Inverse Sine Function Circuit with Temperature Compensation

Perm Apisitticharoonlert, Wandee Petchmaneelumka, and Vanchai Riewruja

***Abstract*—A technique to realize inverse sine function circuit with temperature compensation is presented in this paper. The hyperbolic tangent characteristic of bipolar-transistor differential pair existed in operational transconductance amplifier (OTA) is utilized for the proposed realization method. The proposed scheme provides a simple configuration and low cost. Simulation and experimental results confirming the performance of the proposed scheme are agreed with the theoretical values.**

***Index Terms*—sine-to-triangular waveform converter, operational transconductance amplifier, temperature compensation, hyperbolic tangent**

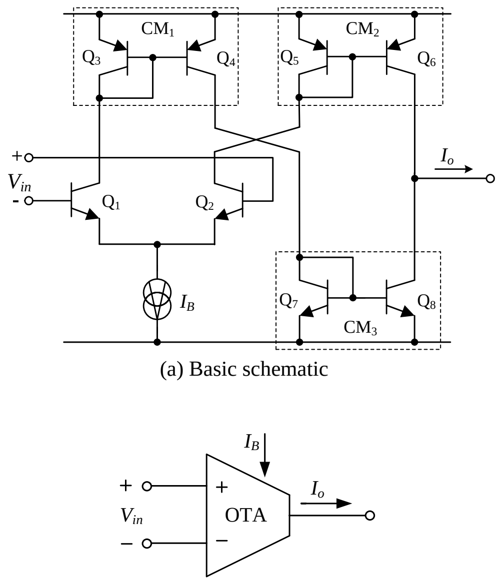
I. Introduction

Inverse sine function circuit or sine-to-triangular waveform converter is important circuit building block in electronic signal processing, instrumentation and measurement system. Many applications of sine-to-triangular waveform converter can be found in the literatures [1-4]. The techniques for implementation of sine-to-triangular waveform converter based on the use of hyperbolic tangent characteristic of bipolar-transistor differential pair existed in OTA have been reported [4-5]. Unfortunately, the performance of these approaches is disturbed by ambient temperature which exists in the behavior of OTA. Therefore, the aim of this paper is to propose a sine-to-triangular waveform converter based on the use of OTA's characteristic. The temperature effect of OTA used in the proposed scheme is compensated. Moreover, the circuit configuration is simple and low cost. PSPICE simulation and experimental results verifying the performance of the proposed circuit agreed with theoretical values are given.

II. Circuit Description

A. Principle of OTA

Basic scheme of BJT-based OTA and its symbol is shown in Fig. 1, where V_{in}, I_B and I_o define the input voltage, bias current and output current of OTA, respectively.



(a) Basic schematic

(b) Symbol

Fig. 1. BJT-based of OTA.

Transistors $Q_1 - Q_2$ form the differential pair. Transistors $Q_3 - Q_4$, $Q_5 - Q_6$ and $Q_7 - Q_8$ function as the current mirrors CM_1, CM_2 and CM_3, respectively, with unity gain. The relation between V_{in} and I_o can be given by

$$I_o = I_B \tanh(V_{in} / 2V_T) \tag{1a}$$

or

$$V_{in} = 2V_T \tanh^{-1}(I_o / I_B) \tag{1b}$$

where V_T is the thermal voltage. From (1b), the hyperbolic tangent term in (1a) can be expressed as

$$I_o = I_B\left(\frac{V_{in}}{2V_T} - \frac{1}{3}\left(\frac{V_{in}}{2V_T}\right)^3 + \frac{2}{15}\left(\frac{V_{in}}{2V_T}\right)^5 - ...\right) \tag{2}$$

It can be seen that the series covers to a sine function as

$$\sin(x) = x - \frac{x^3}{3!} + \frac{x^5}{5!} - ... \tag{3}$$

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If the input voltage of OTA V_{in} is weighted with the appropriated value of the factor m for $0 < m < 1$, then the output current I_o can be approximated as

$$I_o \cong I_B \sin\left(\frac{V_{in}}{2V_T}\right) \tag{4}$$

B. Proposed circuit

The proposed principle is based on the use of the inverse function technique of an inverting amplifier using operational amplifier (opamp) as shown in Fig. 2.

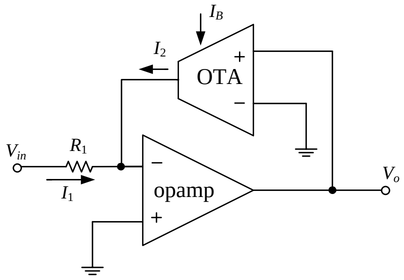


Fig. 2 Simple inverse sine function.

From routine circuit analysis, the relation between the currents i_1 and i_2 can be stated as

$$I_1 + I_2 = 0 \tag{5}$$

For (1a), (5) can be rewritten as

$$\frac{V_{in}}{R_1} + I_B \tanh\left(\frac{V_o}{2V_T}\right) = 0 \tag{6a}$$

or

$$V_o = -2V_T \tanh^{-1}\left(\frac{V_{in}}{I_B R}\right) \tag{6b}$$

The power series of (6b) can be stated as

$$V_o = -2V_T\left(\frac{V_{in}}{I_B R} + \frac{1}{3}\left(\frac{V_{in}}{I_B R}\right)^3 + \frac{1}{5}\left(\frac{V_{in}}{I_B R}\right)^5 + \ldots\right) \tag{7}$$

From (7), the series is corresponded to an inverse sine function as [6]

$$K\sin^{-1}(x) = K_T\left(x + B_3\frac{x^3}{3} + B_5\frac{x^5}{5} + \ldots\right) \tag{8a}$$

and

$$B_i = \prod_{j=1}^{\left(\frac{i-1}{2}\right)}\left[\frac{(i-2j)}{i-2j+1}\right] \qquad for \quad i = 3,5,7,\ldots \tag{8b}$$

If the current I_2 is chosen with the appropriated value by the weighting factor m at the output voltage V_o, then the series in (7) can then be expressed as

$$V_o = -2V_T \sin^{-1}\left(\frac{mV_{in}}{I_B R}\right) \tag{9}$$

From (9), the term of thermal voltage V_T causes the output voltage V_o depended on the ambient temperature. The proposed inverse sine function with temperature compensation is shown in Fig. 3. It consists of opamp OA_1, OTAs A_1 – A_2, constant resistors R_1 and R_L and variable resistor R_v. The operation of the proposed scheme can be explained as follow. The input voltage V_{in} is applied to the proposed circuit in Fig. 3.

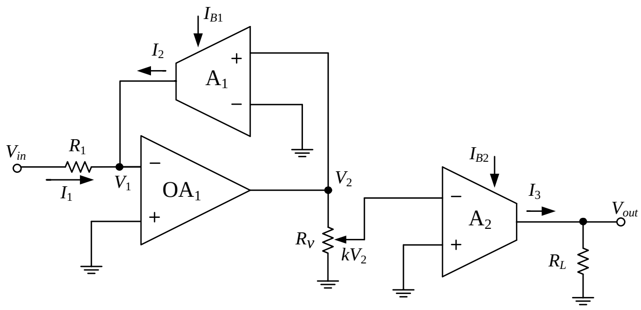


Fig. 3. Proposed inverse sine function circuit.

The voltage V_2 can be expressed as

$$V_2 = -2V_T \sin^{-1}\left(\frac{mV_{in}}{I_{B1} R}\right) \tag{10}$$

The voltage V_2 is attenuated by the variable resistor R_v to obtain the appropriated value for OTA A_2. The output voltage V_{out} can be expressed as

$$V_{out} = -\frac{I_{B2}}{2V_T} R_L k V_2 \tag{11}$$

where k is the optimal gain of the voltages V_2 for OTA A_2. Substitute V_2 from (10) into (11), the output voltage V_{out} of the proposed converter can be rewritten as

$$\begin{aligned} V_{out} &= -\frac{I_{B2}}{2V_T} R_L k\left(-2V_T \sin^{-1}\left(\frac{mV_{in}}{I_{B1} R}\right)\right) \\ &= I_{B2} R_L k \sin^{-1}\left(\frac{mV_{in}}{I_{B1} R}\right) \end{aligned} \tag{12}$$

It should be noted that the output of the proposed sine-to-triangular converter is in the form of inverse sine. Moreover, temperature existing in thermal voltage V_T is compensated.

III. Simulation Results

To verify the performance of the proposed inverse sine function, the circuit in Fig. 3 was simulated using PSPICE simulation program. The commercial opamp and OTA models are selected for OA_1 and $A_1 - A_2$, respectively. The circuit parameters R_1 = 1kΩ, R_L = 10kΩ, I_{B1} = 100μA and I_{B2} = 400μA were chosen. The supply voltage was set to ±10V. Fig. 4 demonstrates the simulation result of the proposed inverse sine function circuit, where V_{in} is 500Hz sinusoidal with 200mV_{pp}.

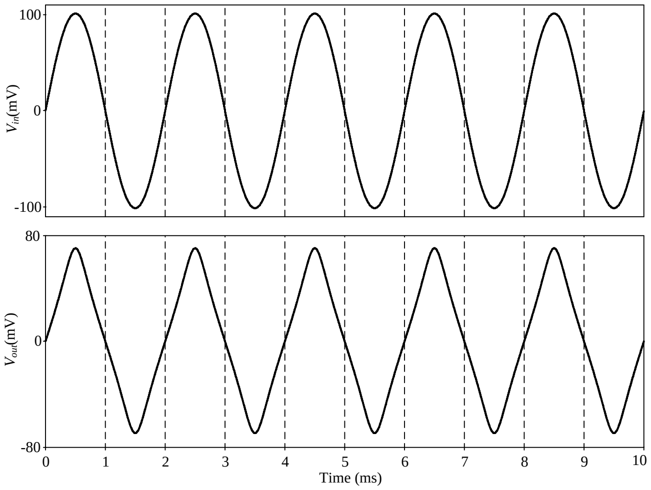


Fig. 4. Simulation result of the proposed sine-to-triangular waveform converter.

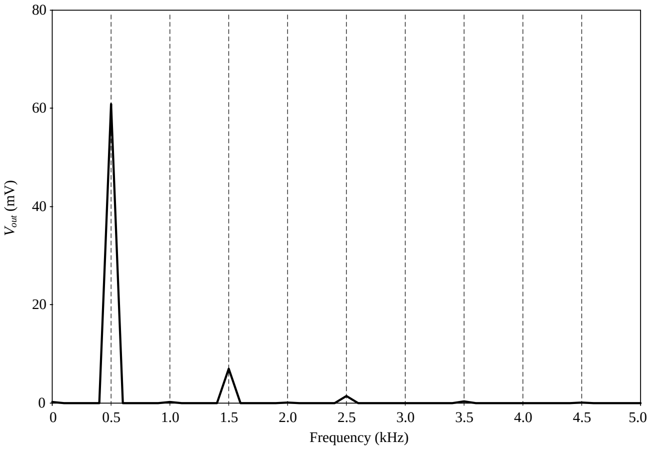
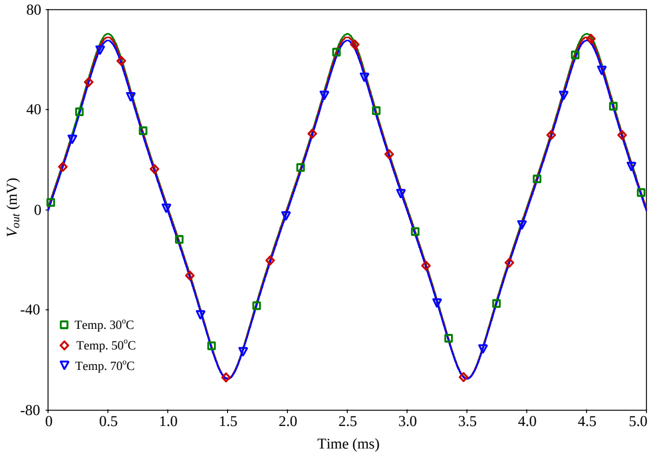
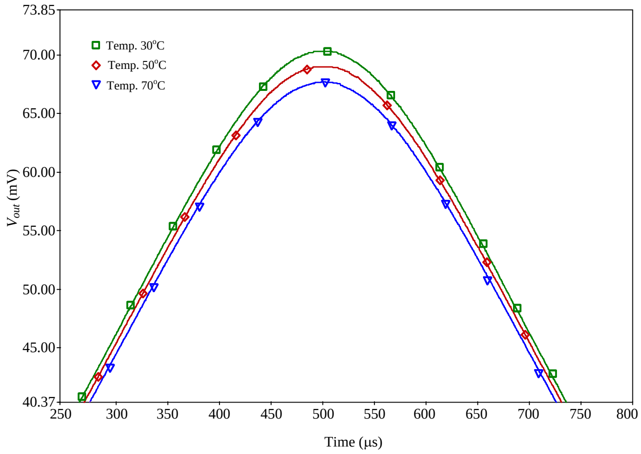


Fig. 5. Simulated frequency spectrum of the proposed sine-to-triangular waveform converter.



(a)



(b)

Fig. 6. Simulation results of temperature change by 3 difference values.
(a) obtained triangular wave
(b) zoom in at the peak of the obtained output

Fig. 5 shows simulated frequency spectrum of the obtained triangular signal in Fig. 4. Fig. 6 illustrates the simulated results by changing temperature with 3 difference values (30°C, 50°C and 70°C). From Fig. 6(b), the proposed circuit can minimize the effect from the ambient temperature, which the error caused by temperature changing is about 1.9%. The error of the It is evident that the performance of the proposed scheme is agreed with the expected values.

IV. Experimental Results

The proposed inverse sine function circuit in Fig. 3 was also experimentally implemented using commercial available devices LM351 and CA3280 for opamp OA_1 and OTAs $A_1 - A_2$, respectively. The circuit parameters are summarized in Table I. Experimental result of the proposed inverse sine function circuit is shown in Fig. 7(a). Frequency spectrum of the obtained triangular wave provided from the proposed circuit is shown in Fig. 7(b). It is clearly seen that the proposed converter is close agreement with the expected value.

TABLE I
Parameters Set in Practice Realization in Fig. 3

parameter	value
Supply voltage	±10V
I_{B1}	300μA
I_{B2}	700μA
R_1	1kΩ
R_L	10kΩ

V. Conclusion

Simple technique to realize inverse sine function or sine-to-triangular waveform converter with temperature compensation has been introduced in this paper. The proposed circuit provides simple configuration and low cost. Simulation and experimental results confirming the circuit performance are agreed with the expected values.

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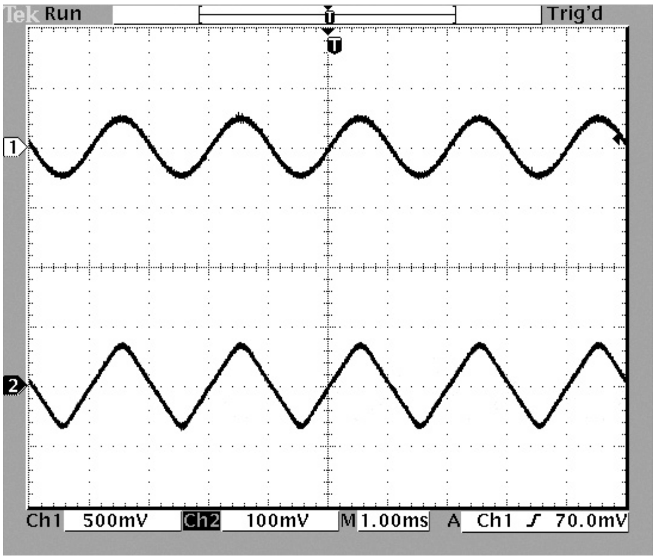
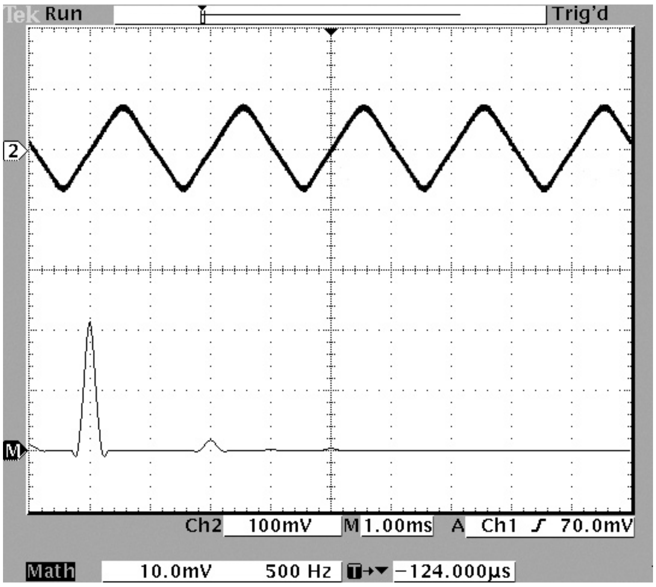


(a)



(b)

Fig. 7. Experimental results of the proposed sine-to-triangular waveform converter.

(a) behavior of the proposed circuit

(b) frequency spectrum

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