MICROCHIP

TB3250

Using PWM to Generate an Analog Output

Introduction

A wide variety of microcontroller applications require the use of analog output signals. Many low-cost microcontrollers have peripherals to process analog input signals, such as an Analog-to-Digital Converter (ADC), but often do not have a Digital-to-Analog Converter (DAC) included. Of course, there are options for external DACs; however, those may require extra I/O connections or PCB space, and will add cost to the application. Fortunately, most microcontrollers offer a Pulse-Width Modulation (PWM) module, which can be combined with a low-pass filter to create an analog output. This technical brief highlights the use of a low-pass filter to transform a PWM signal into an analog signal.

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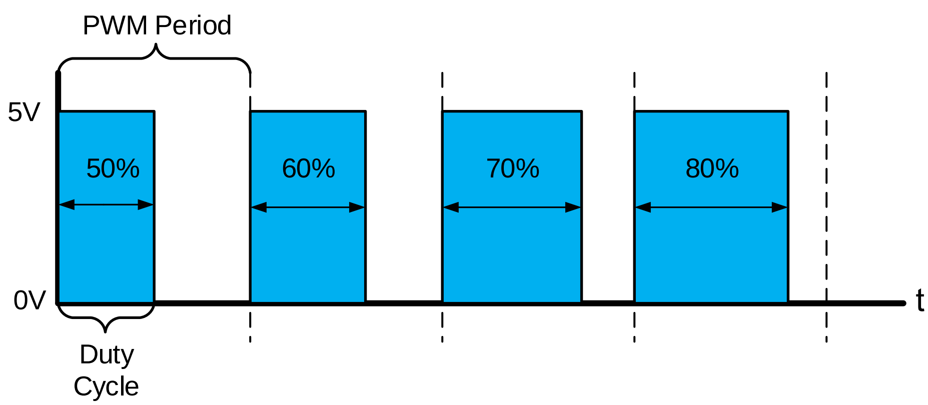
1. Pulse-Width Modulation (PWM)

PWM modules generate pulse-width modulated digital signals. In a typical PWM signal, the base frequency is fixed, while the pulse-width is variable (see Figure 1-1). The pulse-width, also referred to as duty cycle, is directly proportional to the amplitude of the original unmodulated signal as shown in Equation 1-1. For example, if a 2.5V output signal is desired, and the PWM signal has a logic high voltage of 5V and a logic low of 0V, a PWM signal with a duty cycle of 50% will suffice. A 50% duty cycle means that for half of the period, the PWM outputs 5V and the average output per period is 2.5V.

Figure 1-1. PWM Waveform



Equation 1-1. Voltage Output

$$VOUT = A \times Duty\ Cycle$$

$where:$

$$A = Logic\ 'high'\ voltage\ amplitude$$

1.1 Configuring the PWM Module

Example 1-1 shows how to configure a standard 10-bit PWM. The example includes the initialization routines for the PWM and Timer2 modules, both of which are necessary to generate a PWM signal.

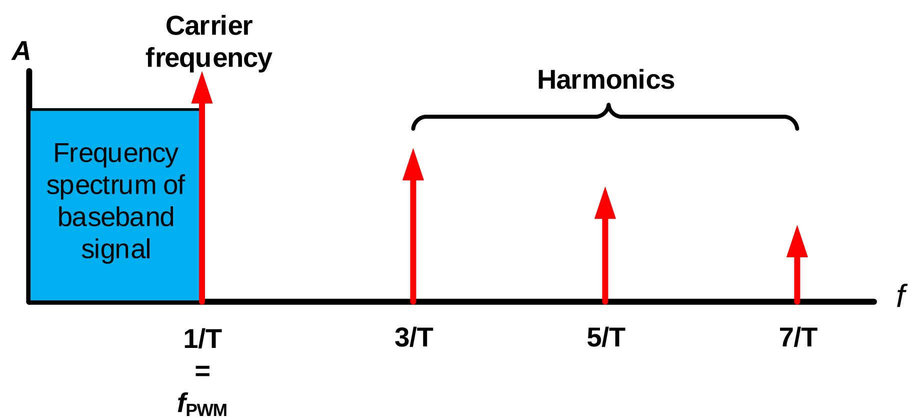
Example 1-1. PWM and Timer2 Initialization Routines

```
void PWM3_Initialize(void)
 {
    PWM3CON = 0x80;                                 // POL active_hi; EN enabled
    PWM3DCH = 0x27;                                 // DC = 50%
    PWM3DCL = 0xC0;
 }

 void PWM3_LoadDutyValue(uint16_t dutyValue)
 {
     PWM3DCH = (dutyValue & 0x03FC)>>2;          // 8 MSBs of PWM duty cycle
     PWM3DCL = (dutyValue & 0x0003)<<6;          // 2 LSBs of PWM duty cycle
 }

 void TMR2_Initialize(void)
 {
    T2CLKCON = 0x01;                              // T2CS FOSC/4
    T2HLT = 0x00;
    T2RST = 0x00;
    T2PR = 0x4F;                                  // Rollover every 10 us
    T2TMR = 0x00;
    PIR4bits.TMR2IF = 0;                          // Clear IF flag
    T2CON = 0x80;                                 // CKPS 1:1; OUTPS 1:1; ON on
 }
```

2. Low-Pass Filtering

A Fourier analysis of a typical PWM signal shows a peak at the carrier frequency, with higher order harmonics present at the integer multiples of the carrier (see Figure 2-1). These signals add unwanted noise to the system and can be reduced or eliminated using a simple low-pass filter.

Figure 2-1. Fourier Analysis of a PWM Signal



The bandwidth of the desired signal should be less than or equal to the PWM frequency (see Figure 2-2). If the bandwidth of the desired signal is equal to the PWM frequency, a brick-wall type of filter may be used. The brick-wall type of filter transitions from no attenuation to complete attenuation almost instantly, but is a very expensive and complex filter to create. If that type of precision is necessary, it might be less expensive to use an external DAC than to build an expensive filter. For practical purposes, an external RC low-pass filter can be used as shown in Figure 2-3. If the simple RC filter is used, the bandwidth of the desired signal must be less than the PWM frequency.

Figure 2-2. Desired Bandwidth of a PWM Signal

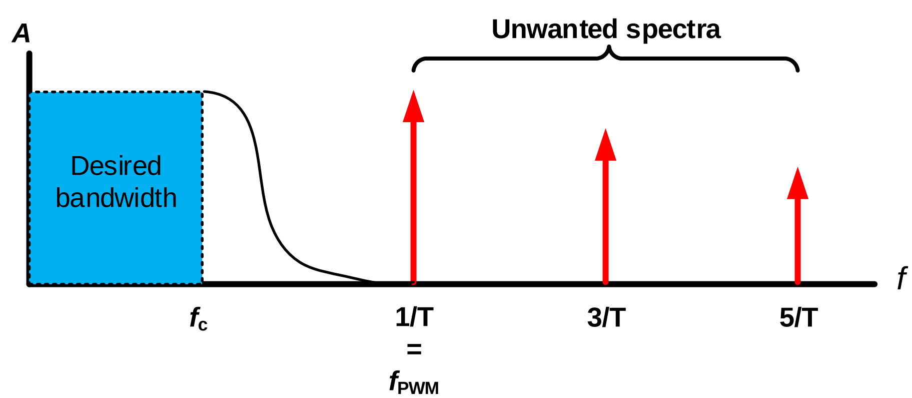
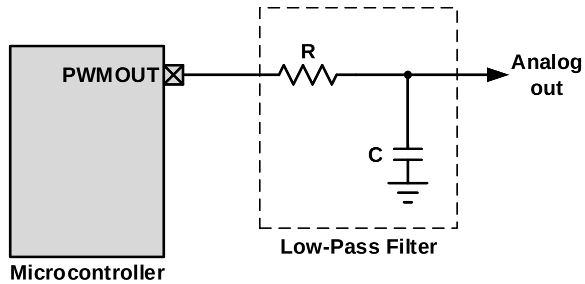


Figure 2-3. External RC Low-Pass Filter



2.1 RC Filter Example

For this example, it is required to design a simple RC low-pass filter to obtain an analog output from a pulse-width modulated signal with a bandwidth of 4 kHz.

Step 1: Select the low-pass filter's resistor and capacitor values.

Equation 2-1 shows how to calculate the values for R and C based on the cut-off frequency, f_C. In this example, the resistor values were calculated based on fixed capacitor values, as shown in Table 2-1.

Equation 2-1. RC Time Constant

$$RC = \frac{1}{2\pi \times f_C}$$

$where:$

$R: Resistance$

$C: Capactiance$

$f_C: cut-off\ frequency$

Table 2-1. Calculated Resistor Values

Capacitor Value	Calculated Resistor Value
1 pF	40 MΩ
0.01 µF	4 kΩ
0.022 µF	1.8 kΩ

Step 2: Calculate attenuation at the PWM frequency.

Equation 2-2 shows the attenuation in decibels (dB) based on the RC values and the PWM frequency.

Equation 2-2. Attenuation in Decibels (dB)

$$Attenuation\left(dB\right) @\ f_{PWM} = -10\log\left[1 + (2\pi \times f_{PWM} \times RC)^2\right]$$

Table 2-2. Attenuation at the PWM Frequency (F_{PWM})

F_{PWM}	R Value	C Value	Attenuation (dB) @ F_{PWM}
10 kHz	40 MΩ	1 pF	-8.64
10 kHz	4 kΩ	0.01 µF	-8.64

...........continued

F_{PWM}	R Value	C Value	Attenuation (dB) @ F_{PWM}
10 kHz	1.8 kΩ	0.022 µF	-8.57
100 kHz	40 MΩ	1 pF	-28.01
100 kHz	4 kΩ	0.01 µF	-28.01
100 kHz	1.8 kΩ	0.022 µF	-27.92

Figure 2-4. Bode Plot

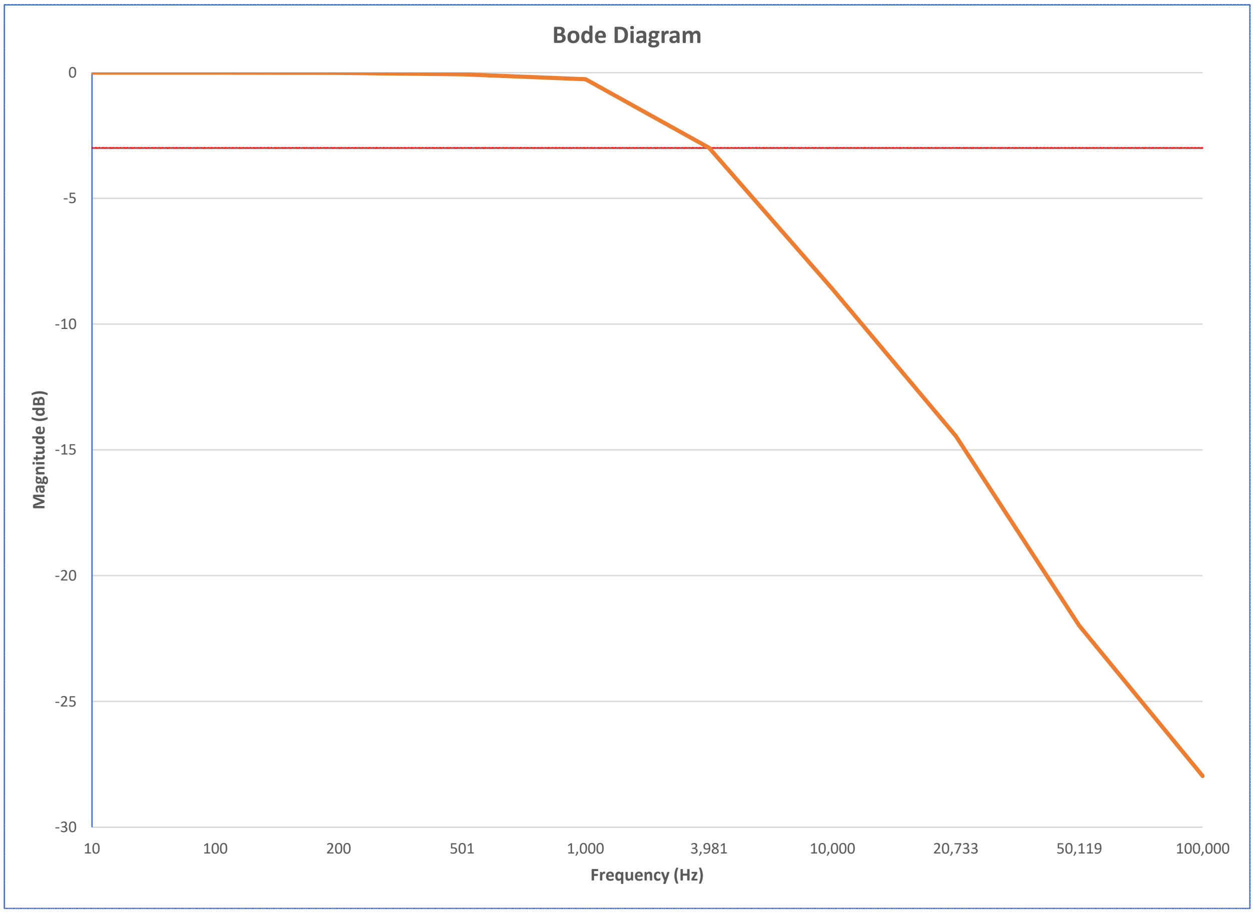


Figure 2-5. Step Response (R = 40 MΩ, C = 1 pF, F_{PWM} = 10 kHz)

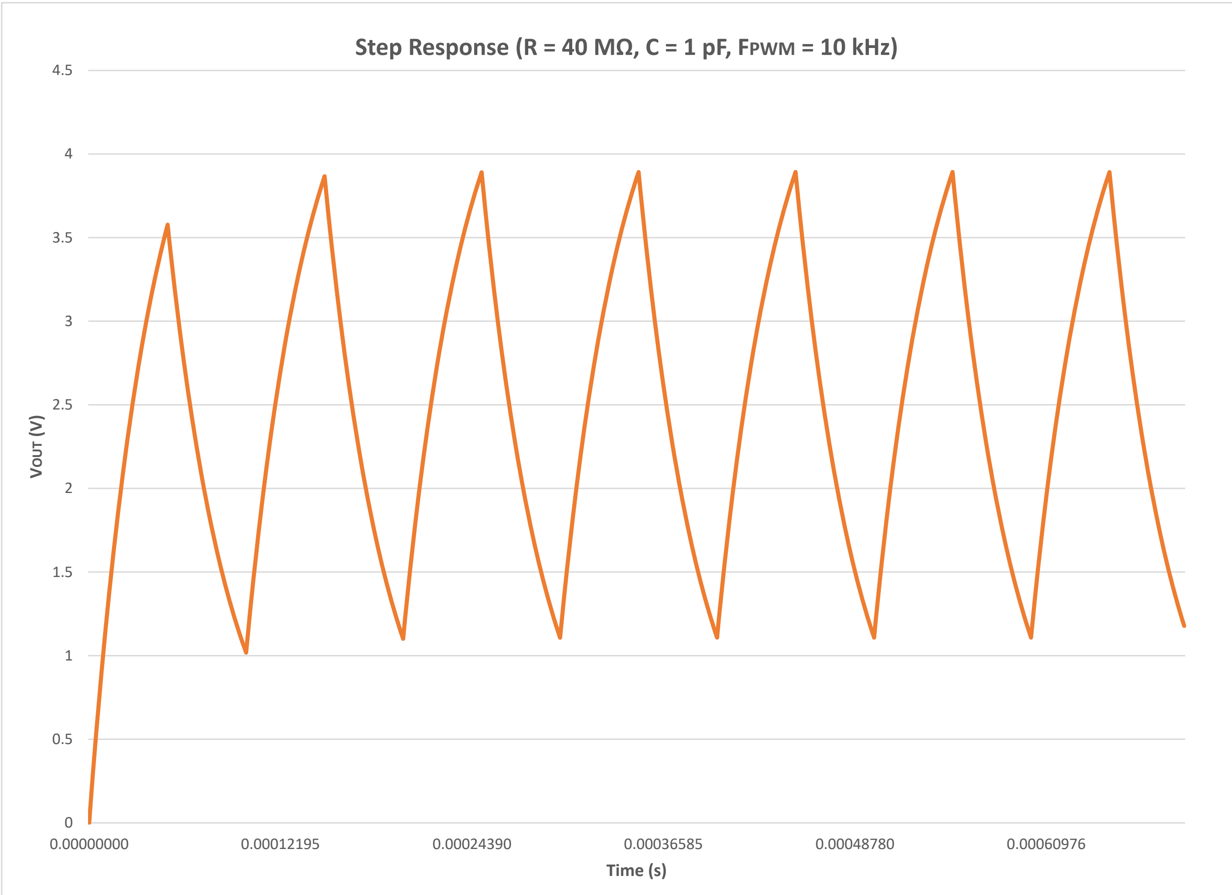


Figure 2-6. Step Response (R = 40 MΩ, C = 1 pF, F_{PWM} = 100 kHz)

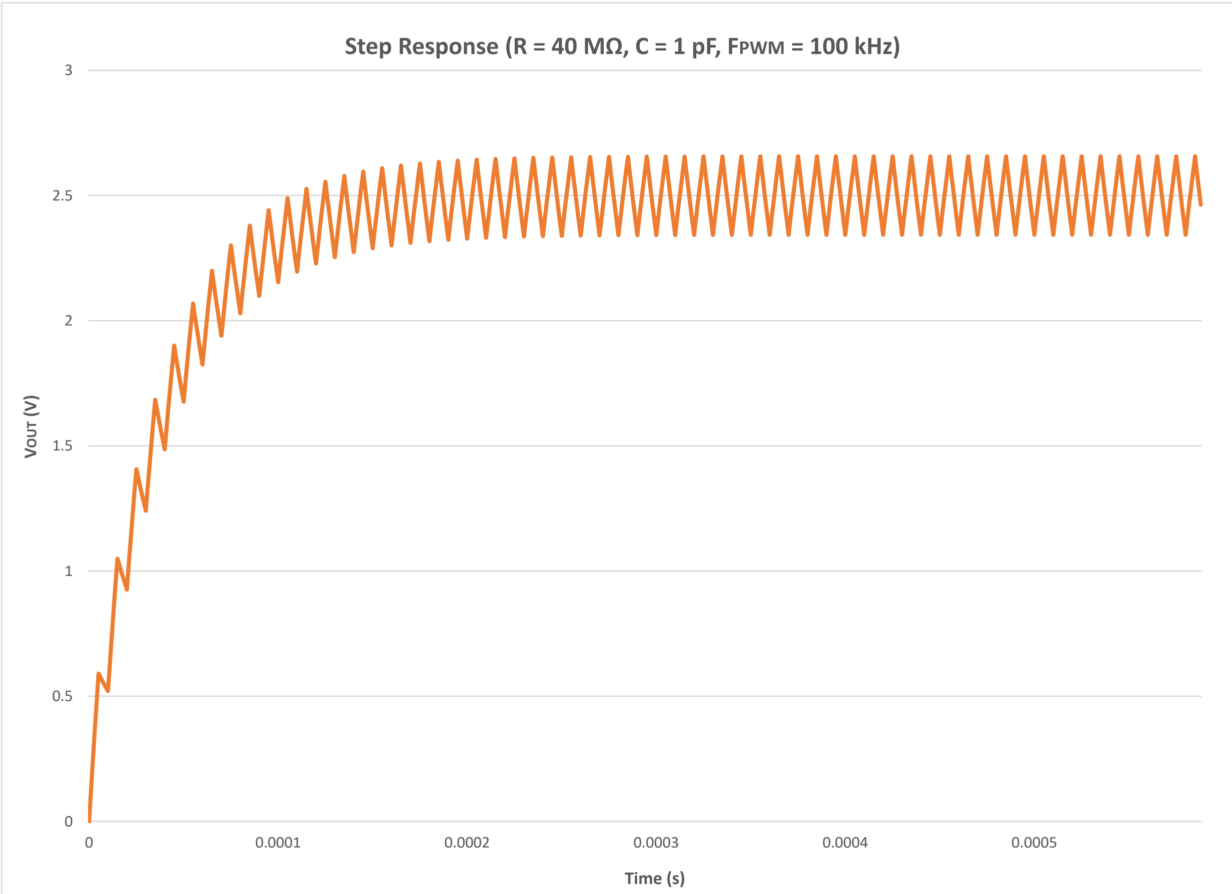


Figure 2-7. Step Response (R = 4 kΩ, C = 0.01 µF, FPWM = 10 kHz)

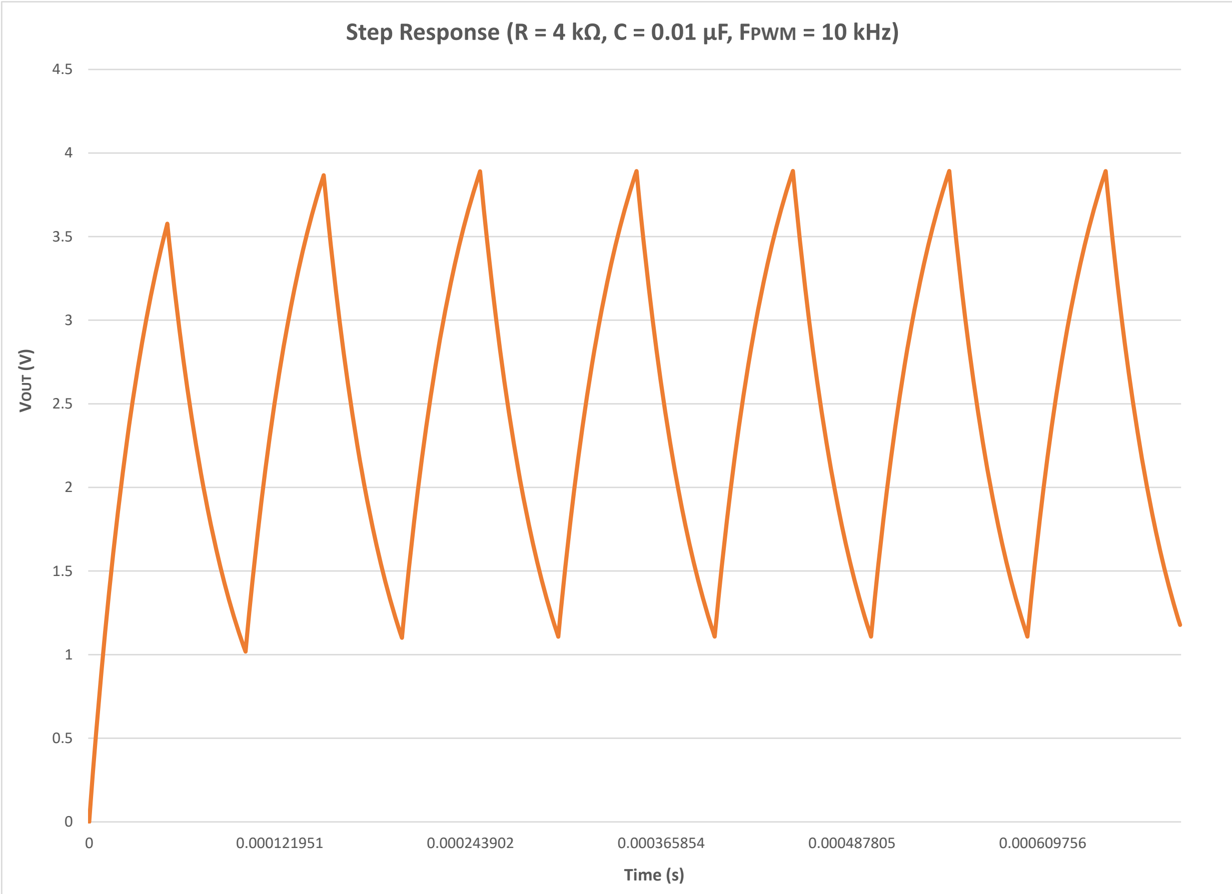


Figure 2-8. Step Response (R = 4 kΩ, C = 0.01 µF, F_{PWM} = 100 kHz)

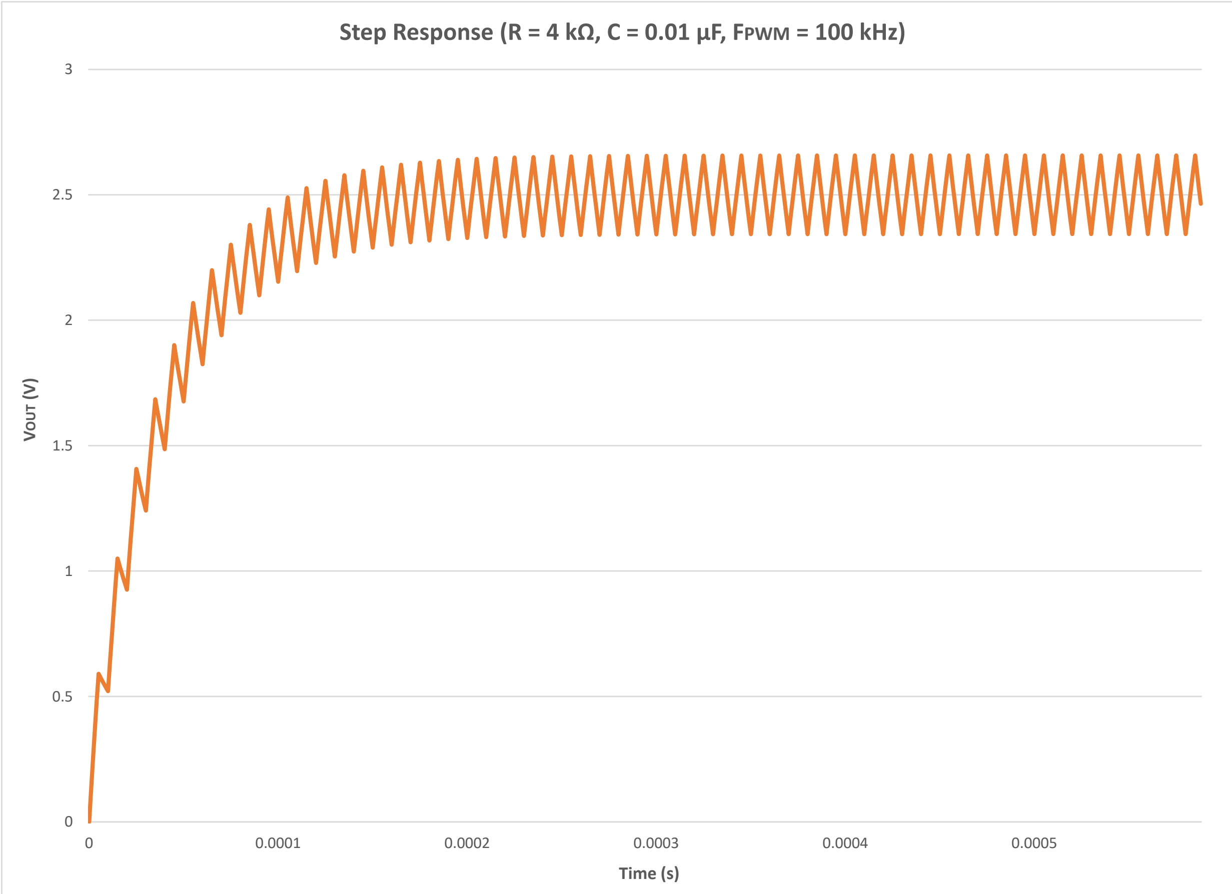


Figure 2-9. Step Response (R = 1.8 kΩ, C = 0.022 µF, F_{PWM} = 10 kHz)

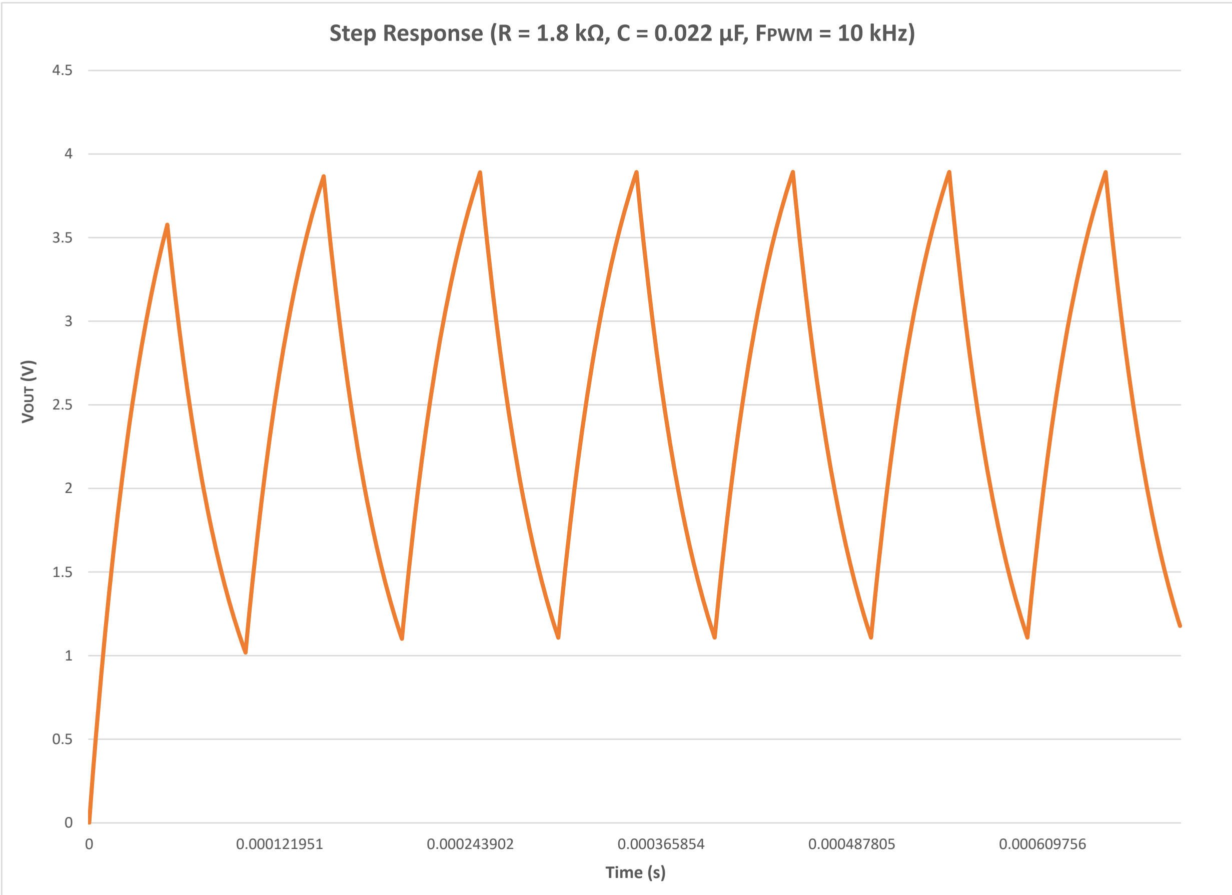
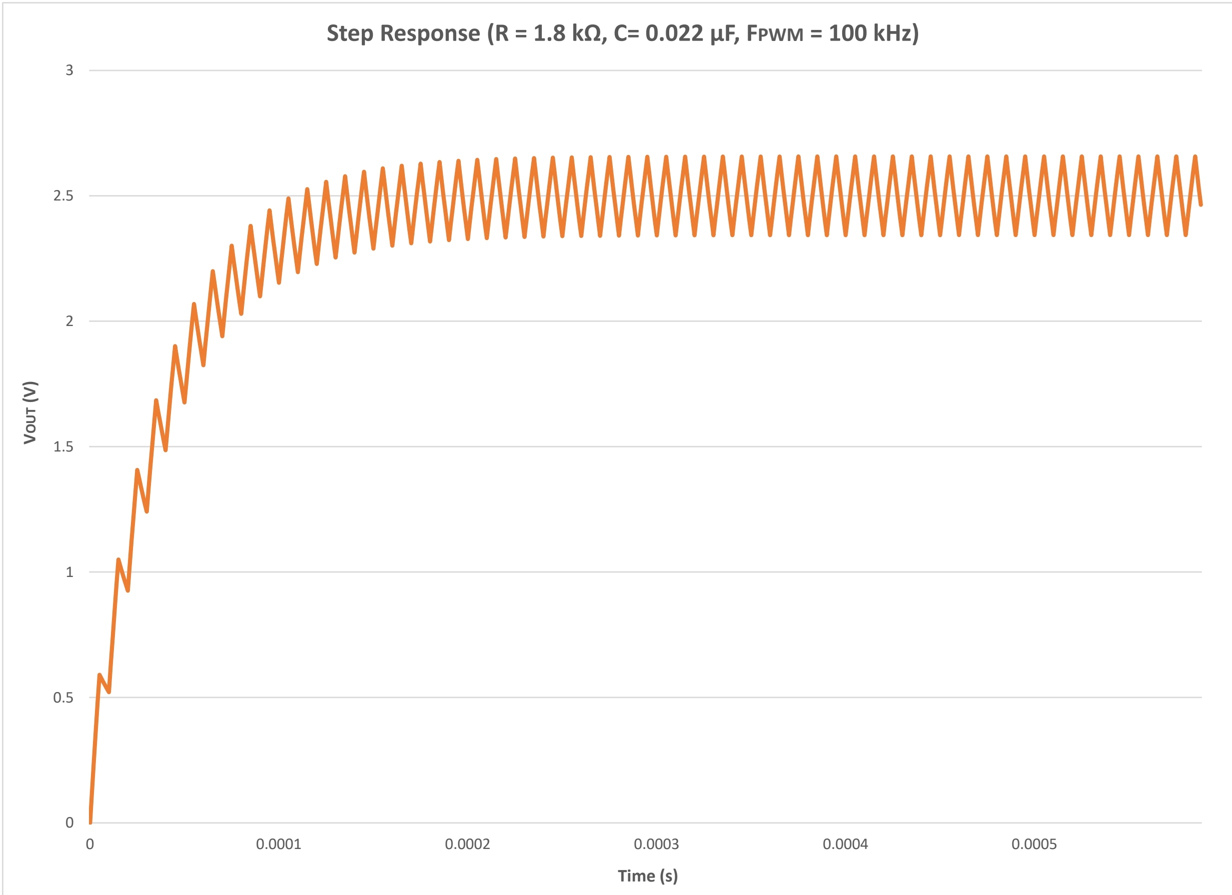


Figure 2-10. Step Response (R = 1.8 kΩ, C = 0.022 µF, F_{PWM} = 100 kHz)



3. Conclusion

PWM signals can be transformed into analog signals using a simple RC type low-pass filter. The PWM duty cycle determines the magnitude of the filter’s voltage output. As the duty cycle increases, the average voltage output increases, and vice versa. The PWM frequency determines the amount of attenuation the filter can produce. When the PWM frequency is close to the cut-off frequency, the filter responds quickly, but produces a high amount of ripple in the output signal. As the distance between the cut-off frequency and PWM frequency increases, the response time decreases, but the ripple in the output signal also decreases.

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