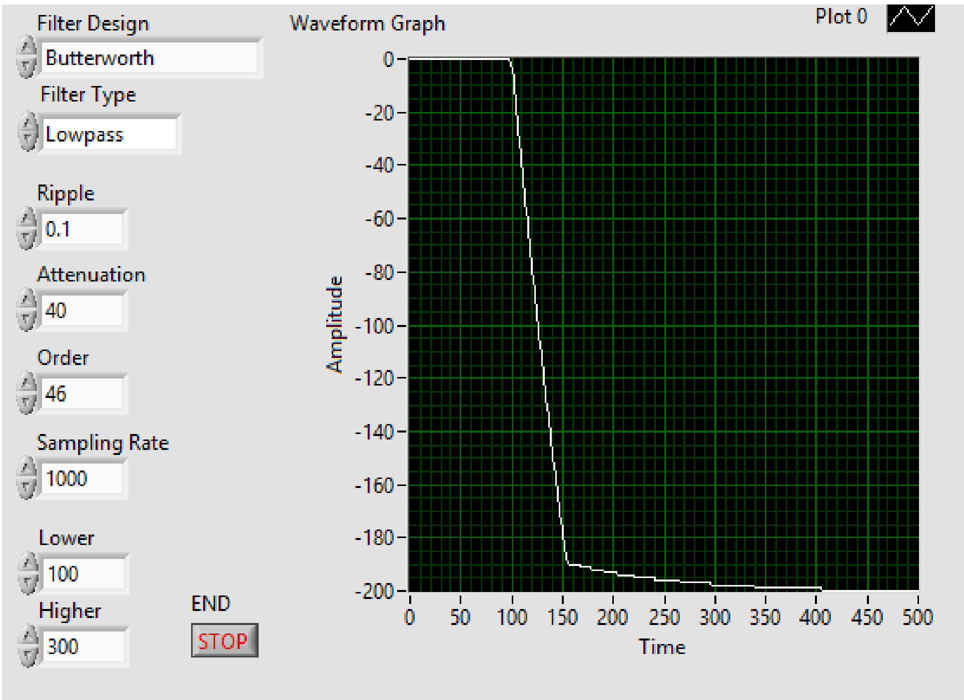

Figure 3.8: Butterworth Low-pass Response

3.3 Chebyshev Type I Filter

Chebyshev Type I filters are characterized by equiripple in the passband and monotonic decay in the stopband. They offer a steeper roll-off compared to Butterworth filters, at the expense of passband ripple.

3.3.1 Chebyshev Type I Band-pass

The Chebyshev band-pass (Figure 3.9) features a ±0.05 dB equi-ripple in the 100–300 Hz pass-band, visible as tiny wiggles around 0 dB. On either side, the skirts plunge steeply—dropping below –60 dB within just a few hertz of each cutoff—and ultimately reach around –65 dB out in the far stop-bands. This sharp transition comes at the cost of that small pass-band ripple.

3.3.2 Chebyshev Type I Band-stop

In band-stop mode (Figure 3.10), Chebyshev I trades a razor-sharp notch (≈–55 dB depth around 200 Hz) for a slightly rippled pass-band outside the stop region. The two flanking pass-bands sit at 0 dB ±0.05 dB, and the skirts into the notch are far steeper than Butterworth's.

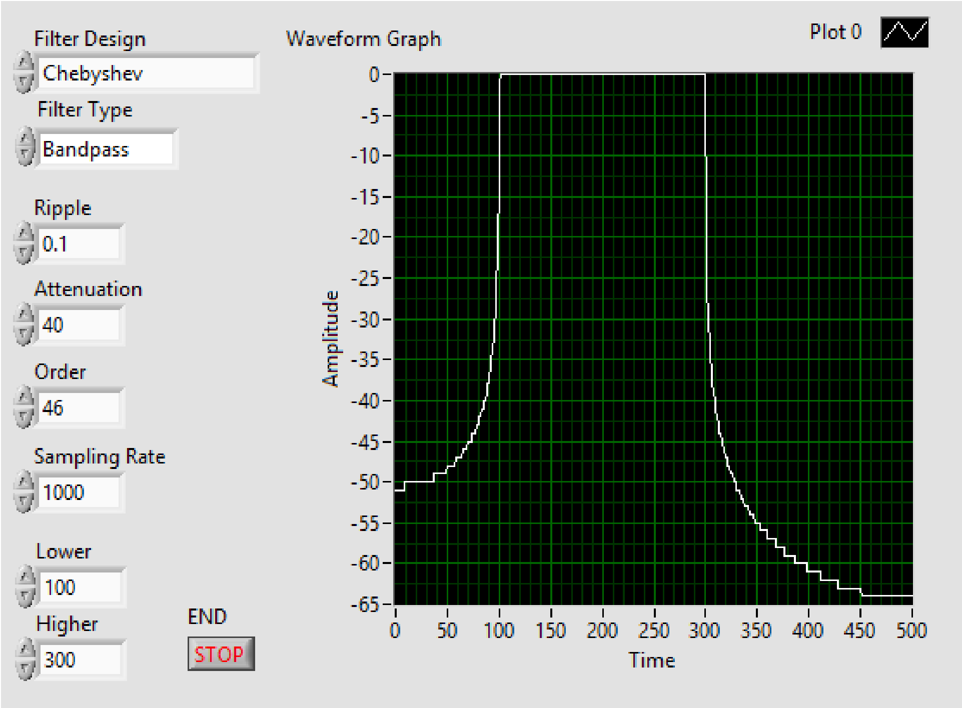

Figure 3.9: Chebyshev Type I Band-pass Response

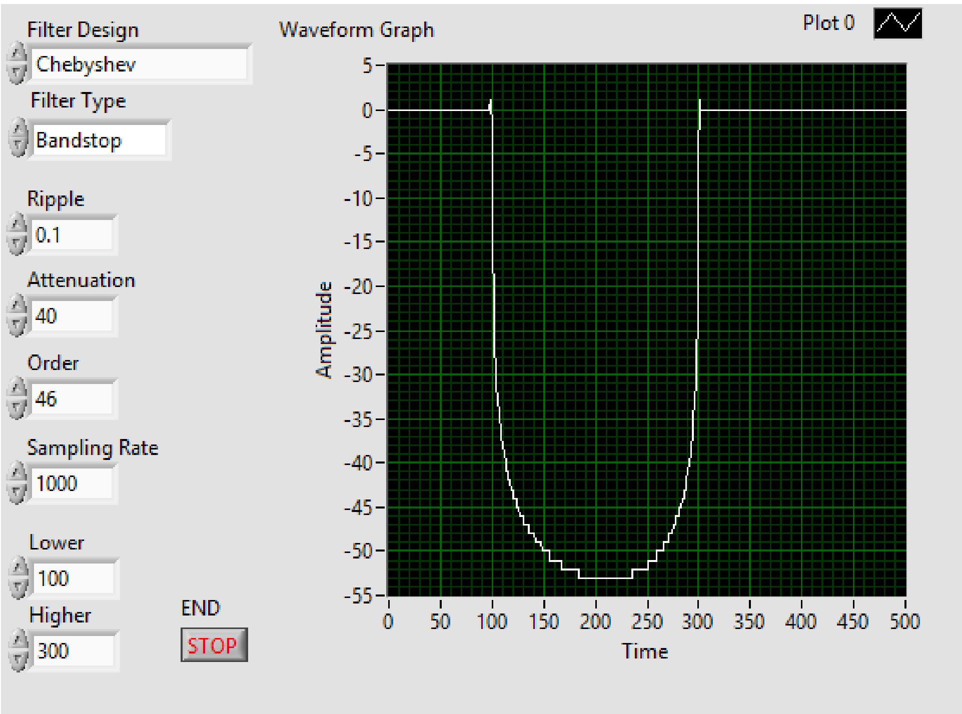

Figure 3.10: Chebyshev Type I Band-stop Response

3.3.3 Chebyshev Type I High-pass

The Chebyshev high-pass (Figure 3.11) shows its –3 dB corner at ∼100 Hz, then thrusts up to 0 dB with ≤0.1 dB ripple immediately thereafter. Low frequencies below cutoff are suppressed

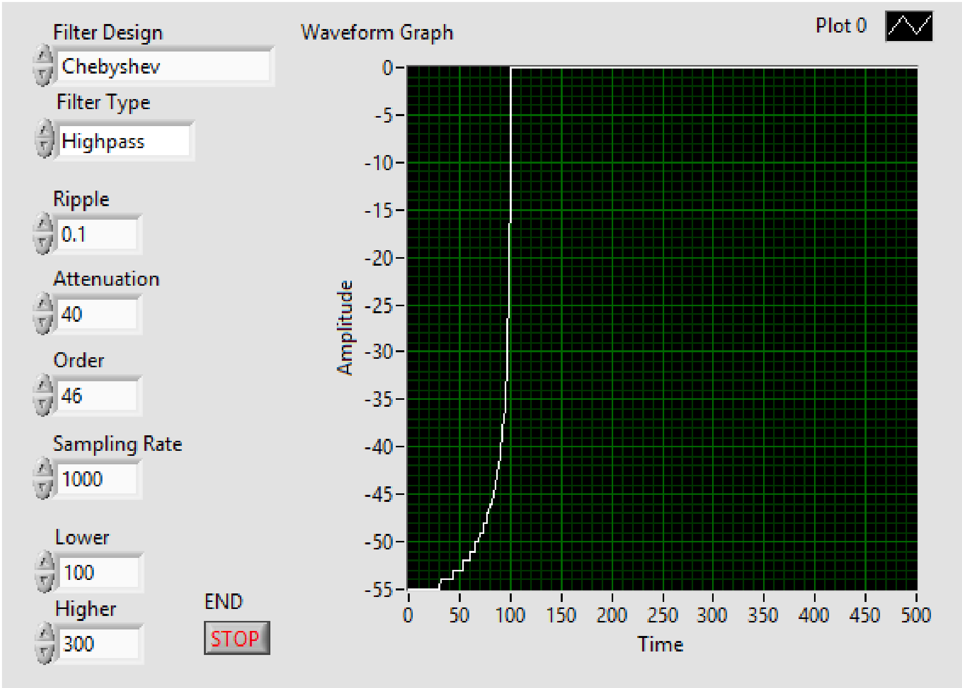

Figure 3.11: Chebyshev Type I High-pass Response

to around –55 dB or more, and the steepness of the rise is markedly greater than the Butterworth counterpart.

3.3.4 Chebyshev Type I Low-pass

The Chebyshev low-pass (Figure 3.12) remains flat (within 0.1 dB) up to 300 Hz, then drops off nearly vertically—crossing –40 dB by ∼330 Hz and reaching –65 dB toward Nyquist. The tight pass-band specification and aggressive attenuation make Chebyshev Type I ideal when transition sharpness outweighs ripple concerns.

3.4 Elliptic (Cauer) Filter

Elliptic filters offer the steepest roll-off for a given filter order. They achieve this by allowing ripple in both the passband and stopband.

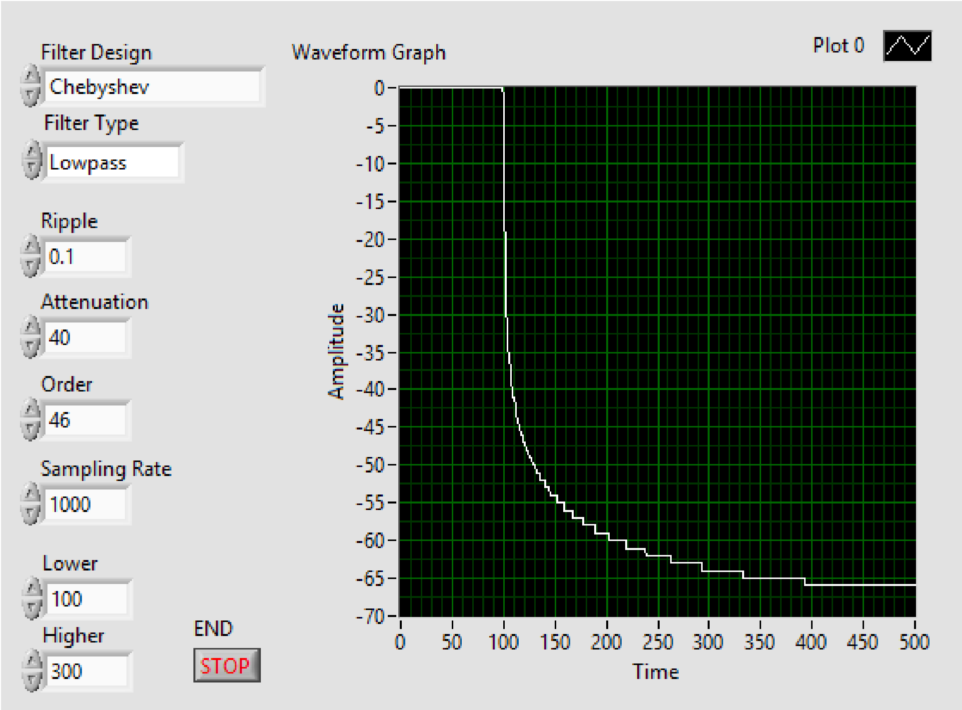

Figure 3.12: Chebyshev Type I Low-pass Response

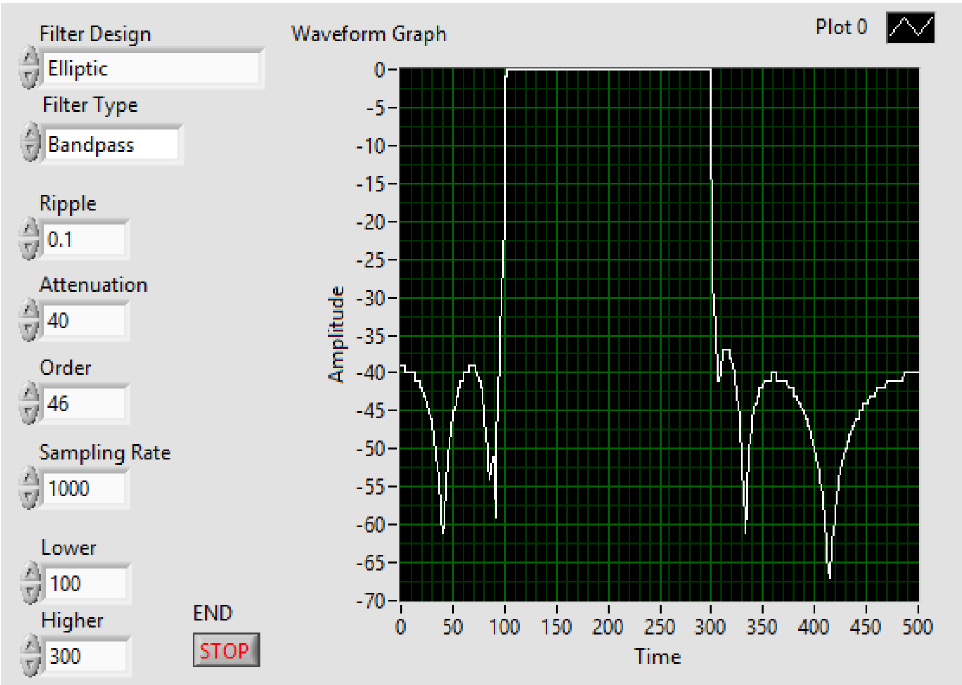

Figure 3.13: Elliptic Band-pass Response

3.4.1 Elliptic Band-pass

The elliptic band-pass response (Figure 3.13) shows equi-ripple in both the passband (±0.05 dB around 0 dB) and the stopbands (oscillating around –40 dB). The transition from passband to stopband is extremely sharp, achieving full stopband attenuation within just a few hertz of the cutoff frequencies.

3.4.2 Elliptic Band-stop

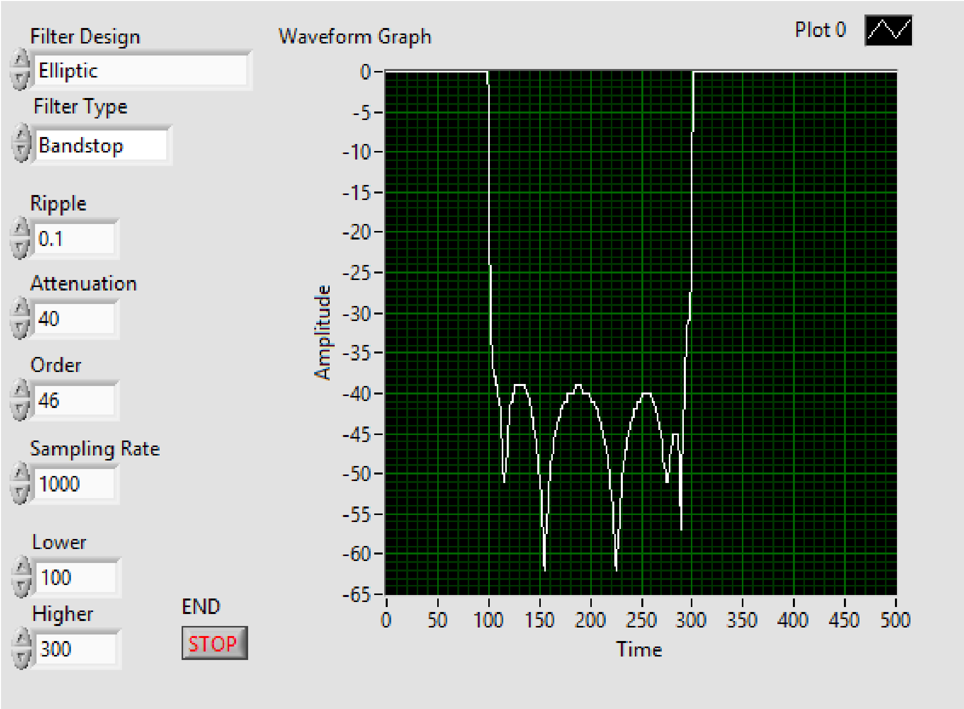

Figure 3.14: Elliptic Band-stop Response

The elliptic band-stop (Figure 3.14) shows two equi-ripple pass-bands below 100 Hz and above 300 Hz, each ±0.1 dB in variation. Between 100 Hz and 300 Hz, the stop-band oscillates around –40 dB (with some deeper notches down near –60 dB), reflecting the specified 40 dB minimum attenuation. The skirts into and out of the notch are extremely steep—losing full attenuation in just a few hertz—at the expense of ripple in both pass- and stop-bands.

3.4.3 Elliptic High-pass

Above $\sim$100 Hz the response (Figure 3.15) is flat within ±0.1 dB. Below that cutoff, the elliptic design forces an equi-ripple stop-band: you see roughly –40 dB of attenuation on average, with oscillations between about –30 dB and –65 dB. The transition edge is remarkably sharp, climbing from deep attenuation to the flat pass-band over only a few hertz.

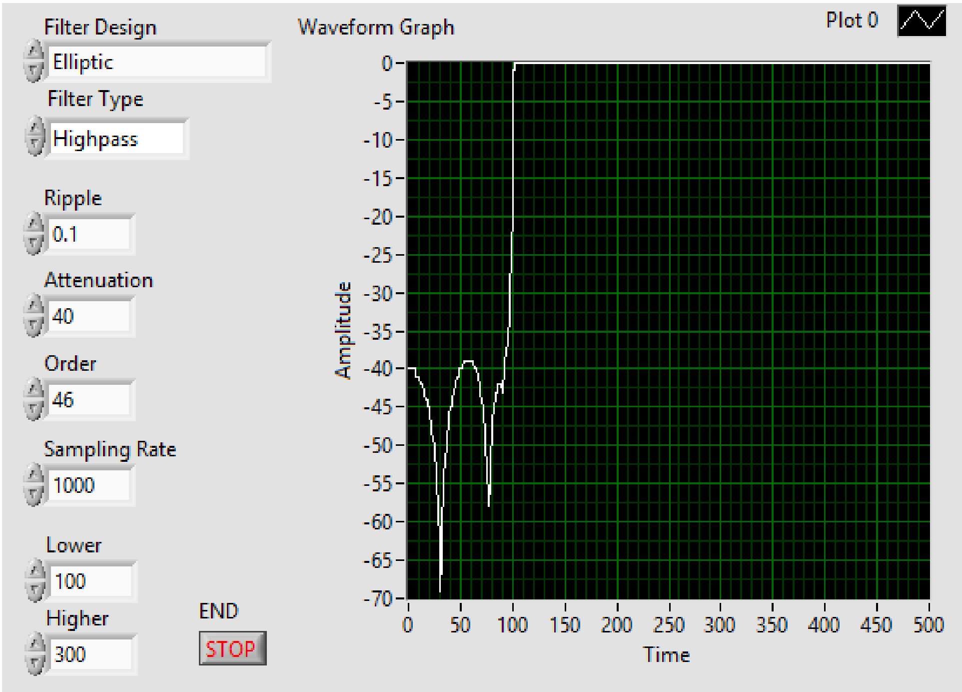

Figure 3.15: Elliptic High-pass Response

3.4.4 Elliptic Low-pass

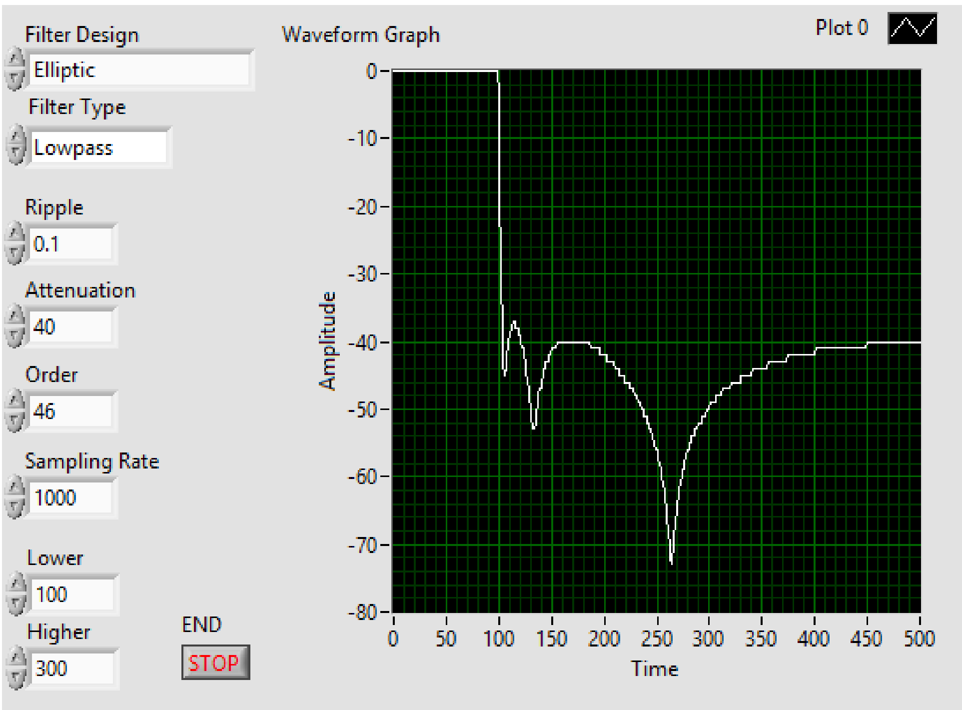

Figure 3.16: Elliptic Low-pass Response

From 0–300 Hz the magnitude (Figure 3.16) holds at 0 dB ±0.1 dB. Beyond 300 Hz the stop-band is again equi-ripple around –40 dB, with the deepest notch near –75 dB around ∼250 Hz (due to aliasing of the elliptic poles). As with all elliptic filters, the trade-off is extreme roll-off and dual-band ripple.

3.5 Chebyshev Type II (Inverse Chebyshev) Filter

Chebyshev Type II filters are characterized by a monotonic passband and equiripple in the stop-band. They offer a compromise between Butterworth and Chebyshev Type I filters, providing a flat passband with a steeper roll-off than Butterworth.

3.5.1 Inverse Chebyshev Band-pass

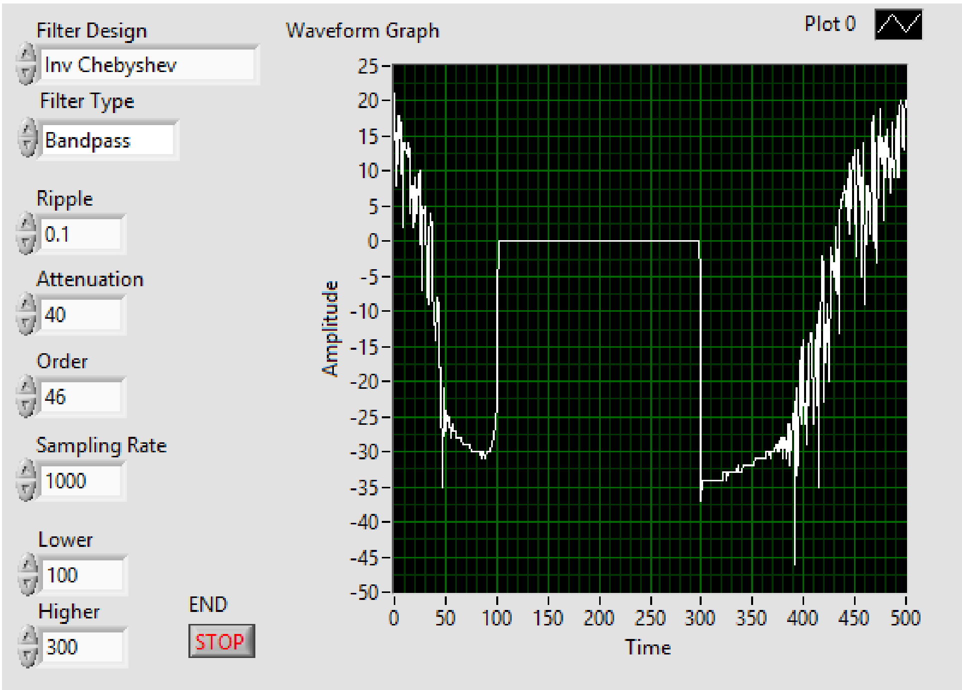

Figure 3.17: Inverse Chebyshev Band-pass Response

The pass-band between 100 Hz and 300 Hz (Figure 3.17) is perfectly flat (no ripple), thanks to the inverse-Chebyshev's monotonic pass-band design. Outside that band, the dual stop-bands equi-ripple around –40 dB, oscillating between roughly –30 dB and –50 dB. The transitions at each cutoff are extremely abrupt—attaining full stop-band ripple within only a few hertz.

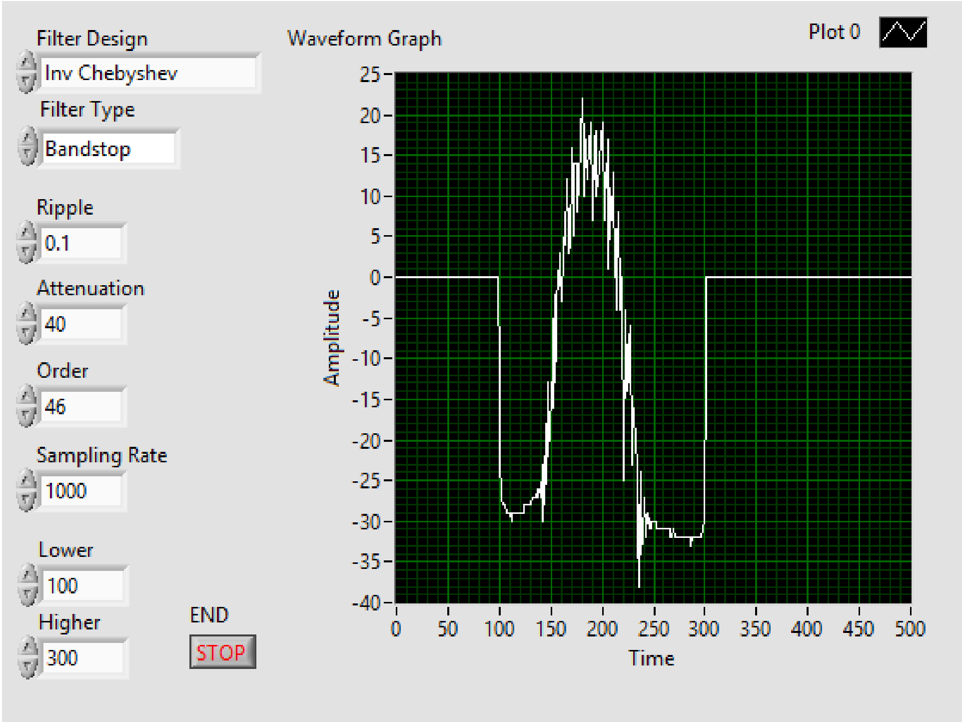

Figure 3.18: Inverse Chebyshev Band-stop Response

3.5.2 Inverse Chebyshev Band-stop

Here the roles reverse (Figure 3.18): the 100–300 Hz region is the stop-band and shows equi-ripple attenuation (∼–40 dB on average, with peaks around –30 dB and valleys near –50 dB). Below 100 Hz and above 300 Hz the pass-bands are totally flat at 0 dB. The skirts on either side of the notch are razor-sharp, achieving the stop-band spec almost instantaneously.

3.5.3 Inverse Chebyshev High-pass

Above ∼100 Hz the response (Figure 3.19) rises to and remains at 0 dB with zero ripple. Below that cutoff, the stop-band ripples around –40 dB (you'll see oscillations between about –20 dB and –60 dB). The transition itself is among the steepest you'll get in IIR filtering.

3.5.4 Inverse Chebyshev Low-pass

From DC up to 300 Hz the pass-band (Figure 3.20) is flat at 0 dB. Beyond the cutoff, the inverse-Chebyshev stop-band exhibits equi-ripple attenuation centered on –40 dB (with peaks near –30 dB and troughs near –50 dB). The roll-off is extremely tight, plunging to full stop-band

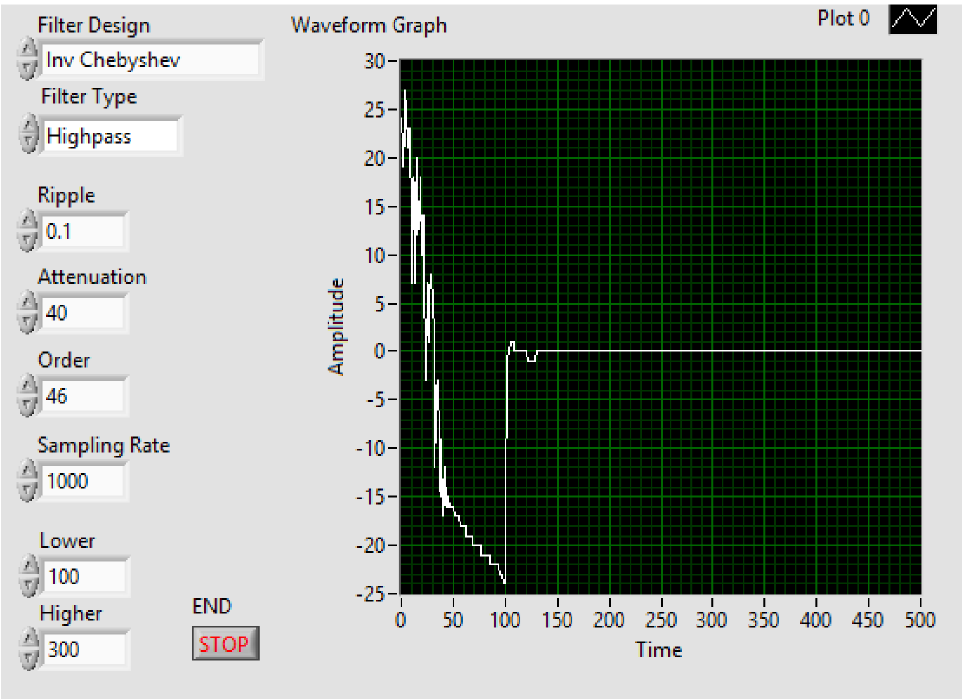

Figure 3.19: Inverse Chebyshev High-pass Response

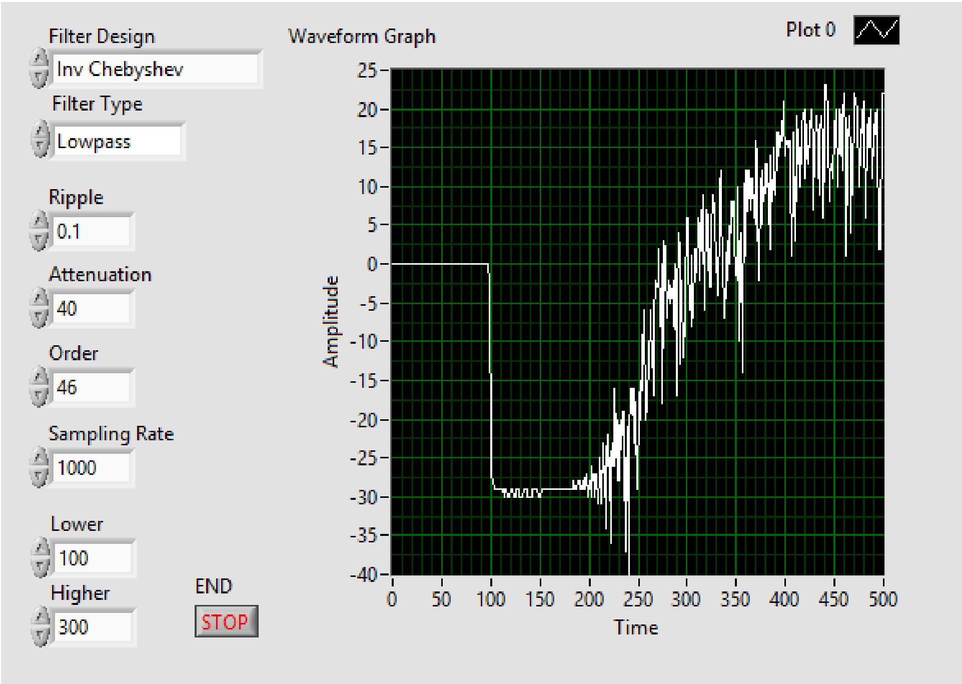

Figure 3.20: Inverse Chebyshev Low-pass Response

performance within only a few hertz of the corner.

Chapter 4

Filter Response Analysis

4.1 Comparison of Filter Types

Filter Type	Passband	Stopband	Roll-off	Phase
Bessel	Flat	Monotonic	Gradual	Linear (constant group delay)
Butterworth	Maximally flat	Monotonic	Moderate	Non-linear
Chebyshev I	Equiripple	Monotonic	Steep	Highly non-linear
Elliptic	Equiripple	Equiripple	Steepest	Highly non-linear
Chebyshev II	Flat	Equiripple	Steep	Non-linear

Table 4.1: Comparison of Filter Characteristics

4.2 Filter Selection Guidelines

Based on the analysis of the different filter types, the following guidelines can be used for filter selection:

1. **Bessel filters** are optimal when preserving the wave shape of signals in the passband is critical, such as in pulse or step response applications.

2. **Butterworth filters** are ideal when a flat magnitude response is required without passband ripple, and moderate roll-off is acceptable.

3. **Chebyshev Type I filters** should be used when a steeper roll-off is needed and some passband ripple can be tolerated.

4. **Elliptic filters** provide the steepest roll-off for a given order and are suitable when transition bandwidth must be minimized, even if it means accepting ripple in both passband and stopband.

5. **Chebyshev Type II filters** are appropriate when both a flat passband and defined stop-

band attenuation are required, offering a compromise between Butterworth and Chebyshev Type I filters.

4.3 Impact of Filter Parameters

4.3.1 Filter Order

The filter order significantly impacts the roll-off steepness. Higher-order filters provide steeper transitions between passband and stopband, but at the cost of increased computational complexity and potential phase distortion.

4.3.2 Passband Ripple

The passband ripple parameter (for Chebyshev Type I and Elliptic filters) controls the amount of amplitude variation allowed in the passband. Smaller ripple values result in flatter passbands but less steep roll-offs.

4.3.3 Stopband Attenuation

The stopband attenuation parameter (for Chebyshev Type II and Elliptic filters) determines the minimum attenuation in the stopband. Higher attenuation values result in better stopband rejection but may require higher filter orders or increased passband ripple.

Chapter 5

Comparison and Conclusion

5.1 Performance Trade-offs

The comparison of different filter types reveals several important trade-offs:

- **Roll-off vs. Passband Flatness:** Filters with steeper roll-offs (Chebyshev I, Elliptic) typically exhibit passband ripple, while filters with flat passbands (Bessel, Butterworth, Chebyshev II) have more gradual roll-offs.
- **Phase Response vs. Magnitude Response:** Bessel filters provide the best phase response (linear phase) but at the expense of magnitude response, particularly in terms of roll-off steepness.
- **Computational Complexity vs. Performance:** Higher-order filters provide better performance but require more computational resources.

5.2 Application-Specific Recommendations

Based on the analysis, the following recommendations can be made for specific applications:

1. **Audio Processing:** Butterworth filters are often preferred for their flat passband and absence of ripple, which prevents audible artifacts.
2. **Communications:** Chebyshev or Elliptic filters are suitable for their steep roll-offs, which help in channel separation and bandwidth efficiency.
3. **Medical Signal Processing:** Bessel filters are advantageous due to their linear phase response, which preserves the temporal characteristics of biomedical signals.

4. **Instrumentation:** Butterworth and Chebyshev II filters provide a good balance between passband flatness and stopband attenuation for measurement applications.

5.3 Final Summary

This assignment has demonstrated the design and analysis of various filter types using LabVIEW. Key findings include:

- The Bessel filter offers the best phase response but the slowest roll-off.
- The Butterworth filter provides a maximally flat passband with moderate roll-off.
- The Chebyshev Type I filter offers steeper roll-off at the expense of passband ripple.
- The Elliptic filter achieves the steepest roll-off by allowing ripple in both passband and stopband.
- The Chebyshev Type II filter maintains a flat passband while allowing stopband ripple.

Understanding these filter characteristics and trade-offs is essential for selecting the appropriate filter type for specific signal processing applications. The LabVIEW implementation demonstrated in this report provides a practical framework for designing and analyzing these filters in real-time applications.

List of Abbreviations

BIBO	Bounded-Input Bounded-Output (stability criterion)
CT	Continuous-Time
DC	Direct Current (refers to steady-state value)
DSP	Digital Signal Processing
DT	Discrete-Time
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
GUI	Graphical User Interface
IIR	Infinite Impulse Response
LTI	Linear Time-Invariant
NI	National Instruments (manufacturer of LabVIEW)
VI	Virtual Instrument (LabVIEW program)

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