In this paper, we present a technique to realize an inverse sine function circuit with temperature compensation. The hyperbolic tangent characteristic of the bipolar-transistor differential pair in an operational transconductance amplifier (OTA) is utilized for this purpose. The proposed method provides a simple configuration and cost-effective solution. Simulation and experimental results confirm the performance of the proposed scheme agrees well with the theoretical values.

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

**I. INTRODUCTION**

The inverse sine function circuit or sine-to-triangular waveform converter is an essential building block in electronic signal processing, instrumentation, and measurement systems. Many applications of sine-to-triangular waveform converters can be found in the literature [1-4]. Techniques for implementing sine-to-triangular waveform converters based on the hyperbolic tangent characteristic of bipolar-transistor differential pairs have been reported [4-5]. Unfortunately, the performance of these approaches is affected by ambient temperature, which alters the behavior of the OTA. Therefore, the aim of this work is to present a sine-to-triangular waveform converter based on the OTA's characteristic, where the temperature effect of the OTA used in the proposed scheme is compensated. The circuit configuration is simple and cost-effective. Simulation and experimental results verify the performance of the proposed circuit, which agrees well with theoretical values.

**II. CIRCUIT DESCRIPTION**

**A. Principle of OTA**

A basic scheme of the BJT-based OTA and its symbol are shown in Fig. 1, where \( V_{in} \), \( I_B \), and \( I_o \) define the input voltage, bias current, and output current of the OTA, respectively.

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

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

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

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

\[
sin(x) = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \ldots \tag{3}
\]
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

$$I_o \equiv \frac{V_{in}}{2V_T}$$

(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

$$I_1 + I_2 = 0$$

(5)

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

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

(6a)

or

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

(6b)

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

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

(7)

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

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

(8a)

and

$$B_i = \prod_{j=1}^{(i+1)} \frac{(i-2j)}{i-2j+1} \text{ for } i = 3, 5, 7, \ldots$$

(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

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

(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 OA1, OTAs $A_1 - A_2$, constant resistors $R_1$ and $R_2$ 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

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

(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

$$V_{out} = \frac{I_{B2}}{2V_T} R_1 k V_2$$

(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

$$V_{out} = \frac{I_{B2}}{2V_T} R_1 k \left(-2V_T \sin^{-1}\left(\frac{mV_{in}}{I_B R}\right)\right)$$

$$= I_{B2} R_1 k \sin^{-1}\left(\frac{mV_{in}}{I_B R}\right)$$

(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 OA1 and A1 – A2, respectively. The circuit parameters \( R_1 = 1\, k\Omega \), \( R_L = 10\, k\Omega \), \( I_{B1} = 100\, \mu A \) and \( I_{B2} = 400\, \mu A \) were chosen. The supply voltage was set to \( \pm 10V \). Fig. 4 demonstrates the simulation result of the proposed inverse sine function circuit, where \( V_{in} \) is 500Hz sinusoidal with 200mVpp.

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

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 OA1 and OTAs A1 – A2, 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**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>( \pm 10V )</td>
</tr>
<tr>
<td>( I_{B1} )</td>
<td>300, \mu A</td>
</tr>
<tr>
<td>( I_{B2} )</td>
<td>700, \mu A</td>
</tr>
<tr>
<td>( R_1 )</td>
<td>1, k\Omega</td>
</tr>
<tr>
<td>( R_L )</td>
<td>10, k\Omega</td>
</tr>
</tbody>
</table>

**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.
Fig. 7. Experimental results of the proposed sine-to-triangular waveform converter.
(a) behavior of the proposed circuit
(b) frequency spectrum

REFERENCES


