Square/ Triangular Wave Generator

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Second order low pass active filter

NDSU, ECE 723

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Spring 2008
This document includes the design description and analytical results of implementing the Square/Triangular wave generator and second order low pass active filter.

1. Design specifications

Square/Triangular wave generator:
- Frequency = 1 KHz ~10 KHz
- Duty cycle= 50%

Second order low pass active filter:
- \( f_0 = 2 \text{ kHz} \)
- \( Q=1.6 \)
- Unity gain (k=1)
- Frequency response should be captured

Square and Triangular wave are to be applied to the filter and the output waveforms should be obtained for frequency of 1 kHz, 2 kHz and 10 kHz.

2. Implementation

Square/Triangular wave generator:

The triangular waves are generated by alternately charging and discharging a capacitor (C1) with a constant current. The current is provided by the Op-amp. The comparator is configured as a non-inverting Schmitt trigger. It receives its input (positive and negative voltage) from Op-amp. The Zener diode clamp is used to stabilize the Schmitt trigger output levels at \( +\frac{V_{\text{clamp}}}{2} - \frac{Z+V_{\text{Don}}}{2} \), therefore the Schmitt input thresholds are \( V_i = \frac{R_1}{R_2} V_{\text{clamp}} \). We can calculate the frequency as:
\[
f_0 = \frac{R_1}{R_2} 4RC,
\]
hence \( f_0 \) can be varied by means of \( R \) or \( C \). \( R \) and \( C \) also determines the lower end of operating frequency range.
Figure 1. Square/Triangular wave generator

Circuit elements:

- The Op-amp is LM741. (Dual power supply= +/-15)
- The comparator is LM301A. (Dual power supply= +/-15)
- The Zener diode is 1N5229B; \( V_Z = 4.3V, I_R = 5.0\mu A, V_R = 1.0V, I_F = 200mA \).

\[ V_{\text{clamp}} = 4.3 + 1 = 5.3V. \]

- \( R_1 \) is selected as 20K\( \Omega \), \( R_2 \) is selected as 10K\( \Omega \). Therefore \( R_2/R_1 = 0.5 \) and \( V_v = V_{\text{clamp}}/0.5 = 5.3/0.5 = 10.6 \). However the proportion of \( R_2 \) and \( R_1 \) can be selected to result in any desirable gain and \( V_v \).

- \( f_0 \) must be variable over the range of 1kHz-10kHz. Therefore\( R \) is implemented with a potentiometer (\( R_p \)) and a series resistance (\( R_s \)). \( R_p + R_s \approx 10R_s \). We select \( R_p \) as 25K\( \Omega \) then \( R_s \) will be 2.5K\( \Omega \).

For \( f_0 = f_{\text{max}} = 10 \) kHz, we should set \( R_p = 0, R = R_{\text{min}} = R_s = 2.5K\Omega \). Therefore \( C = (R_2/R_1) / 4Rf_0 = 0.5/ 4 \times 10^4 \times 2.5 \times 10^3 = 5 \) nF.

- \( R_3 \) provides current to \( R, R_2, \) zener diodes and the load. \( I_{R_{\text{max}}} = V_{\text{clamp}}/R_{\text{min}} = 5.3/2.5 = 2.12 \) mA. \( I_{R_{2\text{max}}} = V_{\text{clamp}}/R_2 = 5.3/10 = 0.5 \) mA. For zener diode \( I_r \) is 5 \( \mu A \). The load current is allowed to be the maximum of 1mA. Hence \( I_{R_3_{\text{max}}} = 2.12 + 0.5 + 0.005 + 1 = 3.62 \) mA. Then \( R_3 = (13 - 5.3)/3.62 = 2.12 \) K\( \Omega \).
Second order low pass active filter:

The circuit of the second order, low pass active filter with unity gain is shown in figure 2.

\[ H(s) = \frac{1}{(s/w_0)^2 + (1/Q)(s/w_0) + 1} \]

![Figure 2. Second order low pass active filter.](image)

To design the circuit, assume \( R_2 = R \), \( C_2 = C \), \( R_1 = mR \), \( C_1 = nC \). Then:

- Assume \( n \rightarrow 4Q^2 = 4 \times 1.6^2 = 10.24 \) → we selected \( n \) as 15.
- We chose \( C_2 = 10 \text{ nF} \), so \( C_1 = 10 \times 15 = 150 \text{nF} \).
- Based on \( Q \) and \( n \), \( m \) was equal to 3.55.
- Based on \( m \) and \( f_0 \), \( R_2 \) was calculated and it was equal to 1.08 K. Now \( R_1 \) was calculated to be 3.88K.
- We used LM741 for the op-amp.

The circuit was built with these defined elements, and then the output of square/triangular wave generator was applied to the input of the filter.
3. Simulation results

The simulation was done by means of PSIM and Pspice. The simulation results are categorized in two sections; these two sections correspond to the output plots and FFT of output plots. In each section simulation is done for both square and triangular waves with frequencies 1 kHz, 2 kHz and 10 kHz.

Based on the $f_0 (=2\text{kHz})$ and $Q (=1.6)$, $|H(s)|$ of filter is calculated.

$|H(s)| = \left| \frac{1}{(jf/2)^2 + (1/1.6)(jf/2) + 1} \right|$. Therefore we can calculate the voltage gain for all frequencies.

If $f=1 \text{ kHz}$, $|H(s)|= 1.23$

If $f=2 \text{ kHz}$, $|H(s)|= 1$

If $f=10 \text{ kHz}$, $|H(s)|= 0.0413$

In the following figures, these gain values can be used to justify the amplitude of filtered signals, which are gotten through simulation.

<table>
<thead>
<tr>
<th></th>
<th>Theoretical Gain</th>
<th>Simulated Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square wave (1 kHz)</td>
<td>1.23</td>
<td></td>
</tr>
<tr>
<td>Square wave (2 kHz)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Square wave (10 kHz)</td>
<td>0.0413</td>
<td></td>
</tr>
<tr>
<td>Triangular wave (1 kHz)</td>
<td>1.23</td>
<td></td>
</tr>
<tr>
<td>Triangular wave (2 kHz)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Triangular wave (10 kHz)</td>
<td>0.0413</td>
<td></td>
</tr>
</tbody>
</table>

- **Section 1 (analysis in time domain)**
  - **Frequency is 1 kHz.**
    - Square wave:
    - Triangular wave:
  - **Frequency is 2 kHz.**
    - Square wave:
- Triangular wave:
  - Frequency is 10 kHz.
    - Square wave:
    - Triangular wave:

- Section 2 (FFT of Outputs)
  - Frequency is 1 kHz.
    - Square wave:
- Triangular wave:
  - Frequency is 2 kHz.

- Square wave:

- Triangular wave:

- Frequency is 10 kHz.
  - Square wave:
The following figure shows the frequency response of the low pass filter. As shown, when $f=f_0=2$ kHz, the voltage gain is 1.7 that is almost equal to $K \times Q = 1 \times 1.6$. When $f=1$ kHz, the voltage gain is 1.2, the correctness can be verified using $|H(s)|$, which is equal to 1.23 for $f=1$ kHz. For other frequencies, the voltage gain can be justified in the same way.

4. Analytical results

We implemented both circuits on the bread board. The Square/Triangular wave genertaor circuit is configured as shown in figure 1. By means of oscilloscope the output voltage is observed. At $V_1$, we observed the triangular wave. The square wave is observed at $V_2$. 

By changing the $R_p$ resistance, we could vary the wave’s frequencies from 1 kHz to 10 kHz.

The output ($V_1$ and $V_2$) were connected (not simultaneously) to the input of the low pass filter which was implemented as shown in figure 2. Therefore, we could observe the low pass filtered waveform. All the obtained waves were saved and plotted. They are represented in the following figures. As stated before, $|H(s)| = \left| \frac{1}{(j \frac{f}{2})^2 + (1/1.6)(j \frac{f}{2}) + 1} \right|$. Therefore we can calculate the voltage gain for all frequencies.

- If $f=1$ kHz, $|H(s)| = 1.23$
- If $f=2$ kHz, $|H(s)| = 1$
- If $f=10$ kHz, $|H(s)| = 0.0413$

In the following figures, these gain values can be used to justify the amplitude of filtered signals, which are gotten from the circuit implemented on the breadboard.

<table>
<thead>
<tr>
<th></th>
<th>Theoretical Gain</th>
<th>Obtained Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square wave (1 kHz)</td>
<td>1.23</td>
<td>1.6</td>
</tr>
<tr>
<td>Square wave (2 kHz)</td>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td>Square wave (10 kHz)</td>
<td>0.0413</td>
<td>0.05</td>
</tr>
<tr>
<td>Triangular wave (1 kHz)</td>
<td>1.23</td>
<td>1</td>
</tr>
<tr>
<td>Triangular wave (2 kHz)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Triangular wave (10 kHz)</td>
<td>0.0413</td>
<td>0.025</td>
</tr>
</tbody>
</table>

In some cases the obtained gain is equal to the theoretical values and in some cases a deviation is seen. Generally we can see that in equal frequency condition, when the input is square wave, the gain is higher than the triangular input, or we can say that for equal gains, when input signal is square wave the output amplitude is higher than the case when the input signal is triangular wave. The reason will be clear when we look at the harmonics of these two waves. According to the following formulas, for a given frequency, the square wave harmonics have higher amplitude than triangular wave.
\[ x_{\text{square}}(t) = \frac{4}{\pi} \sum_{k=1}^{\infty} \frac{\sin \left( (2k - 1)2\pi ft \right)}{(2k - 1)} \]

\[ x_{\text{triangle}}(t) = \frac{8}{\pi^2} \sum_{k=1}^{\infty} \sin \left( \frac{k\pi}{2} \right) \frac{\sin(2\pi k ft)}{k^2} \]

- **Section 1 (analysis in time domain)**
  - Frequency is 1 kHz.
    - **Square wave:**
      ![Square wave graph]
    - **Triangular wave:**
      ![Triangular wave graph]
  - Frequency is 2 kHz.
    - **Square wave:**
      ![Square wave graph]
• Triangular wave:

- Frequency is 10 kHz.

• Square wave:

• Triangular wave:
- **Section 2 (FFT of Outputs)**

- Frequency is 1 kHz.
  - **Square wave:**
    
    ![Graph of Square Wave](image)
  
  - **Triangular wave:**
    
    ![Graph of Triangular Wave](image)

- Frequency is 2 kHz.
  - **Square wave:**
    
    ![Graph of Square Wave](image)
- Triangular wave:

- Frequency is 10 kHz.

- Square wave:

- Triangular wave: