A PROGRAMMABLE PHASE SHIFTER FOR SINUSOIDAL SIGNALS

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A simple current(voltage)-controlled phase shifter is presented. The circuit uses a small number of active and passive components. The feasibility of obtaining a temperature-insensitive phase shifter is explored. Experimental and simulation results are included.

INTRODUCTION

Phase shifters, with accurately, stable, and reproducible phase shifts, are widely used in many areas of electronic instrumentation, telecommunication, audio-frequency measurements, and control. In an ideal phase shifter, the output would be shifted in phase from the input by a specified, adjustable angle while its magnitude would be proportional to that of the input. This can be achieved by using the traditional constant-amplitude phase shifter, shown in Fig. 1, in which the phase shift is changed manually by tuning a variable resistor[1,2]. This method, however, is not suitable for automated operation. On the other hand, digital phase shifters that transform the sinusoidal signal into a pulse signal, apply the resulting pulse signal to digital counters and finally convert the output phase-shifted pulse signal into a sinusoidal signal have been reported [3,4]. While these techniques are suitable for generating computer-controlled phase shifters, they are too complicated. Alternatively, an RC phase shifter, with the tunable resistor replaced by a circuit built around a digital-to-analog converter whose input resistance is digitally controlled has been proposed [5]. This method requires an excessive number of active and passive electronic

FIGURE 1 Traditional Constant-Amplitude Phase-Shifter [1]

components; namely seven operational amplifiers, a digital-to-analog converter, 14 resistors, and six capacitors. Frequency-independent phase shifters using various design techniques have also been reported [6-11]. Conventional designs using switched-capacitor circuits suffer from aliasing effects and switching transients [6-8]. Removal of these unwanted effects can be achieved, but at the expense of using additional circuitry, which results in too complicated designs. Other designs of frequency-independent phase shifters require the use of variable delay lines [9], a frequency-to-voltage converter [10], or a frequency-to-current converter [11] in addition to many resistors and capacitors, and are unattractive because of their inherent limitations [9-11].

It is the purpose of this paper to present a simple programmable phase shifter for sinusoidal signals. The proposed circuit exploits to advantage the fact that the operational transconductance amplifier (OTA) is basically a differential voltage-controlled current source in designing a voltage(current)-controlled phase shifter.

PROPOSED CIRCUIT

Figure 2 shows the proposed voltage(current)-controlled phase shifter. Assuming an ideal operational amplifier with infinite input impedance, zero output impedance and infinite differential gain, and an ideal OTA with $I_O = g_m(V_+ - V_-)$, infinite input impedance and zero output impedance, routine analysis yields the transfer function of the circuit of Fig. 2, which can be expressed as

$$T(s) = \frac{V_o}{V_i} = -\frac{1 + g_m R_B - sC(R_A + R_B)}{1 + g_m R_B + sC(R_A + R_B)} \quad (1)$$

FIGURE 2 Proposed Voltage (Current)- Controlled Phase Shifter

Equation (1) corresponds to the transfer function of a first-order all-pass filter, or phase shifter, with a unity-gain and a phase shift, between the input voltage and the output voltage of

$$\Phi = \pi - 2 \tan^{-1} \frac{\omega C(R_A + R_B)}{1 + g_m R_B} \quad (2)$$

Equation (2) shows that the phase shift can be easily controlled by adjusting the transconductance g_m of the OTA. For a bipolar OTA, the transconductance g_m can be expressed as

$$g_m = \frac{I_{abc}}{2V_T} \quad (3)$$

where I_{abc} is the auxiliary bias current of the OTA and V_T is the thermal voltage $\cong 26$ mV at room temperature. From (2) and (3), it can be seen that the phase shift can be adjusted by controlling the current I_{abc} . This current can be obtained from the output of a digital-to-analog converter (DAC). Thus the realization of a digitally programmable sinusoidal phase shifter is feasible. But such a realization suffers from the temperature dependence of the phase shift. This is attributed to the dependence of V_T , and consequently g_m , on the temperature. However, a temperature insensitive phase shifter can be realized if the resistance R_B is replaced by an OTA-based grounded-resistance realization as shown in Fig. 3. Re-analysis yields the transfer function of the circuit of Fig. 3, which can be expressed as

$$\Phi = \pi - 2 \tan^{-1} \frac{\omega C(g_{m2}R_A + 1)}{g_{m1} + g_{m2}} \quad (4)$$

where g_{mi} , $i = 1, 2$ is the transconductance of the i th OTA. If we choose $g_{m2}R_A \gg 1$, then (4) reduces to

$$\Phi = \pi - 2 \tan^{-1} \frac{\omega C R_A}{1 + g_{m1}/g_{m2}} = \pi - 2 \tan^{-1} \frac{\omega C R_A}{1 + I_{abc1}/I_{abc2}} \quad (5)$$

From (5), it can be seen that the phase shift is temperature-insensitive and can be controlled by adjusting the current I_{abc1} while the current I_{abc2} is kept constant and satisfying the condition $I_{abc2} \gg \frac{2V_T}{R_A}$

FIGURE 3 Proposed Temperature-Insensitive Current (Voltage)-Controlled Phase Shifter

EXPERIMENTAL AND SIMULATION RESULTS

The proposed phase shifter circuit of Fig. 2 was experimentally tested using the $\mu A741$ operational amplifier (OA) and the LM 13600 OTA. The results obtained with $R = 5K$, $C = 10nF$, $R_A = 7.62K$, and $R_B = 1K$ are shown in Fig. 4. From Fig. 4, it can be seen that the measured results are in good agreement with the presented theory. The temperature-insensitive phase shifter of Fig. 3 was simulated using the SPICE circuit simulation program. The OTAs were modelled using the model of Fig. 5 [12] and the OA was modelled using the $\mu A741$ model available in the file eval.lib of SPICE. The results obtained with $R_A = 10K$, $C = 10nF$, $R = 5K$, and $I_{abc2} = 250\mu A$ are summarized in Fig. 6. From Fig. 6, it can be seen that the simulation results are in good agreement with the theory presented.

FIGURE 4 Experimental Results obtained from the Circuit of Fig. 2 with: $\mu A741$ OA; LM13600 OTA, $R = 5K$; $C = 10nF$; $R_A = 7.62K$.

FIGURE 5 The OTA model used in Simulation [12] $gm_o = 1923 \mu S$; $g_1 = 1/r_1 = 1000 \mu S$; $g_2 = 1/r_2 = 1000 \mu S$; $C_1 = 4.5 \text{ PF}$; $C_2 = 25.3 \text{ PF}$; $C_3 = 2.53 \text{ PF}$; $C_o = 7.5 \text{ PF}$; $R_1 = 65K$; $R_o = 63M\Omega$

FIGURE 6 Simulation Results obtained from the Circuit of Fig. 4 with: $R_A = 10K$; $R = 5K$; $C = 10nF$; $f = 1KHz$, $I_{abc2} = 250 \mu A$.

CONCLUSION

In this paper, a simple current(voltage)-controlled temperature-insensitive phase shifter has been presented. The circuit uses only two OTAs, one OA, three resistors, and one capacitor. The circuit can provide a continuous control on the phase shift rather than the coarse change obtainable from most of the digitally programmable phase shifters.

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