

RC Low-Pass Filter — Frequency Response and Signal Smoothing

Case Study

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1. Overview

Short description: This **Case Study** introduces the fundamental principles of RC low-pass filters and their role in frequency response analysis and signal smoothing. Participants will build a simple RC filter circuit using the Analog Discovery Product Line (AD 3 or AD Studio / Studio MAX, hereafter referred to as Device). The experiment demonstrates how high-frequency components are attenuated and how square signals can be smoothed into exponential waveforms. The **Case Study** utilizes the Waveform Generator and Oscilloscope instruments in Digilent WaveForms software, as well as NI LabVIEW with the WaveForms Toolkit, to analyze filter behavior in both time and frequency domains.

Objectives

- Understand the operating principle of an RC low-pass filter
- Analyze frequency-dependent attenuation
- Determine the cutoff frequency of an RC circuit
- Observe signal smoothing of square wave inputs
- Visualize and measure frequency response using Digilent tools

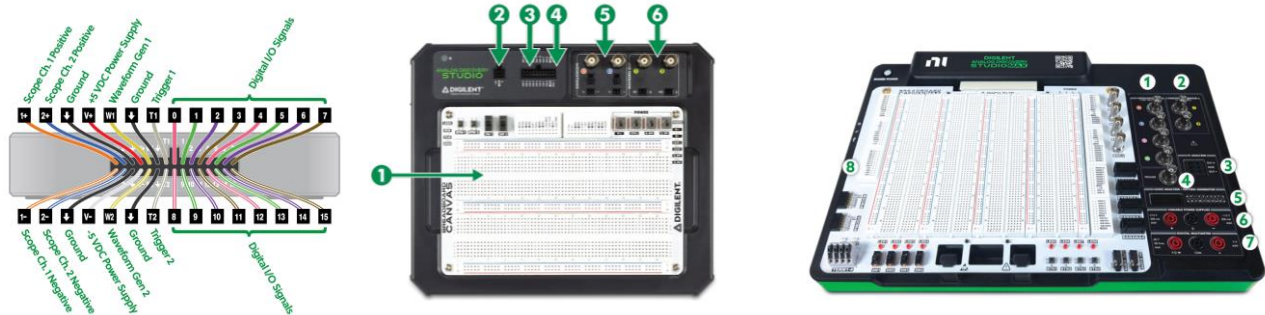
Software & Hardware Requirements

Software		Version
Digilent WaveForms (Runtime + SDK)		Latest (64-bit)
NI LabVIEW		2025 64-bit
WaveForms Toolkit for LabVIEW		Latest
Hardware		Quantity*
Digilent Analog Discovery Product Line		
Option 1	Digilent Analog Discovery 3	1
Option 2	Digilent Analog Discovery Studio	1
Option 3	Digilent Analog Discovery Studio MAX	1
List of Components		Quantity*
Canvas Breadboard		1
Resistor 10kΩ		1
Capacitor (10 nF)		1
Jumper wires		-
BNC to BNC cable ¹		1

¹ BNC cable required only for the Analog Discovery Studio MAX.

2. Hardware Setup

This section describes the **Digilent Analog Discovery Product Line** hardware setup for **Case studies**. Before assembling the measurement circuit, it is essential to understand the pinout and available connections of the **Devices**. **Figure 1** highlights the pinouts and instrumentations of the Digilent Analog Discovery product line.²



a. Analog Discovery 3

- Power Supplies
- Logic Analyzer and Pattern Generator
- Triggers
- Oscilloscope Waveform Generator

b. Analog Discovery Studio

1. Breadboard Canvas
2. Power Supplies
3. Logic Analyzer and Pattern Generator
4. Triggers
5. Oscilloscope
6. Waveform Generator

c. Analog Discovery Studio MAX

1. Oscilloscope
2. Waveform Generator
3. IV Analyzer
4. Trigger
5. Logic Analyzer and Pattern Generator
6. Variable Power Supplies
7. Digital Multimeter
8. Breadboard Canvas

Figure 1. Digilent Analog Discovery Products Pinout and Instrumentations

Table 1 provides a common reference for physical channels' names across the **Digilent Analog Discovery product line**. The **Case studies** are designed to work with all supported devices, so the generic channels' names shown in the first row are used consistently in all circuit diagrams and wiring instructions.

Table 2 provides a common reference for device names and instrument identifiers used in NI LabVIEW with the WaveForms Toolkit across the **Digilent Analog Discovery product line**. The Case studies are designed to work with all supported devices; therefore, the generic instruments and

² For detailed electrical specifications, pin descriptions, and operating limits, always refer to the official datasheets of each device (Analog Discovery 3, Analog Discovery Studio, and Analog Discovery Studio MAX). The latest datasheets are available on the Digilent website:

- [Analog Discovery 3](#)
- [Analog Discovery Studio](#)
- [Analog Discovery Studio MAX](#)

channels identifiers shown in Table 2 are used consistently throughout the LabVIEW block diagrams and configuration steps.

Table 1 Physical Channels Mapping for Digilent Analog Discovery Devices

<i>Channel Device</i>	<i>Scope Ch.1 Positive</i>	<i>Scope Ch.1 Negative</i>	<i>Scope Ch.2 Positive</i>	<i>Scope Ch.2 Negative</i>	<i>Wavegen Output (W1)</i>	<i>GND</i>
AD 3	Scope Ch.1 Positive (Pin 1+)	Scope Ch.1 Negative (Pin 1-)	Scope Ch.2 Positive (Pin 2+)	Scope Ch.1 Negative (Pin 2-)	Wavegen 1 (W1)	GND Pin
AD Studio ³	OSCILLOSCOPE 1 (Pin + or BNC +)	OSCILLOSCOPE 1 (Pin - or BNC -)	OSCILLOSCOPE 1 (Pin + or BNC +)	OSCILLOSCOPE 2 (Pin - or BNC -)	Wavegen 1 (W1)	GND (Canvas)
AD Studio MAX ³	OSCILLOSCOPE 1 (BNC +)	OSCILLOSCOPE 1 (BNC -)	OSCILLOSCOPE 2 (BNC +)	OSCILLOSCOPE 2 (BNC -)	Wavegen 1 (BNC W1)	GND (Canvas)

Table 2 Device Names and Instruments Identifiers in NI LabVIEW (WaveForms Toolkit)

<i>Identifier Device</i>	<i>Device name</i>	<i>Scope Ch.1</i>	<i>Scope Ch.2</i>	<i>FGEN Channel</i>
AD 3	Discovery3	mso/1	mso/2	fgen/1
AD Studio ³	DiscoveryStudio			
AD Studio MAX ³	ADS_Max			

³ For the Analog Discovery Studio and Analog Discovery Studio MAX, ensure the devices are powered by turning ON the main power switch before use.

3. Background Information

A low-pass filter is a frequency-selective circuit that allows low-frequency signals to pass while attenuating high-frequency components. The simplest implementation is a first-order **RC** network consisting of a resistor (R) and capacitor (C).

The impedance of the capacitor is:

$$Z_c = \frac{1}{j\omega C}$$

At low frequencies, the capacitor impedance is high, meaning most of the input voltage appears across it. Therefore, the output amplitude is nearly equal to the input amplitude.

At high frequencies, the capacitor impedance decreases. The capacitor effectively shunts high-frequency components to ground, reducing the output amplitude.

The transfer function of the **RC low-pass filter** is:

$$H(j\omega) = \frac{V_{out}}{V_{in}} = \frac{1}{1 + j\omega RC}$$

The cutoff frequency (**-3 dB point**) is defined as:

$$f_c = \frac{1}{2\pi RC}$$

For example, using:

R = 10kΩ

C = 10nF

The theoretical **cutoff frequency** is approximately:

$$f_c = \frac{1}{2\pi \times 1 \times 10^{-4}} \approx \frac{1}{6.283 \times 10^{-4}} \approx 1591.5 \text{ Hz}$$

$$f_c \approx 1.59 \text{ kHz}$$

The time constant is:

$$\tau = RC = 100 \mu s$$

At this frequency, the output amplitude drops to **70.7%** of the input amplitude.

When a square wave is applied to the filter:

- The capacitor charges and discharges exponentially.
- Sharp transitions are smoothed.
- At sufficiently high frequency, the output waveform resembles an integrated signal.

This demonstrates the signal-smoothing capability of the **RC low-pass filter**.

4. Circuit Design – step by step instructions

4.1 Description

The measurement circuit is based on a first-order **RC low-pass** filter configuration. The resistor is connected in series with the Waveform Generator output (**W1**), while the capacitor is connected between the filter output node and **GND**.

The input signal is applied to the resistor. The output signal is measured across the capacitor.

Oscilloscope **Channel 1** monitors the input signal.

Oscilloscope **Channel 2** monitors the filtered output signal.

By sweeping the input frequency and comparing input/output amplitudes, the frequency response of the filter can be experimentally determined.

Important! Refer to **Table 1** to determine the exact physical pin, connector, or cable that corresponds to each generic connection on the specific Digilent Analog Discovery device being used. The remaining rows in the table show how each generic channel maps the actual hardware connections for each device.

4.2 Step by step instructions⁴

1. Place the 10kΩ resistor on the breadboard.
2. Connect one terminal of the resistor to Wavegen output (**W1**).
3. Connect the other terminal of the resistor to a new row on the breadboard. This node will serve as the **filter output (V_{out})**.
4. Place the **10nF** capacitor on the breadboard.
5. Connect one terminal of the capacitor to the filter output node (**V_{out}**).
6. Connect the other terminal of the capacitor to Device **GND**.
7. Connect **Scope Ch.1 Positive** to the Wavegen output (**V_{in}**).
8. Connect **Scope Ch.2 Positive** to the filter output node (**V_{out}**).
9. Connect **Scope Ch.1** and **Ch.2 Negative** to Device **GND**.

⁴ Given on Figure 2.

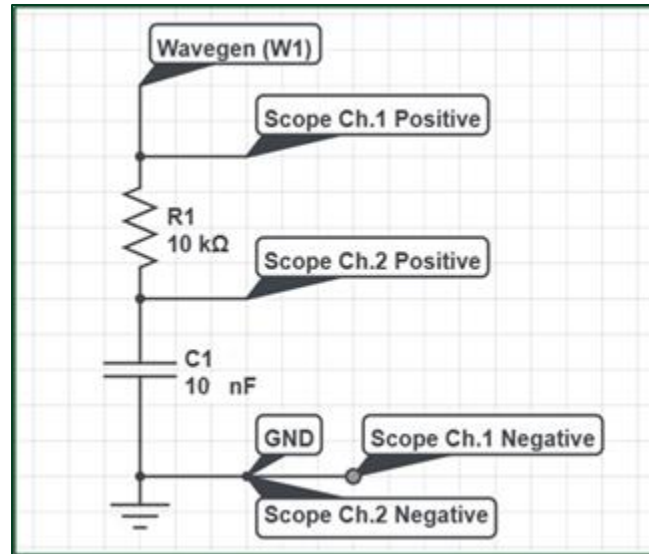
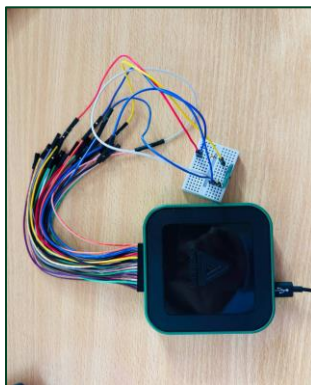


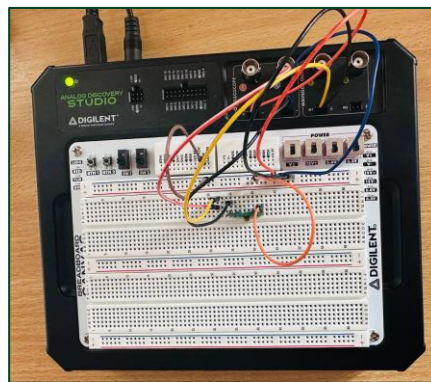
Figure 2. RC Low-Pass Filter Circuit Diagram

4.3 Assembled Circuit

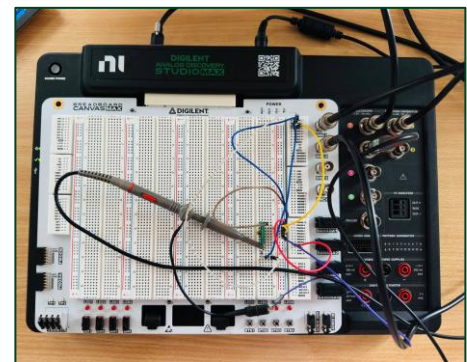
Figure 3 presents complete experimental circuits on different Digilent devices.



a. Analog Discovery 3



b. Analog Discovery Studio



c. Analog Discovery Studio MAX

Figure 3. Assembled circuits for different Devices

5. Software Setup - step by step instructions

5.1 Data Visualization and Analysis in Waveforms

Step 1. Launch WaveForms and connect the device

- 1.1. Connect the **Device** to the computer via USB.
- 1.2. Open the **Digilent WaveForms** software.
- 1.3. Verify that the device is detected and shown as *Currently Selected* in the **Device Manager** (Settings -> Device Manager).

Step 2. Configure the input signal

- 2.1. Open the **Wavegen** instrument in **WaveForms**.
- 2.2. Select **Channel 1 (W1)**.
- 2.3. Choose **Square** waveform.
- 2.4. Set:
 - Frequency: **50 Hz** (initial)
 - Amplitude: **5.0 V**
 - Offset: **0 V**
- 2.5. Enable the output channel to generate the input signal.

Note: For clearer visualization near the cutoff frequency (~ 1.6 kHz), reduce the time base to 200 μ s/div–1 ms/div.

Figure 4 shows the configuration of the **Device** power supply using the Digilent WaveForms environment.



Figure 4. Square Wave Configuration in WaveForms Software

Step 3. Acquire the signal using the Oscilloscope⁵

a. Observe frequency response

- 3.1. Open the **Scope** instrument on WaveForms.
- 3.2. Enable **Channel 1** (input signal) and **Channel 2** (filtered output signal).
- 3.3. Adjust the vertical range to **2 V/div** for both channels.
- 3.4. Adjust the time base to **5ms/div** (for low-frequency observation).

⁵ In the case of AD Studio turn the 5.0V switch on. In the case of AD Studio MAX turn Board Power on.

- 3.5. Gradually increases the frequency from **50 Hz** to **5 kHz**.
- 3.6. Observe amplitude reduction at higher frequencies.

b. Observe signal smoothing

Maintain square waveform input.

Increase frequency near cutoff frequency.

Observe exponential charging/discharging waveform at output.

At low frequency (below cutoff frequency):

- The output waveform closely follows the input waveform.
- Amplitude attenuation is minimal.
- The edges are slightly smoothed due to capacitor charging and discharging.

As Frequency Increases:

- The output amplitude decreases.
- The square wave transitions become increasingly rounded.
- At sufficiently high frequencies, the output resembles an exponential waveform rather than a square wave.

This behavior demonstrates the attenuation of high-frequency components by the RC low-pass filter.

Note: During the experiment, the input frequency is manually varied to observe how the RC low-pass filter attenuates high-frequency components and smooths the output waveform.

c. Measure Amplitude Using Cursors

3.7. Click on the **Quick measure: Vertical tool** in the Scope window.

3.8. Zoom into one full waveform period.

3.9. Use the cursor tools to measure:

- Peak-to-peak input voltage (V_{in})
- Peak-to-peak output voltage (V_{out})

3.10. Calculate the gain:

$$Gain = \frac{V_{out}}{V_{in}}$$

At the cutoff frequency:

$$Gain \approx 0.707$$

This corresponds to the -3 dB attenuation point.

d. Experimental Cutoff Frequency Verification

Using the selected component values:

$R = 10k\Omega$

$C = 10nF$

Calculate the theoretical cutoff frequency:

$$f_c = \frac{1}{2\pi RC}$$

$$\tau = RC = 100 \mu s$$

$$f_c = \frac{1}{2\pi RC} \approx 1.59 \text{ kHz}$$

Gradually adjust the Wavegen frequency around this value and determine experimentally the frequency at which:

$$V_{out} \approx 0.707 \times V_{in}$$

Compare the theoretical and measured cutoff frequencies.

e. Peak-to-Peak Voltage Measurement Using WaveForms Cursor Tools

To accurately measure the peak-to-peak voltages of the input and output signals of the RC low-pass filter, apply horizontal zoom before using the cursor tools.

Zoom into one complete waveform period to clearly observe the signal peaks and transitions.

Right-click inside the Scope window and select **Zoom → X Zoom** or use the mouse scroll wheel to reduce the time base.

After zooming:

Click on **Quick Measure: Vertical Tool** in the Scope window.

Use vertical cursors to measure:

- Peak-to-peak input voltage (V_{in})
- Peak-to-peak output voltage (V_{out})

Calculate the gain:

$$Gain = \frac{V_{out}}{V_{in}}$$

Note: Zooming improves measurement accuracy, especially near the cutoff frequency where the output amplitude decreases due to high frequency attenuation.

Stop all instruments in WaveForms before proceeding to LabVIEW measurements.

Figure 5 illustrates peak-to-peak voltage measurement using cursor tools in the WaveForms Oscilloscope. The measured input and output amplitudes are used to calculate the gain and experimentally verify the cutoff frequency of the RC low-pass filter.

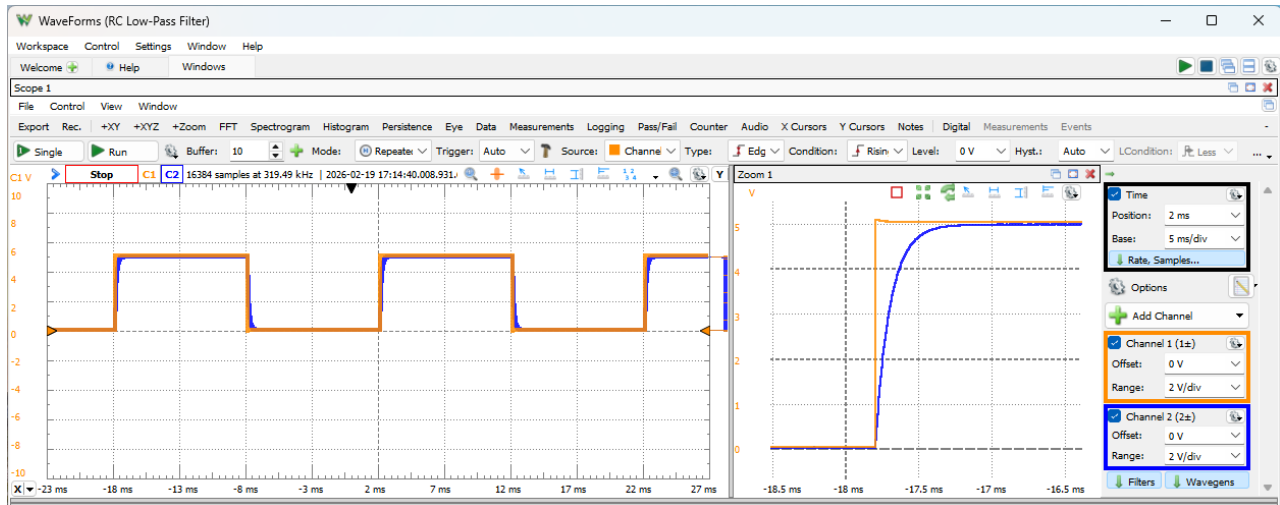


Figure 5. Peak-to-Peak Voltage Measurement Using Waveforms Cursor Tools

5.2 Data Visualization and Analysis Using NI LabVIEW WaveForms Toolkit

Step 1. Launch NI LabVIEW and connect the Device

- 1.1. Connect the **Device** to the computer via USB.
- 1.2. Open **Diligent Waveforms** and verify that **Device** is detected and shown as *Currently Selected* in the **Device Manager** (Settings -> Device Manager), then close **Diligent Waveforms** software⁶.
- 1.3. Open the **NI LabVIEW** software.
- 1.4. Create a new NI LabVIEW VI (**File->New VI**)

Step 2. Create Block Diagram and Front Panel in NI LabVIEW

- 2.1. Modify the block diagram as shown in **Figure 6**.

Figure 6 shows the LabVIEW block diagram applicable to Analog Discovery 3, Analog Discovery Studio, and Analog Discovery Studio MAX devices.

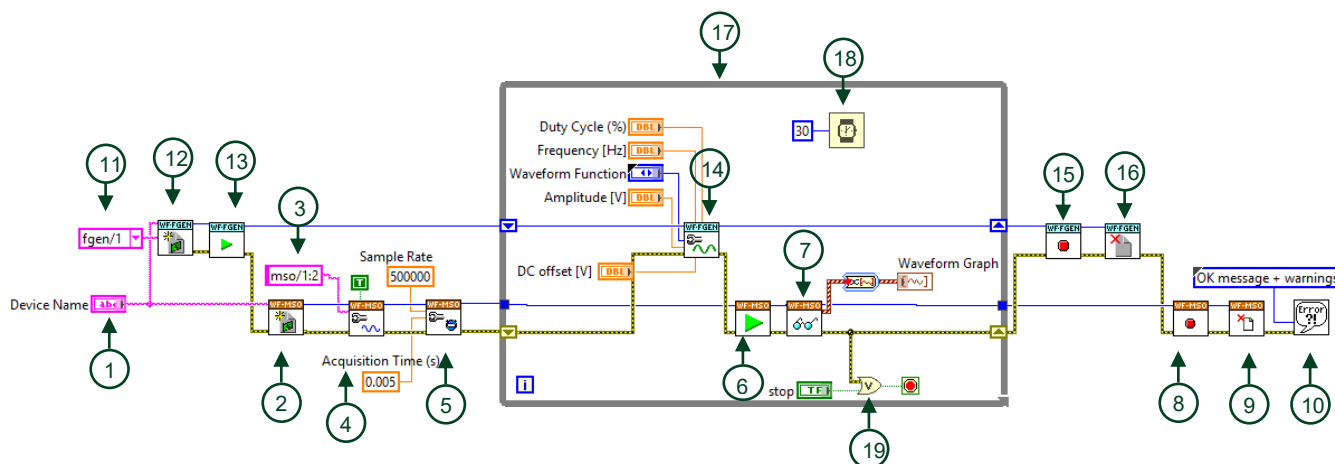


Figure 6. VI Block Diagram for AD3

⁶ Before running NI LabVIEW, please ensure that the Diligent WaveForms software is closed.

Modify the block diagram to include the following VIs:

1. **Device Name** - specify the name of your **Device**. Use **Table 2** for your **Device**.
2. **WF-MSO Initialize** - this VI initializes the scope.
3. **Scope Channel** - specify your **Device Scope Ch.1** and **Device Scope Ch.2** channels. Use **Table 2** for your **Device**.
4. **WF-MSO Configure Analog Channel** - this VI configures the settings for the measurement channel. Connect Enable Channel to True constant.
5. **WF-MSO Configure Timing** - Configures the basic timing settings of the instrument.
6. **WF-MSO Run** - Run the acquisition.
7. **WF-MSO Read** - Transfer data from the **Device** to NI LabVIEW. **Analog Waveforms** output connected to **Convert to Dynamic Data** function then to **Waveform Chart** to visualize the measured data.
8. **WF-MSO Stop** - Stop the acquisition and halt oscilloscope operation.
9. **WF-MSO Close** - Remove the session and reset all values for scope.
10. **Simple Error Handler VI** - Detect and report errors by returning a descriptive error message and optionally displaying an error dialog.
11. **WF-FGEN Channel** - specify your **Device Wavegen** channel. Use **Table 2** for your **Device**. Specify a single waveform generator channel to initialize (e.g., fgen/1).
12. **WF-FGEN Initialize** - Initialize the waveform generator session.
13. **WF-FGEN Run** - start waveform generation on the configured waveform generator channel.
14. **WF-FGEN Configure Standard Waveform** - configure standard waveform parameters for the waveform generator output. Configures the PWM signal parameters (square wave, frequency, duty cycle).
15. **WF-FGEN Stop** - stop the waveform generator output.
16. **WF-FGEN Close** - Remove the waveform generator session and reset its configuration.
17. **While Loop** - used to enable continuous data acquisition.
18. **Wait (ms)** - connect it to an integer constant and set the value to 30 ms.
19. **OR** - Allow the code to stop using the **Stop** button or automatically when an error occurs.

-
- 2.2. Modify the front panel shown in **Figure 7.1** and **Figure 7.2**. Inside **Device name** String Control write your corresponding **Device** name from **Table 2**.

To experimentally demonstrate the frequency-dependent behavior of the RC low-pass filter, the input frequency varied while keeping the component values constant ($R = 10\text{k}\Omega$, $C = 10\text{nF}$) .

The following figures present the VI Front Panel results for two representative cases:

- An input frequency below the theoretical cutoff frequency (1 kHz)
- An input frequency above the theoretical cutoff frequency (5 kHz)

This comparison clearly demonstrates amplitude attenuation and waveform smoothing as the input frequency increases beyond the cutoff frequency.

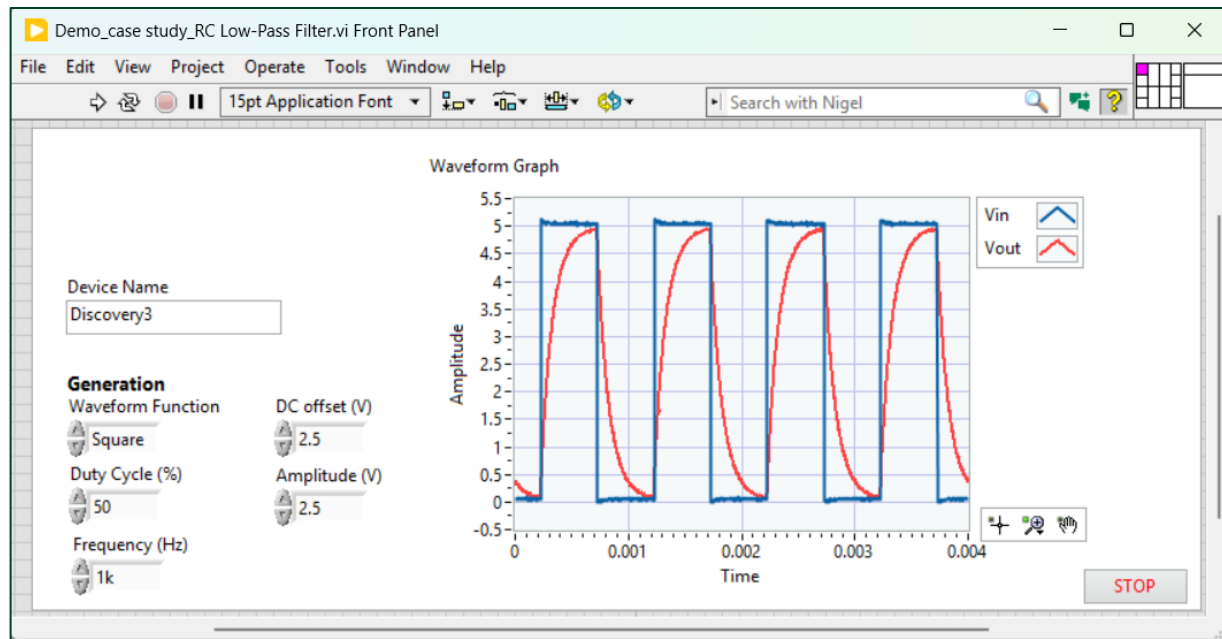


Figure 7.1. VI Front Panel - Input Frequency = 1 kHz (Below Cutoff)

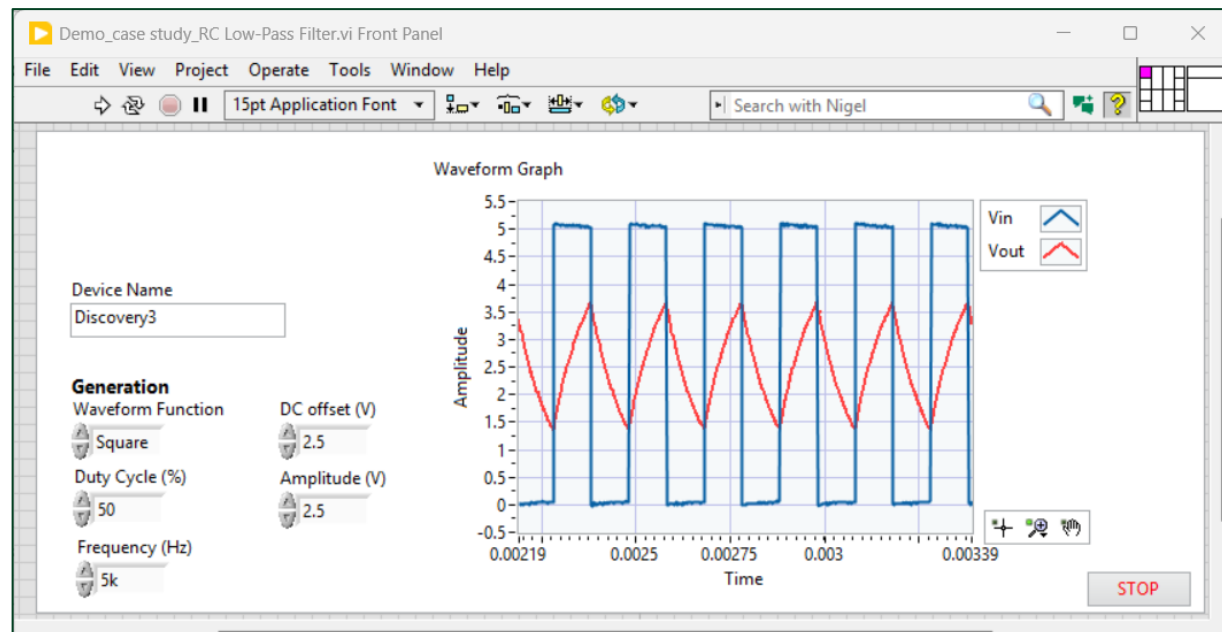


Figure 7.2. VI Front Panel - Input Frequency = 5 kHz (Above Cutoff)

2.3. Save the VI.

Step 3. Run the code and do measurements in LabVIEW

3.1. Click the **Run button** to start the VI.

3.2. Gradually increase the frequency using the Front Panel control.

3.3. Observe:

- The reduction in output amplitude as frequency increases.

- The progressive smoothing of the square wave transitions.
- 3.4. Enable the **Graph Palette** by right-clicking on the **Waveform Graph** and selecting **Visible Items → Graph Palette**.
- 3.5. Use the **Zoom** tool to measure peak-to-peak voltages of both signals.
- 3.6. Calculate the gain:

$$Gain = \frac{V_{out}}{V_{in}}$$

- 3.7. Experimentally determine the cutoff frequency and compare it with the theoretical value.
- 3.8. Stop the code execution in LabVIEW and turn off the **Device**.

Step 4. Effect of Capacitance Variation

- 4.1. Replace the capacitor with a smaller value (for example, 10nF → 1nF or 0.01 μF).
- 4.2. Run the **VI** again and repeat the measurements.
- 4.3. Observe that decreasing the capacitance increases the cutoff frequency according to:

$$f_c = \frac{1}{2\pi RC}$$

- 4.4. Restart the **VI** after replacing the capacitor.