A temperature-insensitive VCO and derivative PWM signal generator

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Abstract
A novel Schmitt trigger oscillator able to generate square/triangular wave is proposed. Its advantages are that the oscillation frequency and amplitudes are independent of not only temperature but also power supply voltage. Electronic adjustment of the oscillation frequency can be obtained with wide sweep range and DC offset adjustment available. In addition, the proposed scheme can produce frequency-constant derivative of PWM signal.

Introduction
Voltage Controlled Oscillator (VCO) and Pulse Width Modulation (PWM) are widely used in many fields. Temperature-insensitive square/triangular wave VCO with a wide sweep capability can be easily realized based on using Operational Transconductance Amplifiers (OTAs) as a switching current source to charge and discharge a grounded timing capacitor followed by a Schmitt trigger [1-2]. Its advantage is that the oscillation frequency is independent of the temperature sensitive transistor parameters of OTAs. However, it has much complicated scheme and small range of the oscillation frequency. Hence this scheme still does not provide sufficient stability to implement it as a precise component in the design of instrumentation and communication systems, especially under varying environment conditions. For the conventional simple PWM signal generator, output frequency depends on modulating signal [3-7]. That makes it is complicated in control systems [8].

A novel scheme whose the oscillation frequency is not only frequency-stable but also relatively wide range. The square/triangular wave DC offset level can be electronically adjusted which does not affect on their frequency. Furthermore, by the proposed scheme, it can originate the precisely derivative PWM signal without an additional device requirement and frequency variation. The circuit is composed of 1 operational amplifier (Op amp), 2 OTAs and single of resistor and capacitor.

Circuit Description and Operation
The Voltage Controlled Oscillator

Fig. 1. The circuit diagram of proposed VCO

The proposed VCO is illustrated in Fig. 1 whereas \( v_i(t) \) is connected to ground. From the circuit, OTA1 and the timing capacitor C function as an integrator whose time constant is proportional to the bias current \( I_{B1} \). The Op amp, OTA2 and the resistors \( R \) work as a Schmitt trigger.

The maximum output current of the OTAs is respectively \( I_{B1} \) or \( I_{B2} \). At the first instant when the power supplies are turned ON the capacitor C is discharged and \( v_{o1}(t) = 0 \). Positive feedback in Op amp and OTA2 results in the maximum output current in these amplifiers. Assume that these currents are flowing out of OTA1 and OTA2, then the voltage \( v_{o1}(t) \) at the threshold resistor jumps to its maximum value of

\[
v_{o1} = I_{B2} R \quad (1)
\]
Simultaneously, OTA1 will provide the maximum output current of $I_{B1}$ and the capacitor $C$ is charged by this current. The voltage $V_{o1}(t)$ is linearly increasing and when it is close to its highest value $V_{o3H}$, which is close to $V_{o3L}$. The output voltage of Op amp starts to turn its direction. As a result, the output current of OTA1 will quickly achieve its maximum value flowing into OTA2. Now the voltage $V_{o3}(t)$ has jumped to its maximum value of

$$V_{o3L} = -I_{B2}R$$  \hspace{1cm} (2)

and the output current of OTA1 changes its direction. The current $I_{B1}$ flows into OTA1 and the capacitor $C$ is discharged by this current. The voltage $V_{o1}(t)$ is linearly decreasing now. When it becomes approximately equal to $V_{o3L}$ which is also close to $V_{o3L}$, the output voltage of Op amp starts to turn its direction again. Therefore $V_{o3}(t)$ jumps up to $V_{o3H}$. The proposed circuit is now in its periodic operation while the waveforms generated from the proposed circuit; $V_{o1}(t)$ and $V_{o2}(t)$ will respectively be triangular and square wave as shown in figure 2.

**The oscillation frequency**

The operating current $I_{B1}$ and $I_{B2}$ and the threshold resistors $R$ should be chosen so that OTA1 and OTA2 are not saturated when their output voltage is maximal. Then the maximum oscillation can be achieved.

The oscillation frequency in such non-saturated VCO can be calculated with sufficient precision if the exact values of capacitor voltage (i.e. $V_{o3H}$ and $V_{o3L}$) at the instants of jumps are known. Owing to the rapid change of states the variation of the charging or discharging current during the short period of time just before a jump can be neglected [9].

In theoretical derivation, it is easy to display that time interval of positive saturation voltage of $V_{o2}(t)$ can be shown as

$$T_1 = \frac{2RCI_{B2}}{I_{B1}}$$  \hspace{1cm} (3)

In similar, that of negative saturation voltage of $V_{o2}(t)$ can be illustrated as

$$T_2 = \frac{2RCI_{B2}}{I_{B1}}$$  \hspace{1cm} (4)

Then we get the period time and frequency of oscillation respectively as

$$T = \frac{4RCI_{B2}}{I_{B1}}$$  \hspace{1cm} (5)

$$f = \frac{1}{4RC} \left( \frac{I_{B1}}{I_{B2}} \right)$$  \hspace{1cm} (6)

From eqn. (6), it is clearly shown that the oscillation frequency is independent of both temperature and power supply level. In addition, it can be electronically adjusted by either $I_{B1}$ or $I_{B2}$.

The peak-to-peak amplitude of square wave; $V_{o2(p-p)}$, and that of triangular wave can be respectively illustrated as

$$V_{o2(p-p)} = 2V_{SAT}$$  \hspace{1cm} (7)

$$V_{o1(p-p)} = 2I_{B2}R$$  \hspace{1cm} (8)

Where magnitude of positive saturation voltage; $V_{SAT^+}$ and that of negative saturation voltage; $V_{SAT^-}$ are assumed to be equal as $V_{SAT}$.

![Fig. 2. The practical signal of the proposed scheme with error analysis.](image-url)
The source of error

In practical, it is mainly assumed that the dominant nonidealities are amplifier slew rate \( (S_s) \) since the secondary source of error arises from current imbalances between positive and negative OTAs output currents which result in asymmetry in the output waveforms is relative small [1]. Then it is easy to show that the period of oscillation is given by

\[
T = \frac{4l_{B2}RC}{I_{B1}} \left[ 1 + \frac{I_{B1}V_{SAT}}{I_{B2}RCS_i} \right] \tag{9}
\]

The oscillation frequency with error analysis can be written as

\[
f_o = \frac{I_{B1}}{4l_{B2}RC} \left[ 1 + \frac{I_{B1}V_{SAT}}{I_{B2}RCS_i} \right]^{-1} \tag{10}
\]

Amplitude of square wave is independent of this error which is shown in Fig. 2. For those of triangular wave, it can be determined from

\[
V_{0\text{d}(p-p)} = 2l_{B2}R \left[ 1 + \frac{I_{B1}V_{SAT}}{I_{B2}RCS_i} \right] \tag{11}
\]

Compared eqn. (11) with eqn. (8), it is found that the second term in brackets also represents error in amplitude of triangular wave. From the error analysis, it is found that the frequency slightly depends on power supply level and slew rate of op amp but this effect can be reduced by using the higher slew rate op amp.

The DC offset Control

The DC offset of output signal of both presented square/triangular wave generation schemes can be adjusted by taking DC voltage source \( V_{\text{offset}} \) at \( V_i(t) \), then the voltage of triangular and square wave \( V_{03}(t) \) can be respectively shown as

\[
V_{03(p-p)} = 2l_{B3}R_1 + V_{\text{offset}} \tag{12}
\]

\[
V_{03(p-p)} = 2l_{B3}R_1 + V_{\text{offset}} \tag{13}
\]

Where magnitude of \( V_{SAT+} \) and \( V_{SAT-} \) are assumed to be equal as \( V_{SAT} \).

The PWM signal generator

If \( V_i(t) \) is assumed as a modulating signal, time interval of positive and negative saturation voltage of \( V_{03}(t) \) depend on the modulating signal respectively shown as

\[
T_1 = \frac{2RCI_{B2}}{I_{B1}} \left[ 1 + \frac{V_i(t_2) - V_i(t_1)}{2} \right] \tag{14}
\]

\[
T_2 = \frac{2RCI_{B2}}{I_{B1}} \left[ \frac{V_i(t_1) - V_i(t_2)}{2l_{B2}R} - 1 \right] \tag{15}
\]

We found that the period time of oscillation (carrier) which comes from summation of \( T_1 \) and \( T_2 \) is equal to eqn. (5), hence the oscillation frequency still be eqn. (6) while its duty cycle (D) depends on the derivative of modulating signal as following

\[
D = \frac{1}{2} \left( 1 + \frac{\Delta V_i}{2l_{B2}R_1} \right) \times 100\% \tag{16}
\]

where \( \Delta V_i \) is derivative of the modulating voltage \( (V_i(t_2) - V_i(t_1)) \). It demonstrates that the proposed scheme can function as the derivative PWM signal generator as well. The features are, independence of frequency against the modulating signal variation, and the relatively simple scheme due to integration of various stages of PWM signal generator such as triangular wave generator, adder and comparator [6-7] into the same circuit. The accurate modulating signal can be recovered by using integrator circuit after demodulation of the PWM output signal.

Experimental results and discussions

The proposed circuit was experimentally tested using the CA3080 OTAs and LF351 Opamp. The results are obtained with resistor \( 10k\Omega \) and capacitor \( \text{InF} \) with supply \( \pm 5V \). The first experimental results in Fig. 3 show the behavior of the circuit working as square/triangular wave generator. It is clear shown that this result is in close accordance with theoretical prediction in eqn. (6)-(11).

Fig. 4 (a) illustrates the operation of the circuit as the derivative PWM signal generator in which the modulating signal was sinusoidal signal with frequency 1kHz and amplitude of 1V whereas the carrier frequency of 50kHz. In addition the derivative PWM output signal was proved by demodulation using second order low pass filter (LPF) with cutoff frequency 1.5kHz [10] shown in Fig. 4(b). These results demonstrate that the recovered signal can be precisely achieved without frequency variation.

Conclusion

A simple circuit able to generate square/triangular wave has been described. Its features are that the oscillation frequency and amplitudes are independent of temperature and power supply voltage with DC offset control is available. Furthermore, it can generate constant frequency derivative of PWM signal without an additional device requirement. It utilizes low cost
commercial devices to obtain electronic frequency, amplitude and DC offset control over a relatively wide range of frequencies.

![Graph](image)

(a) Fig. 3. Experimental results with compared to theory of the first circuit with supply ±5V and (a) $I_{B1} = 50\mu$A

(b) $I_{B1} = 100\mu$A

(a) the derivative PWM signal generator with the upper trace is input voltage and lower trace is derivative PWM output signal

(b) The derivative PWM signal demodulation with the upper trace is input voltage and lower trace is demodulated output signal.

Fig. 4 (Continued)

References