Design of the Voltage-Controlled Sinusoidal Oscillator Using an OTA-C Simulated Inductor

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Abstract: Two sinusoidal voltage-controlled oscillators using linear operational transconductance amplifiers are presented in this paper: One is based on the positive-feedback bandpass oscillator model and the other on the negative-feedback Colpitts model. The bandpass VCO consists of a noninverting amplifier and a current-controlled *LC*-tuned circuit which is realized by two linear OTA's and two grounded capacitors, while the Colpitts VCO consists of an inverting amplifier and a current-controlled *LC*-tuned circuit realized by three linear OTA's and three grounded capacitors. Prototype circuits have been built with discrete components. The experimental results have shown that the Colpitts VCO has a linearity error of less than 5 percent, a temperature coefficient of less than rm 100 ppm/℃, and a ±1.5 Hz frequency drift over an oscillation frequency range from 712Hz to 6.3kHz. A total harmonic distortion of 0.3 percent has been measured for a 3.3kHz oscillation and the corresponding peak-to-peak amplitude was 1V. The experimental results for bandpass VCO are also presented.

1. Introduction

Voltage(current)-controlled oscillators(VCO's) with sinusoidal outputs have a number of important applications in instrumemtation, measurement, and communication systems. Sinusoidal VCO's with wide sweep capability can be realized by using operational transconductance amplifiers(OTA's) as active components [1], [2]. In these realizations, the variation of the oscillation frequency is obtained by controlling the transconductance gain of the OTA incorporated in the frequency-determining network. Since the transconductance gain of the OTA can be varied by an external dc bias current, the VCO operation can be readily implemented. The OTA-based VCO's reported so far are generated from three classical oscillator models, namely the phase-shift[3], the quadrature[4], and the state-variable bandpass oscillators[5]. These VCO's exhibit relatively wide frequency sweep ranges, but do not provide sufficient frequency stability to use them as a precise component in the design of instrumentation and measurement systems. *LC*-tuned oscillators have higher frequency stability than *RC*-active oscillators mentioned above. Therefore, VCO's with higher stability can be generated from *LC*-tuned oscillator models. In these paper two *LC*-tuned VCO's are presented: one is based on the positive-feedback *LC*-tuned oscillator, the other on the negative-feedback one. In these VCO's, the inductor is simulated by interconnecting OTA's and a grounded capacitor, and the resultant equivalent inductance is inversely proportional to the square of the transconductance gain of OTA's. The simulated inductor in turn together with a capacitor forms a *LC* resonent circuit to determine the oscillation frequency.

In the *LC*-tuned VCO using commercial OTA's[6], determining the temperature factor of the oscillation frequency is a temperature characteristics of the OTA's. Therefore, to obtain oscillation frequency of low-temperature factor, the OTA based on the excellent temperature stability is required. In this paper two *LC*-tuned sinusoidal VCO using linear OTA which the transconductance is close insensitive to temperature effect is implemented[7]. And then, prototype circuits have been built with discrete components, and the experimental results have shown the performance and application.

2. Bandpass model VCO

A block diagram of bandpass VCO is shown in Fig. 1. It consists of the bandpass circuit to select sinusoidal oscillation frequency and a noninverting amplifier to sustain a loop gain 1 of the total circuit. The sinusoidal VCO based on this block diagram is shown in Fig 2. In Fig. 2 a noninverting amplifier is formed by operational transconductance amplifier OTA3 and resistor R_{Q1}, and a bandpass circuit is formed by capacitor C_1, C_2 and simlated inductor consisting OTA1, OTA2, and capacitor C_L. Assuming $C_1 = C_2 = C$ and $G_{m1} = G_{m2} = G_m$, the loop gaincan be obtained by

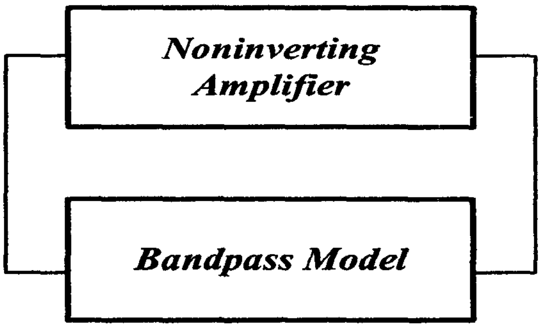

Fig. 1. Block diagram of the bandpass model sinusoidal oscillator.

$$L(s) = G_{m3}R_{Q1}\frac{\frac{1}{R_{Q1}C}s}{s^2 + \frac{1}{R_{Q1}C}s + \frac{1}{L_{eq}C}} \qquad (1)$$

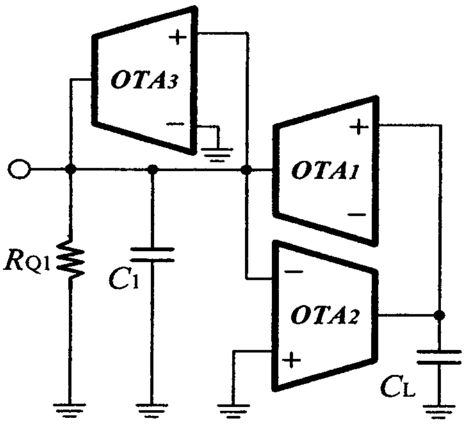

Fig. 2. Circuit diagram of the bandpass model sinusoidal VCO using linear OTA's.

where G_{m1} and G_{m2} are the transconductance of OTA1 and OTA2, respectively. The resulting inductance L_{eq} is given by

$$L_{eq} = \frac{C}{G_{m1}G_{m2}} = \frac{C}{G_m^2} \qquad (2)$$

Since the transconductance of the OTA is given by

$$G_m = \frac{I_Y}{I_X}\frac{1}{R_E} \qquad (3)$$

the simulated inductor using linear OTA will be expressed by

$$L_{eq} = \frac{C_L}{(I_Y/I_X)^2(1/R_E)^2} \qquad (4)$$

where I_X and I_Y are dc bias current. Thus, the frequency of oscillation is given by

$$f_0 = \frac{1}{2\pi R_E\sqrt{C_L C_1}}\left(\frac{I_Y}{I_X}\right) \qquad (5)$$

To obtain sustained oscillation at this frequency, one should set the magnitude of the loop gain to unity. This can be achieved by selecting

$$G_{m3}R_{Q1} = 1 \qquad (6)$$

It should be noted that in deriving (5) no numerical approximations have been made, and there are no temperature dependent terms. Also, note that the transconductance of the OTA is determined by the ratio of the dc bias currents I_X and I_Y.

3. Colpitts model VCO

A block diagram of Colpitts VCO is shown in Fig. 3. It consists of the Colpitts circuit to select sinusoidal oscillation frequency and an inverting amplifier to sustain a loop gain 1 of the total circuit. The sinusoidal VCO based on this block diagram is shown in Fig 4. In Fig. 4 a inverting amplifier is formed by operational transconductance amplifier OTA4 and resistor R_{Q2}, and a Colpitts circuit is formed by capacitor C_1, C_2 and simlated inductor consisting OTA1, OTA2, OTA3, and capacitor C_L. Assuming $C_1 = C_2 = C$ and $G_{m1} = G_{m2} = G_{m3} = G_m$, the loop gaincan be obtained by

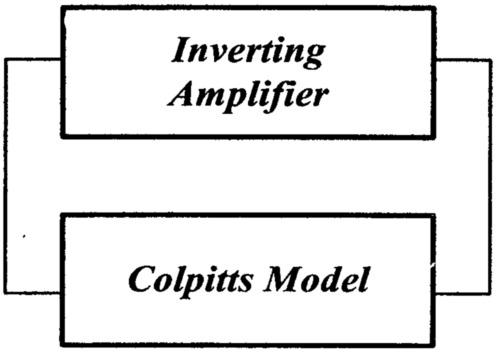

Fig. 3. Block diagram of the Colpitts model sinusoidal oscillator.

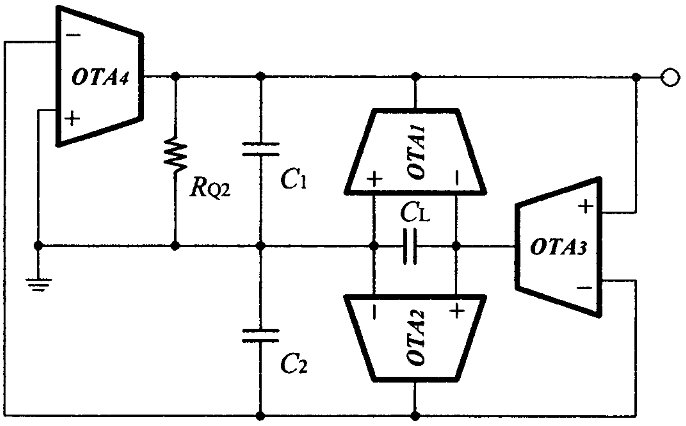

Fig. 4. Circuit diagram of the Colpitts model sinusoidal VCO using linear OTA's.

$$L(s) = -G_{m4}R_{Q2}\frac{1}{s^3C^2L_{eq}R_{Q2} + s^2CL_{eq} + s2CR_{Q2} + 1} \qquad (7)$$

where G_{m1}, G_{m2}, and G_{m3} are the transconductance of OTA1, OTA2, and OTA3, respectively. The inductance results for Colpitts VCO are also presented bandpass VCO. Thus, the frequency of oscillation is given by

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{C_1 + C_2}{C_L C_1 C_2}}\left(\frac{1}{R_E}\right)\left(\frac{I_Y}{I_X}\right) \qquad (8)$$

To obtain sustained oscillation at this frequency, one should set the magnitude of the loop gain to unity. This can be achieved by selecting

$$-G_mR\frac{1}{-\left(\frac{C_1+C_2}{L_{eq}C_1C_2}\right)C_2L_{eq}+1}=1$$

that is,

$$G_mR=\frac{C_1}{C_2}=1 \qquad (9)$$

It should be noted that in deriving (8) no numerical approximations have been made, and there are no temperature dependent terms. Also, note that the transconductance of the OTA is determined by the ratio of the dc bias currents I_X and I_Y. The discussion up to now has been based on the ideal OTA model. However, in reality, an OTA has a nonideal second-order effects. This nonideality is to be limited range of the oscillation frequency and generated the total-harmonic distortion.

4. Experimental Results and Discussion

Two sinusoidal VCO circuits in Fig.2 and Fig. 4 were built on breadboard using the discrete devices. The linear OTA used is shown in Fig. 5. It was built using transistor array MPQ2222(npn) and MPQ2907(pnp). The capacitors used were $C_1 = C_2 = 1nF$ $C_L = 10nF$, and its deviation and temperature factor are found to be ±15% and +350ppm/℃. The resistors were $R_{Q1} = 120k\Omega$, $R_{Q2} = 20k\Omega$, and its deviation and temperature factor are found to be ±0.1% and −5ppm/℃. All measurements were performed at supply voltages of ±10V.

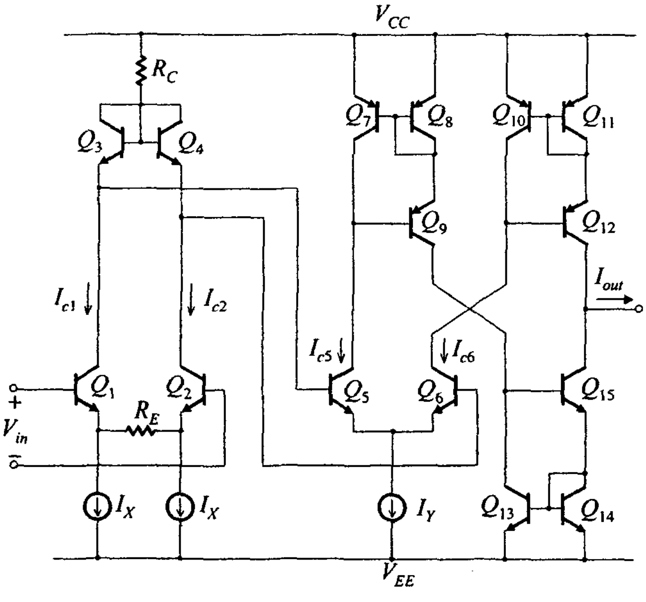

Fig. 5. Circuit diagram of the linear OTA used for experiment.

The resistors used in the linear OTA were $R_E = R_C = 40k\Omega$, and its deviation and temperature factor are found to be ±1% and −45ppm/℃. The bias current I_X was set to 25uA for convenience. The relation between the oscillation frequency and the bias current ratio was measured by varying I_Y from 1uA to 200uA. The results are plotted in Fig. 6 and show that the oscillation frequency is linearly dependent upon the bias current I_Y over the range of 5~50uA. If the deviation of 5% is to be allowed, the linearity exteneds to 100uA. A nonlinearity of the oscillation frequency versus bias current characteristics depends on nonlinear transconductance versus bias current ratio of OTA.

The temperature stability of the oscillator was measured by varying temperature from 20℃ to 60`℃. The results are also shown in Fig 6. The results show that the bandpass VCO has a temperature coefficient of −200~1000ppm/℃ over an oscillation frequency range from 496Hz to 4.655 kHz and the Colpitts VCO has a temperature coefficient of less than rm 100ppm/℃ over an oscillation frequency range from 712 Hz to 6.3kHz(bias current I_Y from 10uA to 100uA). For the Colpitts model VCO, a total harmonic distortion of 0.3 percent was measured for a 3.3kHz oscillation and the corresponding peak-to-peak amplitude was 1V. The result of frequency spectrum is shown in Fig 7.

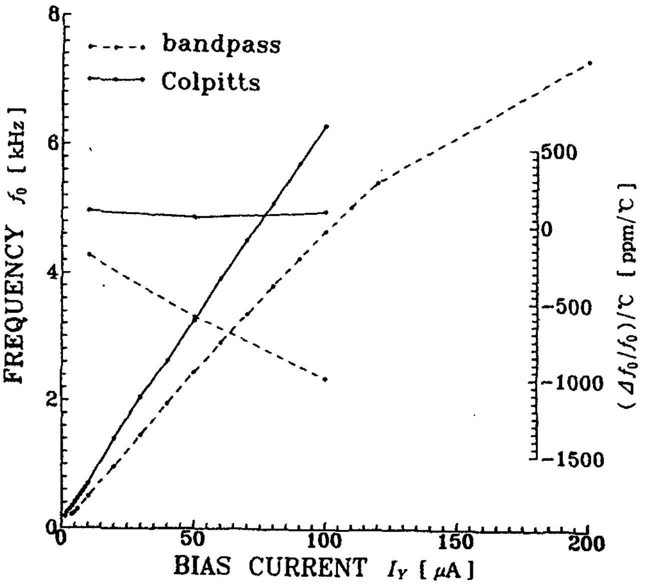

Fig. 6. Oscillation frequency versus bias current characteristics and the temperature stability obtained by the prototype VCO.

5. Conclusions

In this paper two sinusoidal VCO's using linear OTA are presented. An oscillation frequency of the proposed VCO's based on the LC-tuned circuit is linearly tunable over a wide frequency range. Since the linear OTA used is excellent, two proposed VCO's have been shown an excellent oscillation frequency and temperature stability for a bias current. Therefore, the proposed VCO's are expected to find applications in high performance instrumentation and communication circuits. The experimental results with discrete components show close agreement between perdicted behaviour and experimental performance.

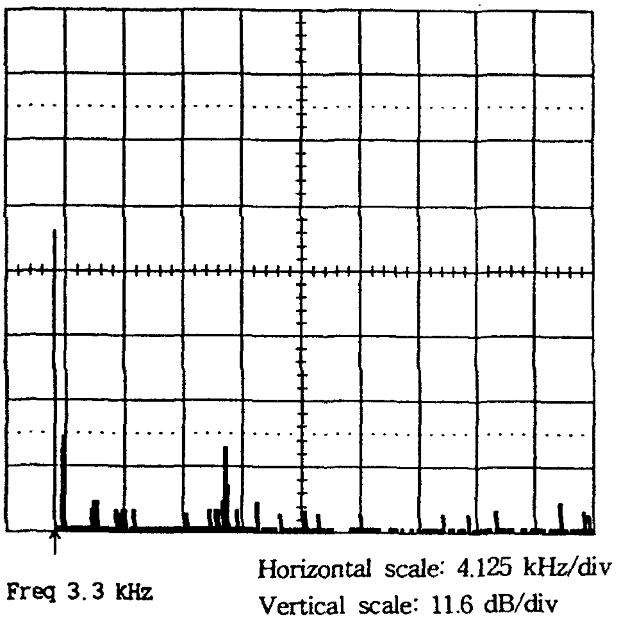

Fig. 7. Experimentally observed frequency spectrum for the Colpitts with $I_Y = 50uA$

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