

LM13700 Dual Operational Transconductance Amplifiers

With Linearizing Diodes and Buffers

1 Features

- $g_m$  Adjustable Over 6 Decades
- Excellent  $g_m$  Linearity
- Excellent Matching Between Amplifiers
- Linearizing Diodes for reduced output distortion
- High Impedance Buffers
- High Output Signal-to-Noise Ratio

2 Applications

- Current-Controlled Amplifiers
- Stereo Audio Amplifiers
- Current-Controlled Impedances
- Current-Controlled Filters
- Current-Controlled Oscillators
- Multiplexers
- Timers
- Sample-and-Hold Circuits

3 Description

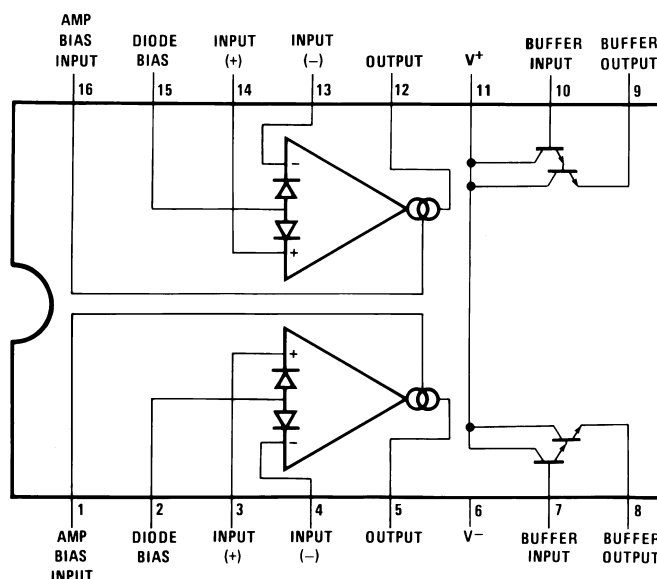
The LM13700 series consists of two current-controlled transconductance amplifiers, each with differential inputs and a push-pull output. The two amplifiers share common supplies but otherwise operate independently. Linearizing diodes are provided at the inputs to reduce distortion and allow higher input levels. The result is a 10-dB signal-to-noise improvement referenced to 0.5 percent THD. High impedance buffers are provided which are especially designed to complement the dynamic range of the amplifiers. The output buffers of the LM13700 differ from those of the LM13600 in that their input bias currents (and thus their output DC levels) are independent of  $I_{ABC}$ . This may result in performance superior to that of the LM13600 in audio applications.

Device Information<sup>(1)</sup>

| PART NUMBER | PACKAGE   | BODY SIZE (NOM)     |
|-------------|-----------|---------------------|
| LM13700     | SOIC (16) | 3.91 mm × 9.90 mm   |
|             | PDIP (16) | 6.35 mm × 19.304 mm |

(1) For all available packages, see the orderable addendum at the end of the data sheet.

Connection Diagram



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## 4 Revision History

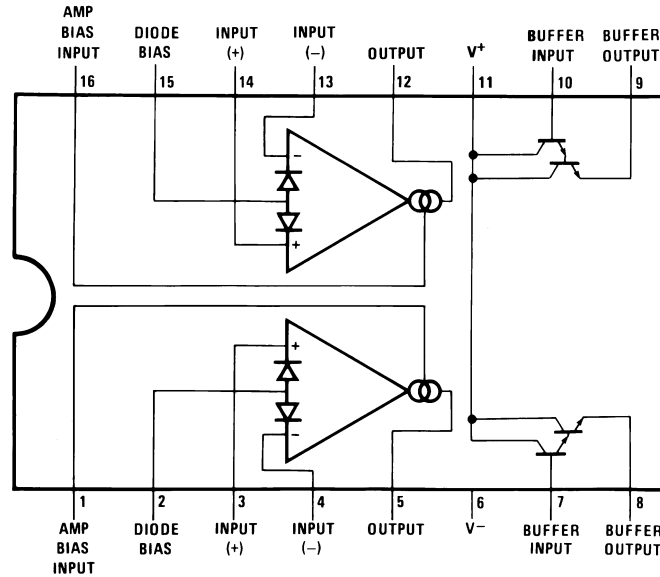
NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

| Changes from Revision E (March 2013) to Revision F                                                                                                                                                                                                                                          | Page     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|
| • Added ESD Ratings table, Feature Description section, Device Functional Modes, Application and Implementation section, Power Supply Recommendations section, Layout section, Device and Documentation Support section, and Mechanical, Packaging, and Orderable Information section. .... | <b>1</b> |
| • Removed soldering information in Absolute Maximum Ratings table .....                                                                                                                                                                                                                     | <b>4</b> |

| Changes from Revision D (March 2013) to Revision E         | Page      |
|------------------------------------------------------------|-----------|
| • Changed layout of National Data Sheet to TI format ..... | <b>27</b> |

## 5 Pin Configuration and Functions

**D or NFG Package  
16-Pin SOIC or PDIP  
Top View**



**Pin Functions**

| PIN            |       | I/O | DESCRIPTION                  |
|----------------|-------|-----|------------------------------|
| NAME           | NO.   |     |                              |
| Amp bias input | 1, 16 | A   | Current bias input           |
| Buffer input   | 7, 10 | A   | Buffer amplifier input       |
| Buffer output  | 8, 9  | A   | Buffer amplifier output      |
| Diode bias     | 2, 15 | A   | Linearizing diode bias input |
| Input+         | 3, 14 | A   | Positive input               |
| Input–         | 4, 13 | A   | Negative input               |
| Output         | 5, 12 | A   | Unbuffered output            |
| V <sup>+</sup> | 11    | P   | Positive power supply        |
| V <sup>–</sup> | 6     | P   | Negative power supply        |

## 6 Specifications

### 6.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)<sup>(1)</sup>

|                                                                   | MIN             | MAX                       | UNIT |
|-------------------------------------------------------------------|-----------------|---------------------------|------|
| Supply voltage                                                    |                 | 36 V <sub>DC</sub> or ±18 | V    |
| DC input voltage                                                  | +V <sub>S</sub> | –V <sub>S</sub>           | V    |
| Differential input voltage                                        |                 | ±5                        | V    |
| Diode bias current (I <sub>D</sub> )                              |                 | 2                         | mA   |
| Amplifier bias current (I <sub>ABC</sub> )                        |                 | 2                         | mA   |
| Buffer output current <sup>(2)</sup>                              |                 | 20                        | mA   |
| Power dissipation <sup>(3)</sup> T <sub>A</sub> = 25°C – LM13700N |                 | 570                       | mW   |
| Output short circuit duration                                     |                 | Continuous                |      |
| Storage temperature, T <sub>stg</sub>                             | –65             | 150                       | °C   |

- (1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, which do not imply functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions*. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
- (2) Buffer output current should be limited so as to not exceed package dissipation.
- (3) For operation at ambient temperatures above 25°C, the device must be derated based on a 150°C maximum junction temperature and a thermal resistance, junction to ambient, as follows: LM13700N, 90°C/W; LM13700M, 110°C/W.

### 6.2 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)

|                                       | MIN      | MAX   | UNIT |
|---------------------------------------|----------|-------|------|
| V+ (single-supply configuration)      | 9.5      | 32    | V    |
| V+ (dual-supply configuration)        | 4.75     | 16    | V    |
| V– (dual-supply configuration)        | –16      | –4.75 | V    |
| Operating temperature, T <sub>A</sub> | LM13700N |       | 0    |
|                                       |          | 70    | °C   |

### 6.3 Thermal Information

| THERMAL METRIC <sup>(1)</sup> |                                              | LM13700  |            | UNIT |
|-------------------------------|----------------------------------------------|----------|------------|------|
|                               |                                              | D (SOIC) | NFG (PDIP) |      |
|                               |                                              | 16 PINS  | 16 PINS    |      |
| R <sub>θJA</sub>              | Junction-to-ambient thermal resistance       | 83.0     | 43.8       | °C/W |
| R <sub>θJC(top)</sub>         | Junction-to-case (top) thermal resistance    | 44.0     | 34.9       | °C/W |
| R <sub>θJB</sub>              | Junction-to-board thermal resistance         | 40.5     | 28.3       | °C/W |
| Ψ <sub>JT</sub>               | Junction-to-top characterization parameter   | 11.5     | 19.1       | °C/W |
| Ψ <sub>JB</sub>               | Junction-to-board characterization parameter | 40.2     | 28.2       | °C/W |

- (1) For more information about traditional and new thermal metrics, see the *Semiconductor and IC Package Thermal Metrics* application report, [SPRA953](#).

## 6.4 Electrical Characteristics

These specifications apply for  $V_S = \pm 15\text{ V}$ ,  $T_A = 25^\circ\text{C}$ , amplifier bias current ( $I_{ABC}$ ) = 500  $\mu\text{A}$ , pins 2 and 15 open unless otherwise specified. The inputs to the buffers are grounded and outputs are open.

| PARAMETER                              | TEST CONDITIONS                                                                  | MIN      | TYP        | MAX   | UNIT             |
|----------------------------------------|----------------------------------------------------------------------------------|----------|------------|-------|------------------|
| Input offset voltage ( $V_{OS}$ )      | Over specified temperature range                                                 |          | 0.4        | 4     | mV               |
|                                        | $I_{ABC} = 5\text{ }\mu\text{A}$                                                 |          | 0.3        | 4     |                  |
| $V_{OS}$ including diodes              | Diode bias current ( $I_D$ ) = 500 $\mu\text{A}$                                 |          | 0.5        | 5     | mV               |
| Input offset change                    | $5\text{ }\mu\text{A} \leq I_{ABC} \leq 500\text{ }\mu\text{A}$                  |          | 0.1        | 3     | mV               |
| Input offset current                   |                                                                                  |          | 0.1        | 0.6   | $\mu\text{A}$    |
| Input bias current                     |                                                                                  |          | 0.4        | 5     | $\mu\text{A}$    |
|                                        | Over specified temperature range                                                 |          | 1          | 8     |                  |
| Forward transconductance ( $g_m$ )     |                                                                                  | 6700     | 9600       | 13000 | $\mu\text{S}$    |
|                                        | Over specified temperature range                                                 | 5400     |            |       |                  |
| $g_m$ tracking                         |                                                                                  |          | 0.3        |       | dB               |
| Peak output current                    | $R_L = 0$ , $I_{ABC} = 5\text{ }\mu\text{A}$                                     |          | 5          |       | $\mu\text{A}$    |
|                                        | $R_L = 0$ , $I_{ABC} = 500\text{ }\mu\text{A}$                                   | 350      | 500        | 650   |                  |
|                                        | $R_L = 0$ , Over Specified Temp Range                                            | 300      |            |       |                  |
| Supply current                         | $I_{ABC} = 500\text{ }\mu\text{A}$ , both channels                               |          | 2.6        |       | mA               |
| CMRR                                   |                                                                                  | 80       | 110        |       | dB               |
| Common-mode range                      |                                                                                  | $\pm 12$ | $\pm 13.5$ |       | V                |
| Crosstalk                              | Referred to input <sup>(1)</sup><br>20 Hz < f < 20 kHz                           |          | 100        |       | dB               |
| Differential input current             | $I_{ABC} = 0$ , input = $\pm 4\text{ V}$                                         |          | 0.02       | 100   | nA               |
| Leakage current                        | $I_{ABC} = 0$ (refer to test circuit)                                            |          | 0.2        | 100   | nA               |
| Input resistance                       |                                                                                  | 10       | 26         |       | k $\Omega$       |
| Open-loop bandwidth                    |                                                                                  |          | 2          |       | MHz              |
| Slew rate                              | Unity gain compensated                                                           |          | 50         |       | V/ $\mu\text{s}$ |
| Buffer input current                   | See <sup>(1)</sup>                                                               |          | 0.5        | 2     | $\mu\text{A}$    |
| Peak buffer output voltage             | See <sup>(1)</sup>                                                               | 10       |            |       | V                |
| <b>PEAK OUTPUT VOLTAGE</b>             |                                                                                  |          |            |       |                  |
| Positive                               | $R_L = \infty$ , $5\text{ }\mu\text{A} \leq I_{ABC} \leq 500\text{ }\mu\text{A}$ | 12       | 14.2       |       | V                |
| Negative                               | $R_L = \infty$ , $5\text{ }\mu\text{A} \leq I_{ABC} \leq 500\text{ }\mu\text{A}$ | -12      | -14.4      |       | V                |
| <b><math>V_{OS}</math> SENSITIVITY</b> |                                                                                  |          |            |       |                  |
| Positive                               | $\Delta V_{OS}/\Delta V^+$                                                       |          | 20         | 150   | $\mu\text{V/V}$  |
| Negative                               | $\Delta V_{OS}/\Delta V^-$                                                       |          | 20         | 150   | $\mu\text{V/V}$  |

(1) These specifications apply for  $V_S = \pm 15\text{ V}$ ,  $I_{ABC} = 500\text{ }\mu\text{A}$ ,  $R_{OUT} = 5\text{-k}\Omega$  connected from the buffer output to  $-V_S$  and the input of the buffer is connected to the transconductance amplifier output.

## 6.5 Typical Characteristics

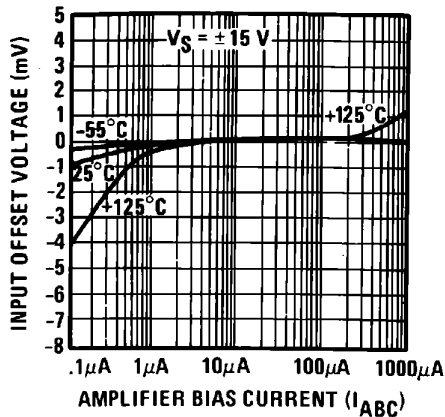


Figure 1. Input Offset Voltage

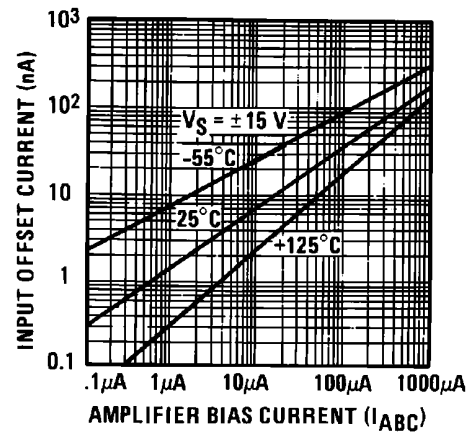


Figure 2. Input Offset Current

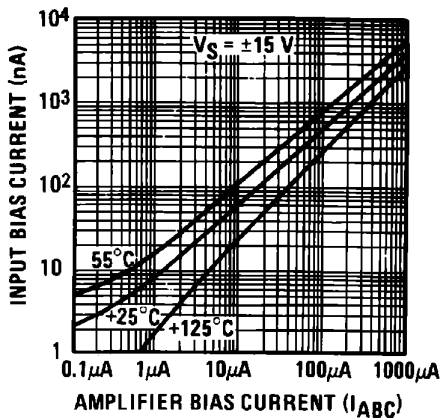


Figure 3. Input Bias Current

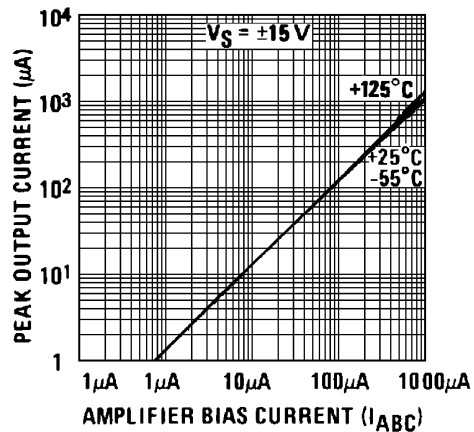


Figure 4. Peak Output Current

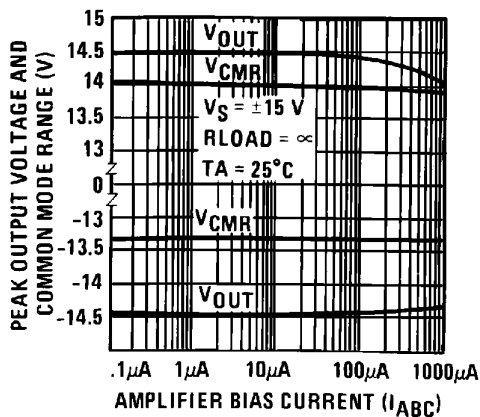


Figure 5. Peak Output Voltage and Common Mode Range

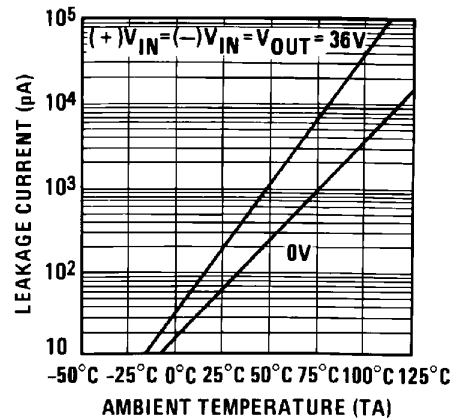


Figure 6. Leakage Current

## Typical Characteristics (continued)

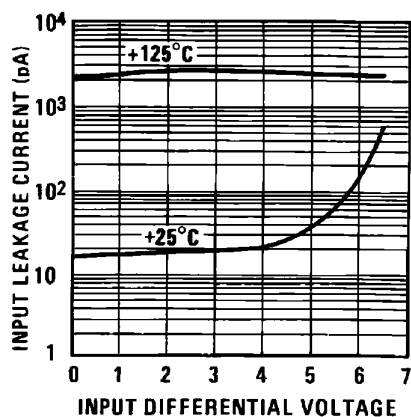


Figure 7. Input Leakage

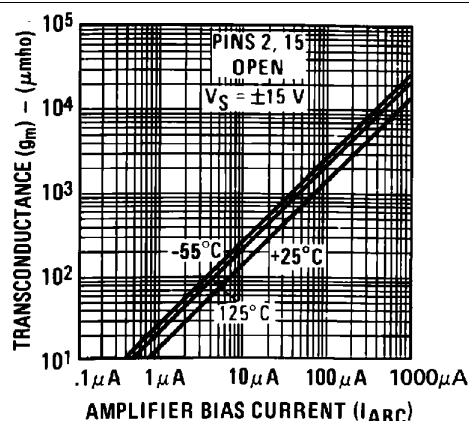


Figure 8. Transconductance

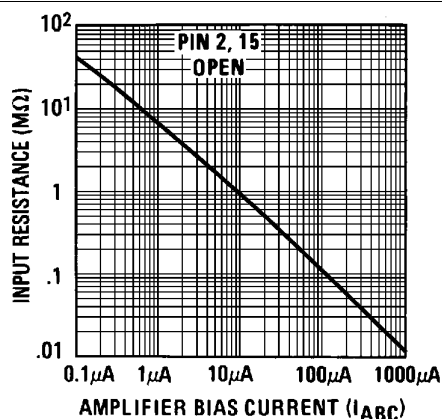


Figure 9. Input Resistance

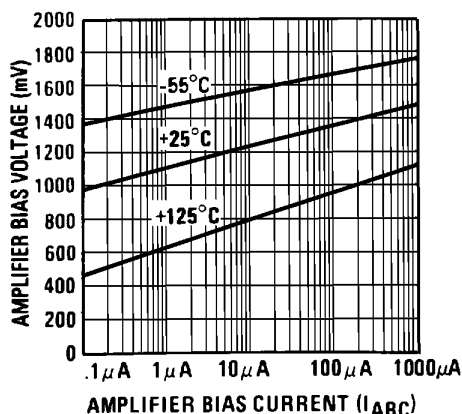


Figure 10. Amplifier Bias Voltage vs. Amplifier Bias Current

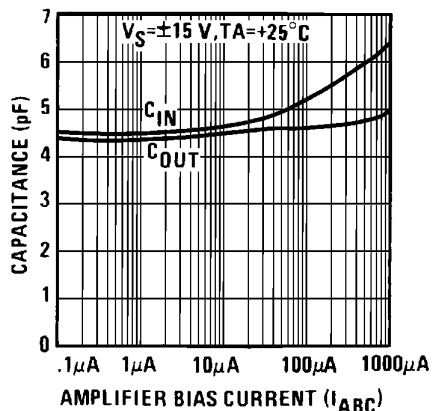


Figure 11. Input and Output Capacitance

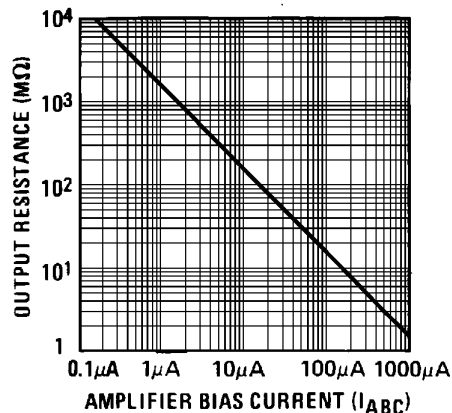
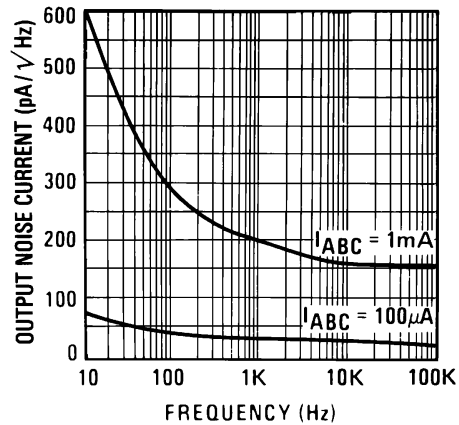
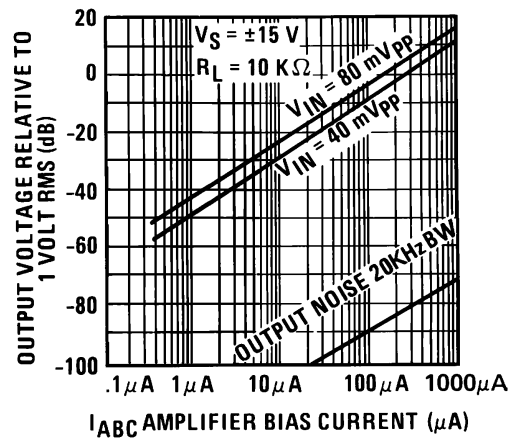
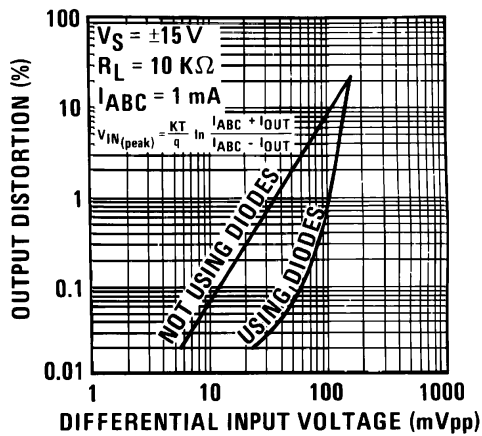


Figure 12. Output Resistance

## Typical Characteristics (continued)



## 7 Detailed Description

### 7.1 Overview

The LM13700 is a two channel current controlled differential input transconductance amplifier with additional output buffers. The inputs include linearizing diodes to reduce distortion, and the output current is controlled by a dedicated pin. The outputs can sustain a continuous short to ground.

### 7.2 Functional Block Diagram

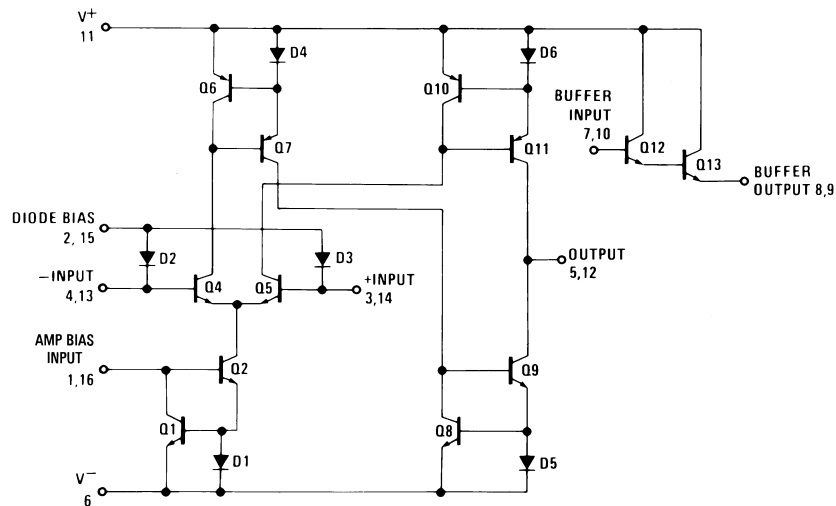


Figure 16. One Operational Transconductance Amplifier

### 7.3 Feature Description

#### 7.3.1 Circuit Description

The differential transistor pair  $Q_4$  and  $Q_5$  form a transconductance stage in that the ratio of their collector currents is defined by the differential input voltage according to the transfer function:

$$V_{IN} = \frac{kT}{q} \ln \frac{I_5}{I_4} \quad (1)$$

where  $V_{IN}$  is the differential input voltage,  $kT/q$  is approximately 26 mV at 25°C and  $I_5$  and  $I_4$  are the collector currents of transistors  $Q_5$  and  $Q_4$  respectively. With the exception of  $Q_{12}$  and  $Q_{13}$ , all transistors and diodes are identical in size. Transistors  $Q_1$  and  $Q_2$  with Diode  $D_1$  form a current mirror which forces the sum of currents  $I_4$  and  $I_5$  to equal  $I_{ABC}$ :

$$I_4 + I_5 = I_{ABC} \quad (2)$$

where  $I_{ABC}$  is the amplifier bias current applied to the gain pin.

For small differential input voltages the ratio of  $I_4$  and  $I_5$  approaches unity and the Taylor series of the  $\ln$  function is approximated as:

$$\begin{aligned} \frac{kT}{q} \ln \frac{I_5}{I_4} &\approx \frac{kT}{q} \frac{I_5 - I_4}{I_4} \\ I_4 \approx I_5 &\approx \frac{I_{ABC}}{2} \end{aligned} \quad (3)$$

$$V_{IN} \left[ \frac{I_{ABC} q}{2kT} \right] = I_5 - I_4 \quad (4)$$

## Feature Description (continued)

Collector currents  $I_4$  and  $I_5$  are not very useful by themselves and it is necessary to subtract one current from the other. The remaining transistors and diodes form three current mirrors that produce an output current equal to  $I_5$  minus  $I_4$  thus:

$$V_{IN} \left[ \frac{I_{ABC} q}{2kT} \right] = I_{OUT} \quad (5)$$

The term in brackets is then the transconductance of the amplifier and is proportional to  $I_{ABC}$ .

### 7.3.2 Linearizing Diodes

For differential voltages greater than a few millivolts, Equation 3 becomes less valid and the transconductance becomes increasingly nonlinear. Figure 19 demonstrates how the internal diodes can linearize the transfer function of the amplifier. For convenience assume the diodes are biased with current sources and the input signal is in the form of current  $I_S$ . Since the sum of  $I_4$  and  $I_5$  is  $I_{ABC}$  and the difference is  $I_{OUT}$ , currents  $I_4$  and  $I_5$  is written as follows:

$$I_4 = \frac{I_{ABC}}{2} - \frac{I_{OUT}}{2}, \quad I_5 = \frac{I_{ABC}}{2} + \frac{I_{OUT}}{2} \quad (6)$$

Since the diodes and the input transistors have identical geometries and are subject to similar voltages and temperatures, the following is true:

$$\begin{aligned} \frac{kT}{q} \ln \frac{\frac{I_D}{2} + I_S}{\frac{I_D}{2} - I_S} &= \frac{kT}{q} \ln \frac{\frac{I_{ABC}}{2} + \frac{I_{OUT}}{2}}{\frac{I_{ABC}}{2} - \frac{I_{OUT}}{2}} \\ \therefore I_{OUT} &= I_S \left( \frac{2I_{ABC}}{I_D} \right) \text{ for } |I_S| < \frac{I_D}{2} \end{aligned} \quad (7)$$

Notice that in deriving Equation 7 no approximations have been made and there are no temperature-dependent terms. The limitations are that the signal current not exceed  $I_D / 2$  and that the diodes be biased with currents. In practice, replacing the current sources with resistors will generate insignificant errors.

## 7.4 Device Functional Modes

Use in single ended or dual supply systems requires minimal changes. The outputs can support a sustained short to ground. Note that use of the LM13700 in  $\pm 5$  V supply systems requires will reduce signal dynamic range; this is due to the PNP transistors having a higher  $V_{BE}$  than the NPN transistors.

### 7.4.1 Output Buffers

Each channel includes a separate output buffer which consists of a Darlington pair transistor that can drive up to 20mA.

## 8 Application and Implementation

### NOTE

Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI's customers are responsible for determining suitability of components for their purposes. Customers should validate and test their design implementation to confirm system functionality.

### 8.1 Application Information

An OTA is a versatile building block analog component that can be considered an ideal transistor. The LM13700 can be used in a wide variety of applications, from voltage-controlled amplifiers and filters to VCOs. The 2 well-matched, independent channels make the LDC13700 well suited for stereo audio applications.

### 8.2 Typical Application

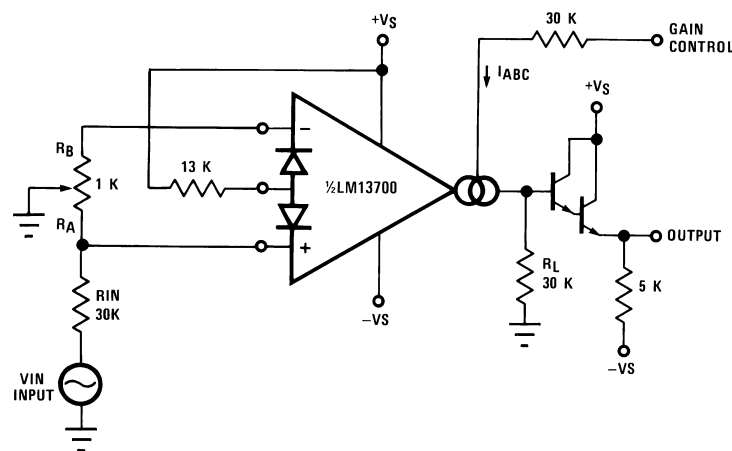


Figure 17. Voltage Controlled Amplifier

#### 8.2.1 Design Requirements

For this example application, the system requirements provide a volume control for a 1 V<sub>P</sub> input signal with a THD < 0.1% using ±15 V supplies. The volume control varies between -13 V and 15 V and needs to provide an adjustable gain range of >30dB.

#### 8.2.2 Detailed Design Procedure

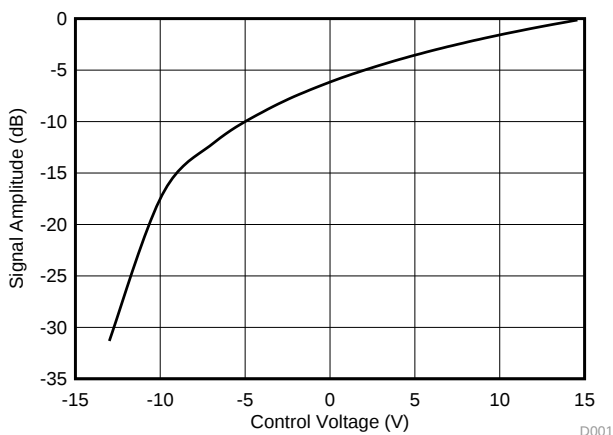
Using the linearizing diodes is recommended for most applications, as they greatly reduce the output distortion. It is required that the diode bias current, I<sub>D</sub> be greater than twice the input current, I<sub>S</sub>. As the input voltage has a DC level of 0 V, the Diode Bias input pins are 1 diode drop above 0 V, which is +0.7 V. Tying the bias to the clean V+ supply, results in a voltage drop of 14.3 V across R<sub>D</sub>. Using the recommended 1mA for I<sub>D</sub> is appropriate here, and with VS=+15 V, the voltage drop is 14.3 V, and so using the standard value of 13-kΩ is acceptable and will provide the desired gain control.

To obtain the <0.1% THD requirement, the differential input voltage must be <60mV<sub>pp</sub> when the linearizing diodes are used. The input divider on the input will reduce the 1 V<sub>P</sub> input to 33mV<sub>pp</sub>, which is within the desired spec.

Next, set I<sub>BIAS</sub>. The Bias Input pins (pins 1 or 16), are 2 diode drops above the negative supply, and therefore V<sub>BIAS</sub> = 2(V<sub>BE</sub>) + V<sub>-</sub>, which for this application is -13.6 V. To set I<sub>BIAS</sub> to 1ma when V<sub>C</sub> = 15 V requires a 28.6-kΩ; 30-kΩ is a standard value and is used for this application. The gain will be linear with the applied voltage.

## Typical Application (continued)

### 8.2.3 Application Curve

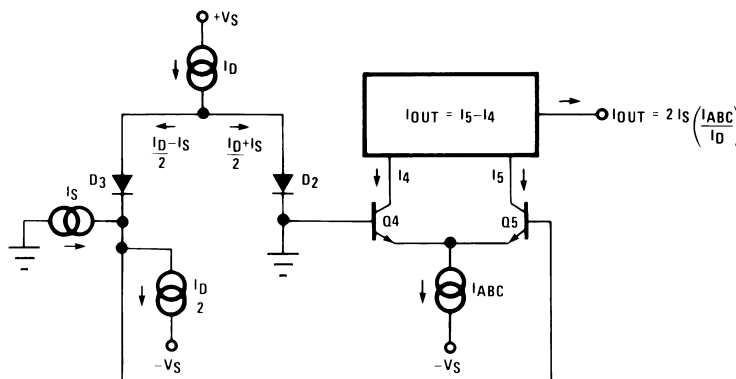


**Figure 18. Signal Amplitude vs Control Voltage**

## 8.3 System Examples

### 8.3.1 Voltage-Controlled Amplifiers

Figure 20 shows how the linearizing diodes is used in a voltage-controlled amplifier. To understand the input biasing, it is best to consider the 13-k $\Omega$  resistor as a current source and use a Thevenin equivalent circuit as shown in Figure 21. This circuit is similar to Figure 19 and operates the same. The potentiometer in Figure 20 is adjusted to minimize the effects of the control signal at the output.



**Figure 19. Linearizing Diodes**

For optimum signal-to-noise performance,  $I_{ABC}$  should be as large as possible as shown by the Output Voltage vs Amplifier Bias Current graph. Larger amplitudes of input signal also improve the S/N ratio. The linearizing diodes help here by allowing larger input signals for the same output distortion as shown by the Distortion vs. Differential Input Voltage graph. S/N may be optimized by adjusting the magnitude of the input signal via  $R_{IN}$  (Figure 20) until the output distortion is below the desired level. The output voltage swing can then be set at any level by selecting  $R_L$ .

Although the noise contribution of the linearizing diodes is negligible relative to the contribution of the amplifier's internal transistors,  $I_D$  should be as large as possible. This minimizes the dynamic junction resistance of the diodes ( $r_e$ ) and maximizes their linearizing action when balanced against  $R_{IN}$ . A value of 1 mA is recommended for  $I_D$  unless the specific application demands otherwise.

## System Examples (continued)

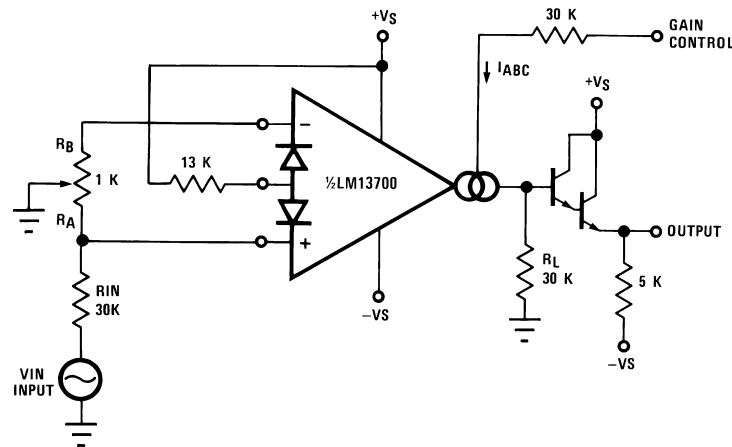


Figure 20. Voltage-Controlled Amplifier

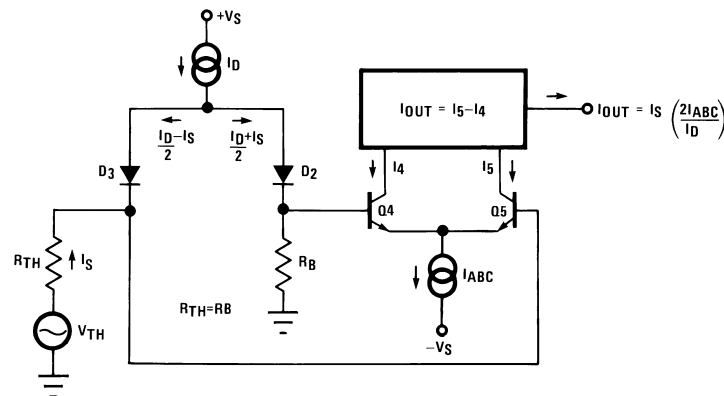


Figure 21. Equivalent VCA Input Circuit

### 8.3.2 Stereo Volume Control

The circuit of Figure 22 uses the excellent matching of the two LM13700 amplifiers to provide a Stereo Volume Control with a typical channel-to-channel gain tracking of 0.3 dB.  $R_P$  is provided to minimize the output offset voltage and may be replaced with two 510Ω resistors in AC-coupled applications. For the component values given, amplifier gain is derived for Figure 20 as being:

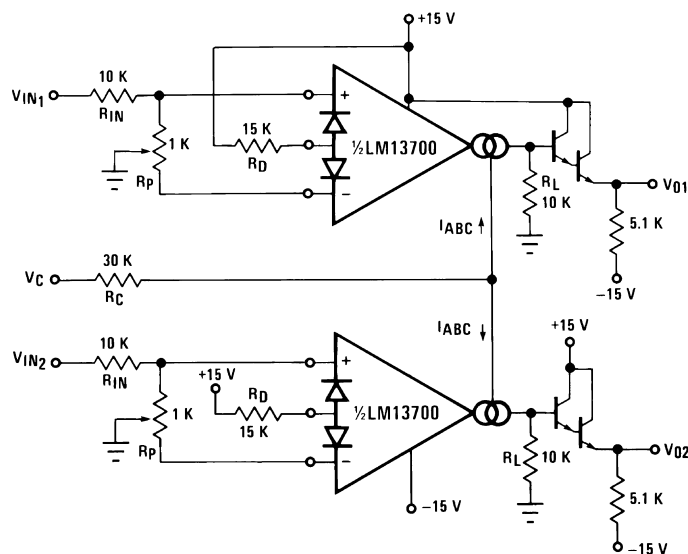
$$\frac{V_O}{V_{IN}} = 940 \times I_{ABC} \quad (8)$$

If  $V_C$  is derived from a second signal source then the circuit becomes an amplitude modulator or two-quadrant multiplier as shown in Figure 23, where:

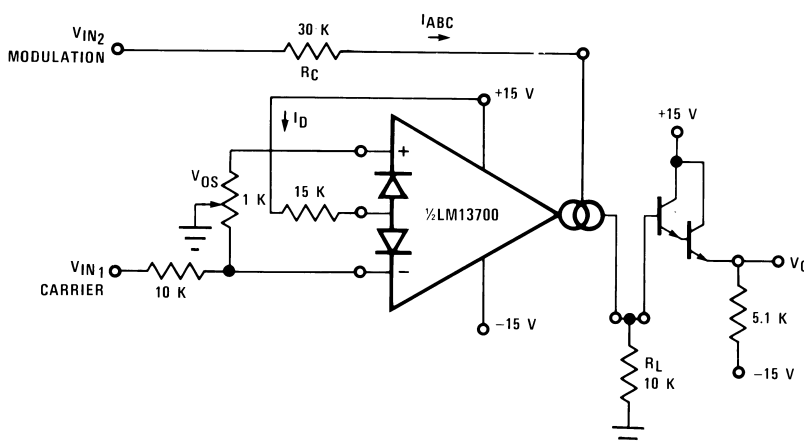
$$I_O = \frac{-2I_S}{I_D} (I_{ABC}) = \frac{-2I_S}{I_D} \frac{V_{IN2}}{R_C} - \frac{2I_S}{I_D} \frac{(V^- + 1.4V)}{R_C} \quad (9)$$

The constant term in the above equation may be cancelled by feeding  $I_S \times I_D R_C / 2(V^- + 1.4V)$  into  $I_O$ . The circuit of Figure 24 adds  $R_M$  to provide this current, resulting in a four-quadrant multiplier where  $R_C$  is trimmed such that  $V_O = 0V$  for  $V_{IN2} = 0V$ .  $R_M$  also serves as the load resistor for  $I_O$ .

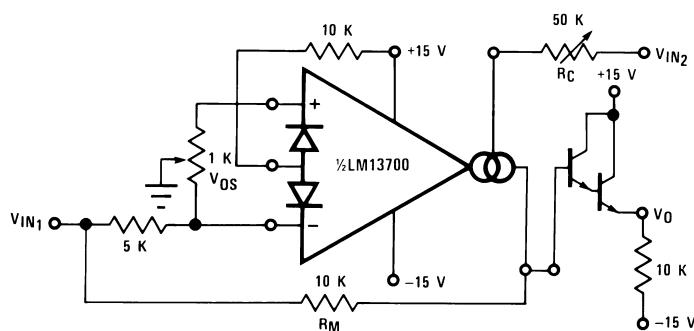
## System Examples (continued)



**Figure 22. Stereo Volume Control**



**Figure 23. Amplitude Modulator**



**Figure 24. Four-Quadrant Multiplier**

## System Examples (continued)

Noting that the gain of the LM13700 amplifier of Figure 21 may be controlled by varying the linearizing diode current  $I_D$  as well as by varying  $I_{ABC}$ , Figure 25 shows an AGC Amplifier using this approach. As  $V_O$  reaches a high enough amplitude ( $3 V_{BE}$ ) to turn on the Darlington transistors and the linearizing diodes, the increase in  $I_D$  reduces the amplifier gain so as to hold  $V_O$  at that level.

### 8.3.3 Voltage-Controlled Resistors

An Operational Transconductance Amplifier (OTA) may be used to implement a Voltage Controlled Resistor as shown in Figure 26. A signal voltage applied at  $R_X$  generates a  $V_{IN}$  to the LM13700 which is then multiplied by the  $g_m$  of the amplifier to produce an output current, thus:

$$R_X = \frac{R + R_A}{g_m R_A} \quad (10)$$

where  $g_m \approx 19.2 I_{ABC}$  at 25°C. Note that the attenuation of  $V_O$  by  $R$  and  $R_A$  is necessary to maintain  $V_{IN}$  within the linear range of the LM13700 input.

Figure 27 shows a similar VCR where the linearizing diodes are added, essentially improving the noise performance of the resistor. A floating VCR is shown in Figure 28, where each “end” of the “resistor” may be at any voltage within the output voltage range of the LM13700.

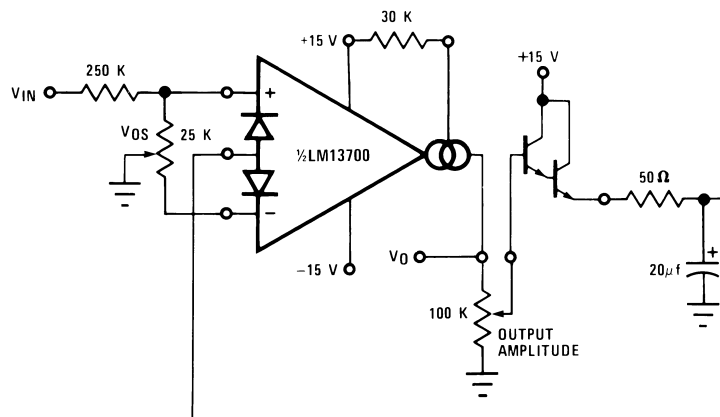


Figure 25. AGC Amplifier

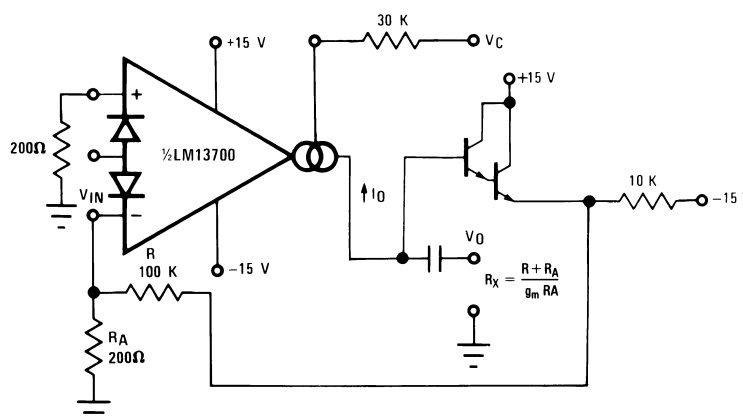
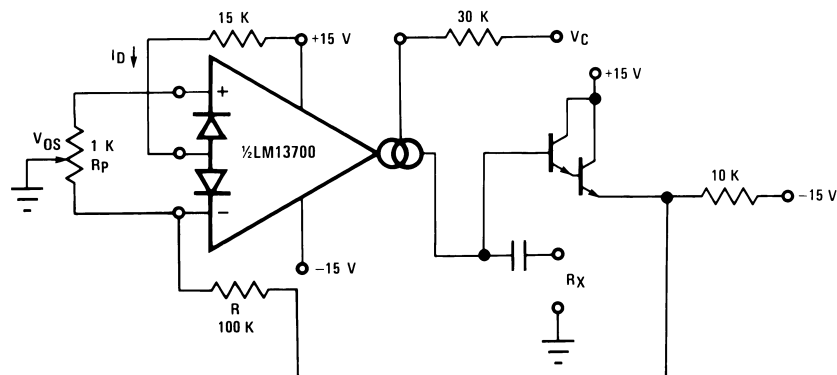


Figure 26. Voltage-Controlled Resistor, Single-Ended

## System Examples (continued)

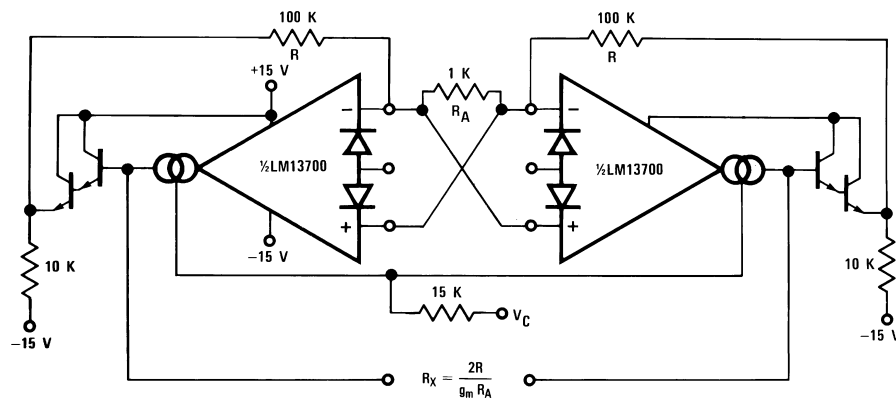


**Figure 27. Voltage-Controlled Resistor with Linearizing Diodes**

### 8.3.4 Voltage-Controlled Filters

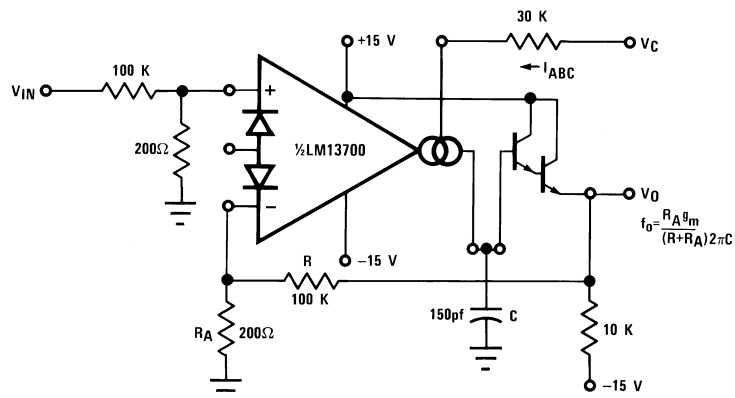
OTA's are extremely useful for implementing voltage controlled filters, with the LM13700 having the advantage that the required buffers are included on the I.C. The VC Lo-Pass Filter of [Figure 29](#) performs as a unity-gain buffer amplifier at frequencies below cut-off, with the cut-off frequency being the point at which  $X_C/g_m$  equals the closed-loop gain of  $(R/R_A)$ . At frequencies above cut-off the circuit provides a single RC roll-off (6 dB per octave) of the input signal amplitude with a -3 dB point defined by the given equation, where  $g_m$  is again  $19.2 \times I_{ABC}$  at room temperature. [Figure 30](#) shows a VC High-Pass Filter which operates in much the same manner, providing a single RC roll-off below the defined cut-off frequency.

Additional amplifiers may be used to implement higher order filters as demonstrated by the two-pole Butterworth Lo-Pass Filter of [Figure 31](#) and the state variable filter of [Figure 32](#). Due to the excellent  $g_m$  tracking of the two amplifiers, these filters perform well over several decades of frequency.

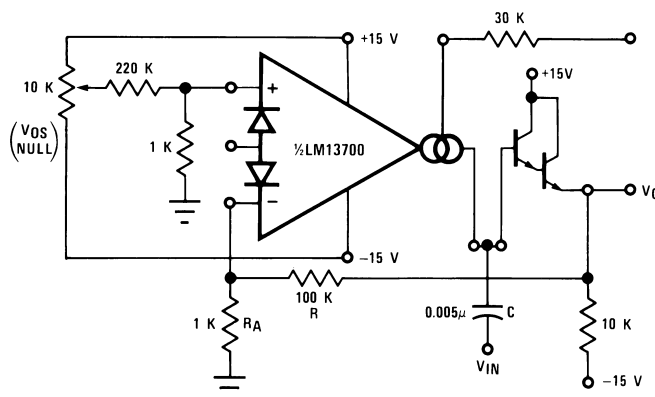


**Figure 28. Floating Voltage-Controlled Resistor**

## System Examples (continued)



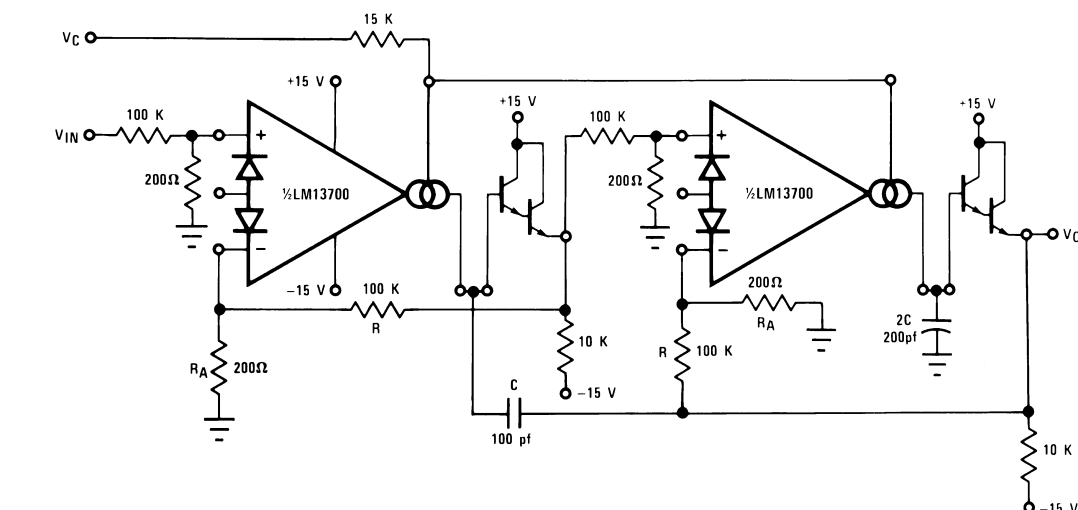
**Figure 29. Voltage-Controlled Low-Pass Filter**



$$f_0 = \frac{R_A g_m}{(R + R_A) 2\pi C}$$

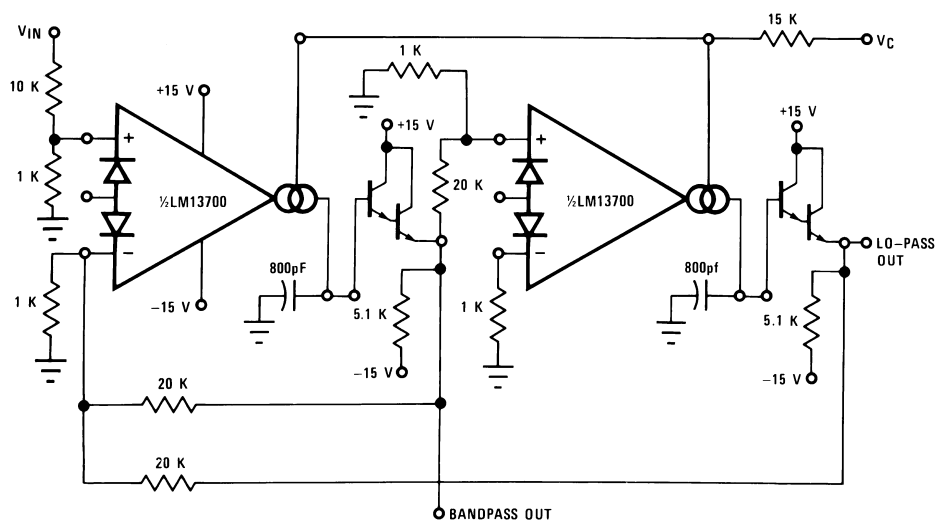
**Figure 30. Voltage-Controlled Hi-Pass Filter**

## System Examples (continued)



$$f_o = \frac{R_A g_m}{(R + R_A) 2\pi C}$$

**Figure 31. Voltage-Controlled 2-Pole Butterworth Lo-Pass Filter**



**Figure 32. Voltage-Controlled State Variable Filter**

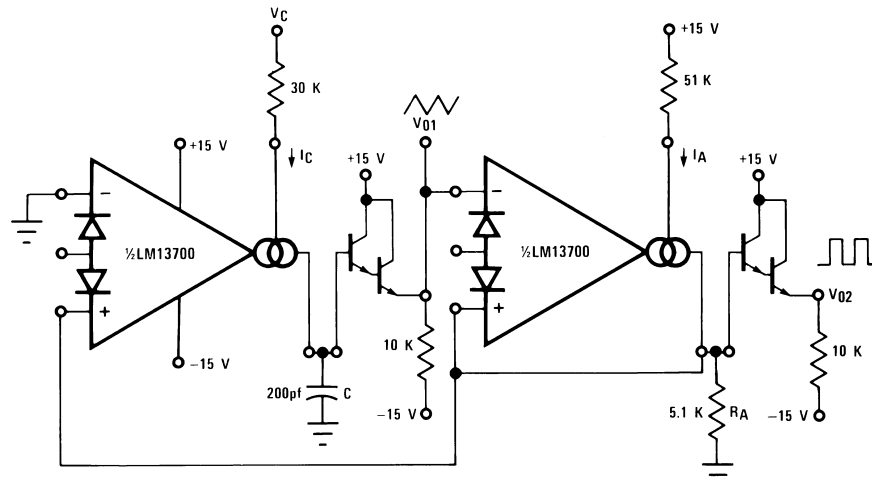
### 8.3.5 Voltage-Controlled Oscillators

The classic Triangular/Square Wave VCO of [Figure 33](#) is one of a variety of Voltage Controlled Oscillators which may be built utilizing the LM13700. With the component values shown, this oscillator provides signals from 200 kHz to below 2 Hz as  $I_C$  is varied from 1 mA to 10 nA. The output amplitudes are set by  $I_A \times R_A$ . Note that the peak differential input voltage must be less than 5 V to prevent zenering the inputs.

A few modifications to this circuit produce the ramp/pulse VCO of [Figure 34](#). When  $V_{O2}$  is high,  $I_F$  is added to  $I_C$  to increase amplifier A1's bias current and thus to increase the charging rate of capacitor C. When  $V_{O2}$  is low,  $I_F$  goes to zero and the capacitor discharge current is set by  $I_C$ .

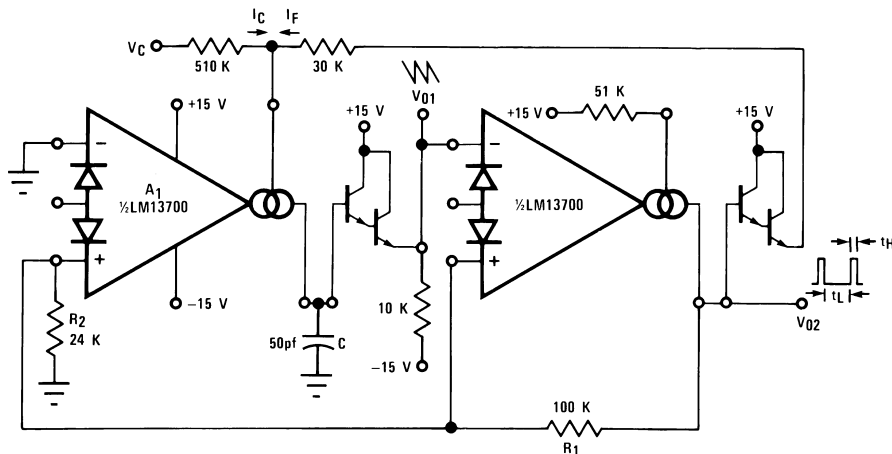
## System Examples (continued)

The VC Lo-Pass Filter of Figure 29 may be used to produce a high-quality sinusoidal VCO. The circuit of Figure 34 employs two LM13700 packages, with three of the amplifiers configured as lo-pass filters and the fourth as a limiter/inverter. The circuit oscillates at the frequency at which the loop phase-shift is 360° or 180° for the inverter and 60° per filter stage. This VCO operates from 5 Hz to 50 kHz with less than 1% THD.



$$f_{\text{OSC}} = \frac{I_C}{4C I_A R_A}$$

**Figure 33. Triangular/Square-Wave VCO**



$$V_{PK} = \frac{(V^+ \pm 0.8V) R_2}{R_1 + R_2}$$

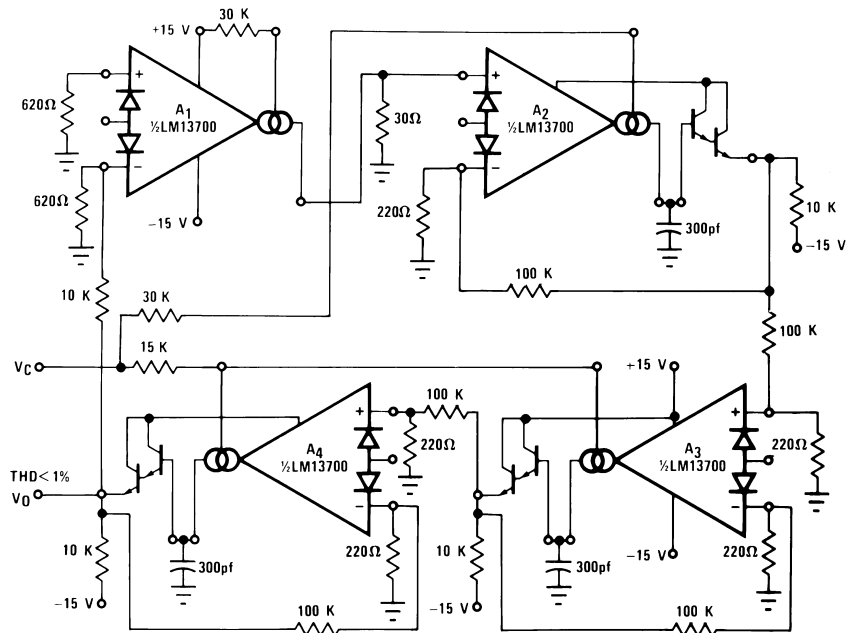
$$t_{H1} \approx \frac{2V_{PK}C}{I_F}$$

$$t_L \approx \frac{2V_{PK}C}{I_C}$$

$$f_0 \approx \frac{I_C}{2V_{PK}C} \text{ for } I_C \ll I_F$$

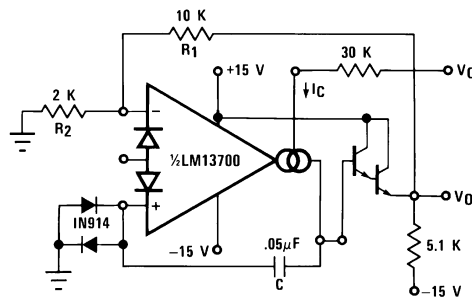
**Figure 34. Ramp/Pulse VCO**

## System Examples (continued)



**Figure 35. Sinusoidal VCO**

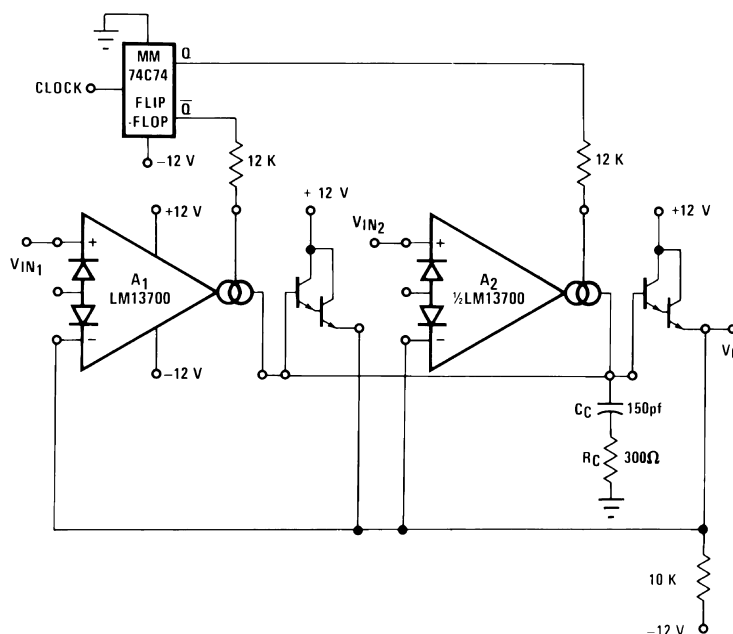
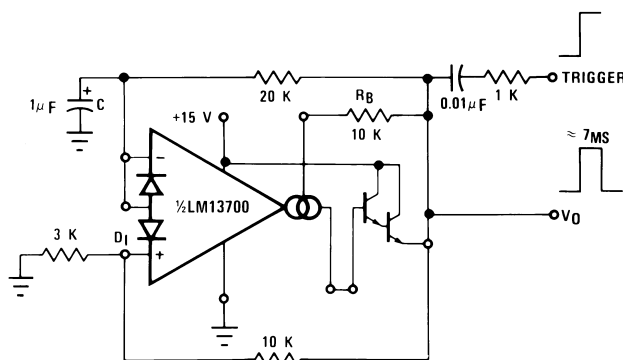
Figure 36 shows how to build a VCO using one amplifier when the other amplifier is needed for another function.



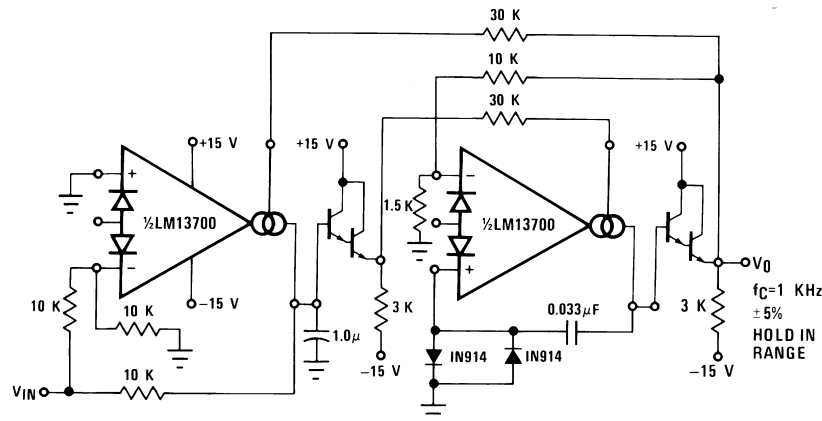
**Figure 36. Single Amplifier VCO**

### 8.3.6 Additional Applications

Figure 37 presents an interesting one-shot which draws no power supply current until it is triggered. A positive-going trigger pulse of at least 2 V amplitude turns on the amplifier through  $R_B$  and pulls the non-inverting input high. The amplifier regenerates and latches its output high until capacitor  $C$  charges to the voltage level on the non-inverting input. The output then switches low, turning off the amplifier and discharging the capacitor. The capacitor discharge rate is speeded up by shorting the diode bias pin to the inverting input so that an additional discharge current flows through  $D_1$  when the amplifier output switches low. A special feature of this timer is that the other amplifier, when biased from  $V_O$ , can perform another function and draw zero stand-by power as well.

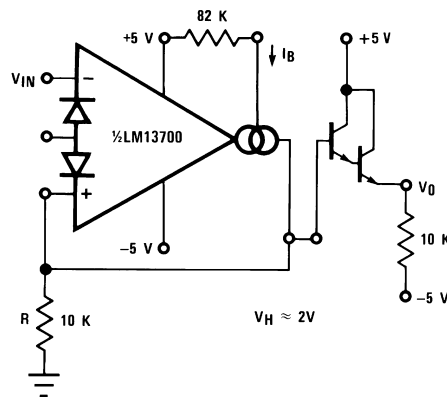


## System Examples (continued)



**Figure 39. Phase Lock Loop**

The Schmitt Trigger of [Figure 40](#) uses the amplifier output current into R to set the hysteresis of the comparator; thus  $V_H = 2 \times R \times I_B$ . Varying  $I_B$  will produce a Schmitt Trigger with variable hysteresis.



**Figure 40. Schmitt Trigger**

[Figure 41](#) shows a Tachometer or Frequency-to-Voltage converter. Whenever A1 is toggled by a positive-going input, an amount of charge equal to  $(V_H - V_L) C_t$  is sourced into  $C_t$  and  $R_t$ . This once per cycle charge is then balanced by the current of  $V_O/R_t$ . The maximum  $F_{IN}$  is limited by the amount of time required to charge  $C_t$  from  $V_L$  to  $V_H$  with a current of  $I_B$ , where  $V_L$  and  $V_H$  represent the maximum low and maximum high output voltage swing of the LM13700. D1 is added to provide a discharge path for  $C_t$  when A1 switches low.

The Peak Detector of [Figure 42](#) uses A2 to turn on A1 whenever  $V_{IN}$  becomes more positive than  $V_O$ . A1 then charges storage capacitor C to hold  $V_O$  equal to  $V_{IN}$  PK. Pulling the output of A2 low through D1 serves to turn off A1 so that  $V_O$  remains constant.

## System Examples (continued)

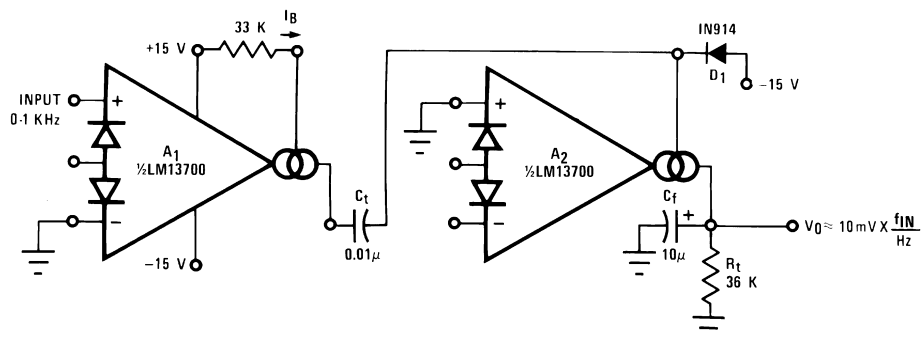


Figure 41. Tachometer

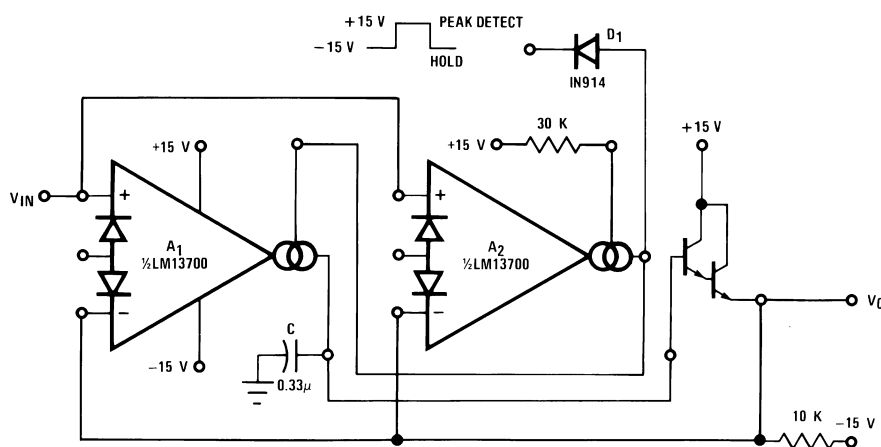
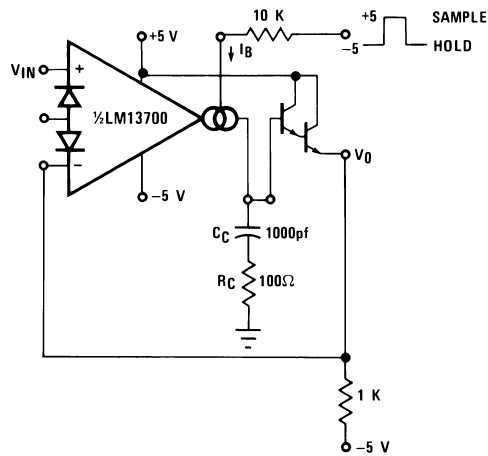


Figure 42. Peak Detector and Hold Circuit

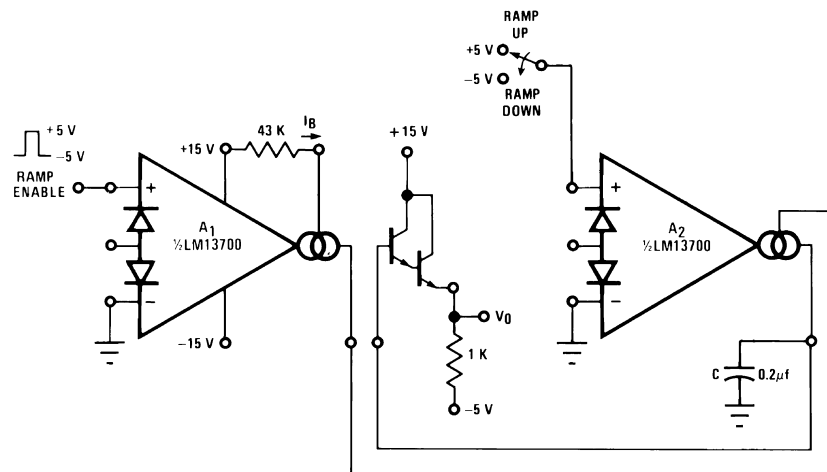
The Ramp-and-Hold of [Figure 44](#) sources  $I_B$  into capacitor C whenever the input to A1 is brought high, giving a ramp-rate of about 1 V/ms for the component values shown.

The true-RMS converter of [Figure 45](#) is essentially an automatic gain control amplifier which adjusts its gain such that the AC power at the output of amplifier A1 is constant. The output power of amplifier A1 is monitored by squaring amplifier A2 and the average compared to a reference voltage with amplifier A3. The output of A3 provides bias current to the diodes of A1 to attenuate the input signal. Because the output power of A1 is held constant, the RMS value is constant and the attenuation is directly proportional to the RMS value of the input voltage. The attenuation is also proportional to the diode bias current. Amplifier A4 adjusts the ratio of currents through the diodes to be equal and therefore the voltage at the output of A4 is proportional to the RMS value of the input voltage. The calibration potentiometer is set such that  $V_O$  reads directly in RMS volts.

## System Examples (continued)



**Figure 43. Sample-Hold Circuit**



**Figure 44. Ramp and Hold**

## System Examples (continued)

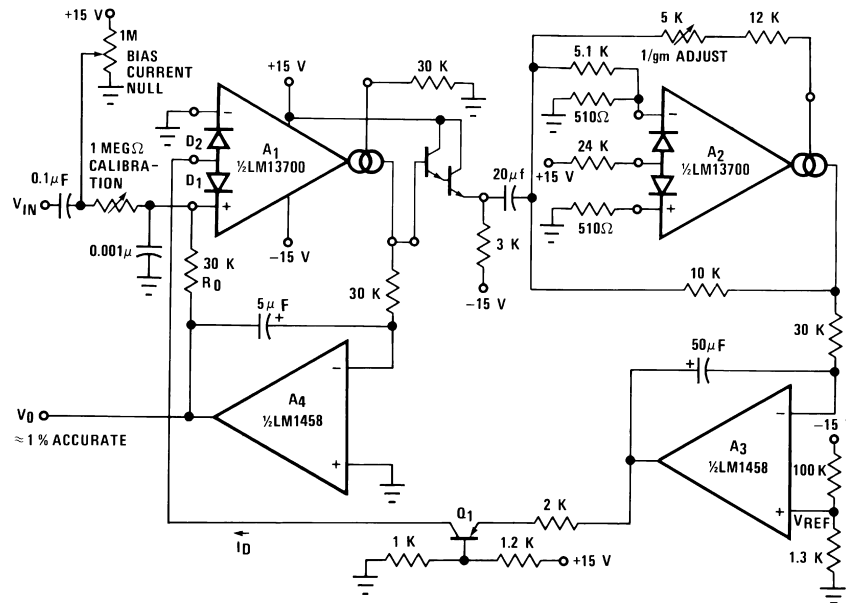


Figure 45. True RMS Converter

The circuit of Figure 46 is a voltage reference of variable Temperature Coefficient. The 100-k\$\Omega\$ potentiometer adjusts the output voltage which has a positive TC above 1.2 V, zero TC at about 1.2 V, and negative TC below 1.2 V. This is accomplished by balancing the TC of the A2 transfer function against the complementary TC of D1. The wide dynamic range of the LM13700 allows easy control of the output pulse width in the Pulse Width Modulator of Figure 47.

For generating \$I\_{ABC}\$ over a range of 4 to 6 decades of current, the system of Figure 48 provides a logarithmic current out for a linear voltage in.

Since the closed-loop configuration ensures that the input to A2 is held equal to 0 V, the output current of A1 is equal to \$I\_3 = -V\_C/R\_C\$.

The differential voltage between Q1 and Q2 is attenuated by the R1,R2 network so that A1 may be assumed to be operating within its linear range. From Equation 5, the input voltage to A1 is:

$$V_{IN1} = \frac{-2kT I_3}{q I_2} = \frac{-2kT V_C}{q I_2 R_C} \quad (11)$$

The voltage on the base of Q1 is then

$$V_{B1} = \frac{(R_1 + R_2) V_{IN1}}{R_1} \quad (12)$$

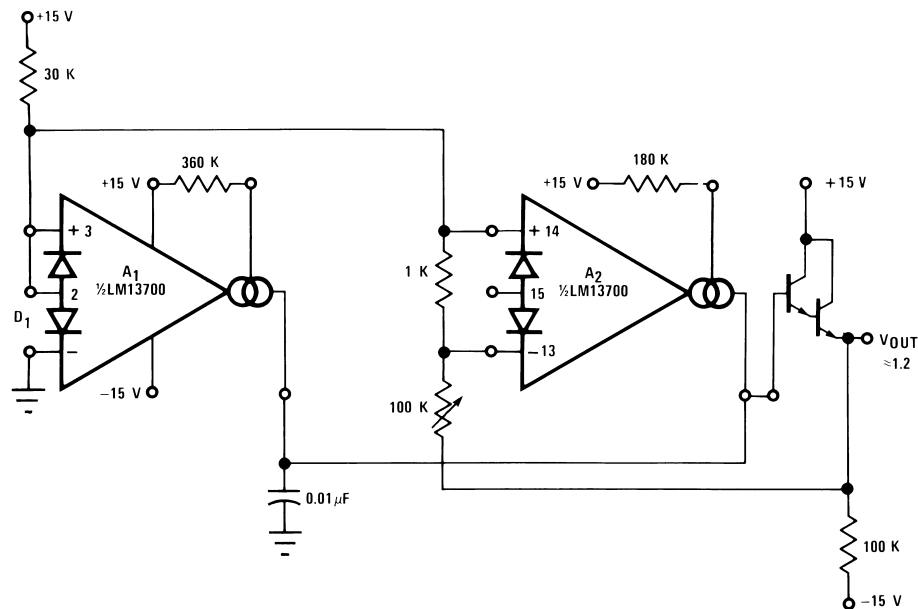
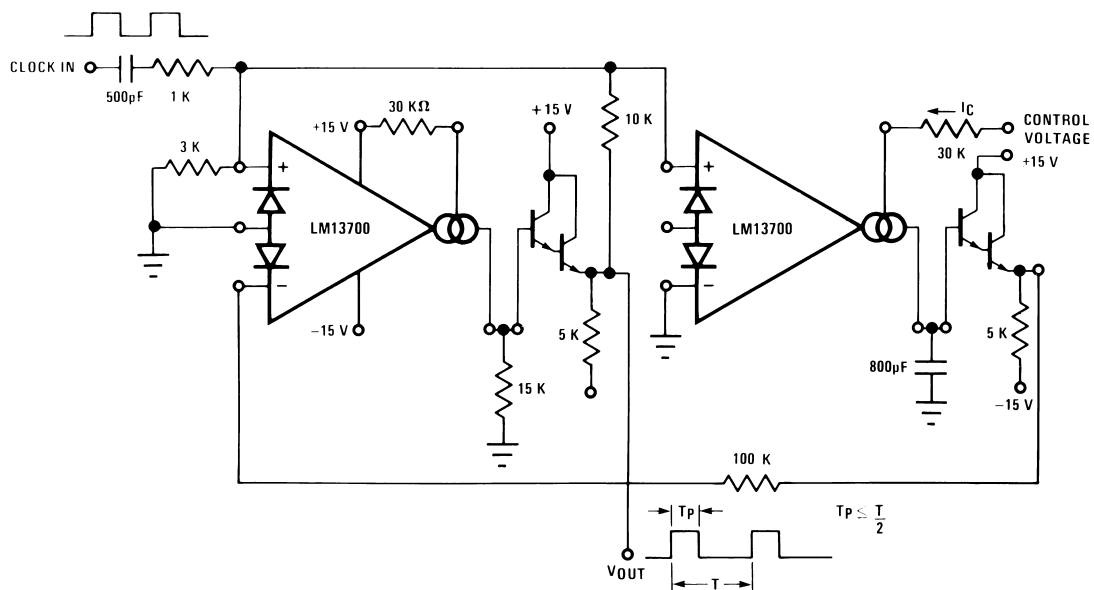
The ratio of the Q1 and Q2 collector currents is defined by:

$$V_{B1} = \frac{kT}{q} \ln \frac{I_{C2}}{I_{C1}} \approx \frac{kT}{q} \ln \frac{I_{ABC}}{I_1} \quad (13)$$

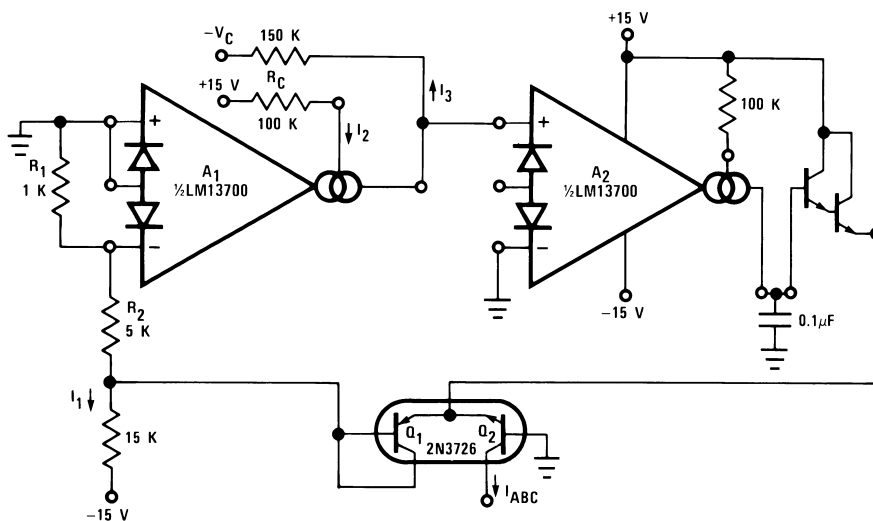
Combining and solving for \$I\_{ABC}\$ yields:

$$I_{ABC} = I_1 \exp \frac{2(R_1 + R_2) V_C}{R_1 I_2 R_C} \quad (14)$$

This logarithmic current is used to bias the circuit of Figure 22 to provide temperature independent stereo attenuation characteristic.

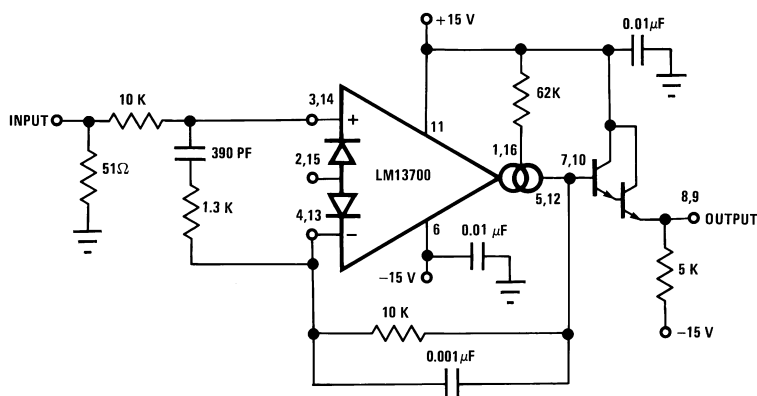
**System Examples (continued)**

**Figure 46. Delta VBE Reference**

**Figure 47. Pulse Width Modulator**

## System Examples (continued)

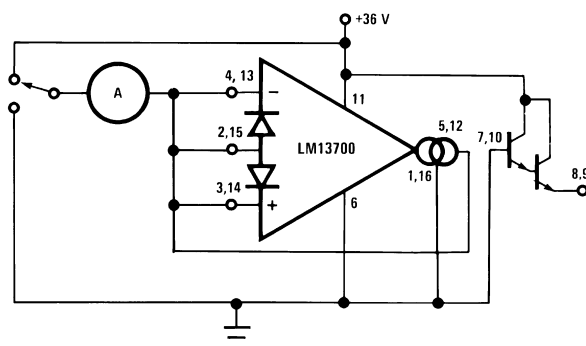


$$I_{ABC} = I_1 \exp \frac{-C_{I3}}{I_2}$$

**Figure 48. Logarithmic Current Source**



**Figure 49. Unity Gain Follower**



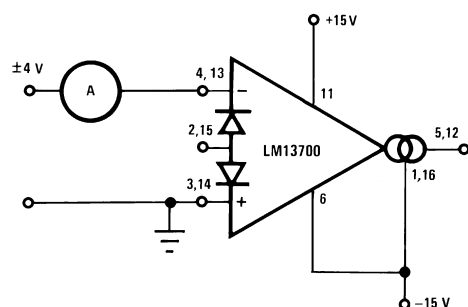
**Figure 50. Leakage Current Test Circuit**

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[www.ti.com](http://www.ti.com)

## System Examples (continued)



**Figure 51. Differential Input Current Test Circuit**

## 9 Power Supply Recommendations

The LM13700 can operate with either a single-ended supply or a dual supplies. The supplies should be low impedance sources with sufficient bypassing. Use of low-ESR sufficiently rated voltage ceramic capacitors is recommended. When bypassing dual supply configurations, the supply bypass capacitors should couple to ground.

## 10 Layout

### 10.1 Layout Guidelines

Place supply bypass capacitors as close to the appropriate supply pins as possible. When multiple bypass capacitors are used, the smallest value capacitor should be closest to the supply pin.

Use of a ground plane to minimize ground impedance and provide constant signal impedance is recommended. Avoid routing signal traces over any gaps in the ground plane.

Feedback components and passives should be placed close to the device pins to minimize parasitic impedances. When using capacitors to limit bandwidth, the capacitor should be closer to the device pin than any ballasting or gain resistors.

### 10.2 Layout Example

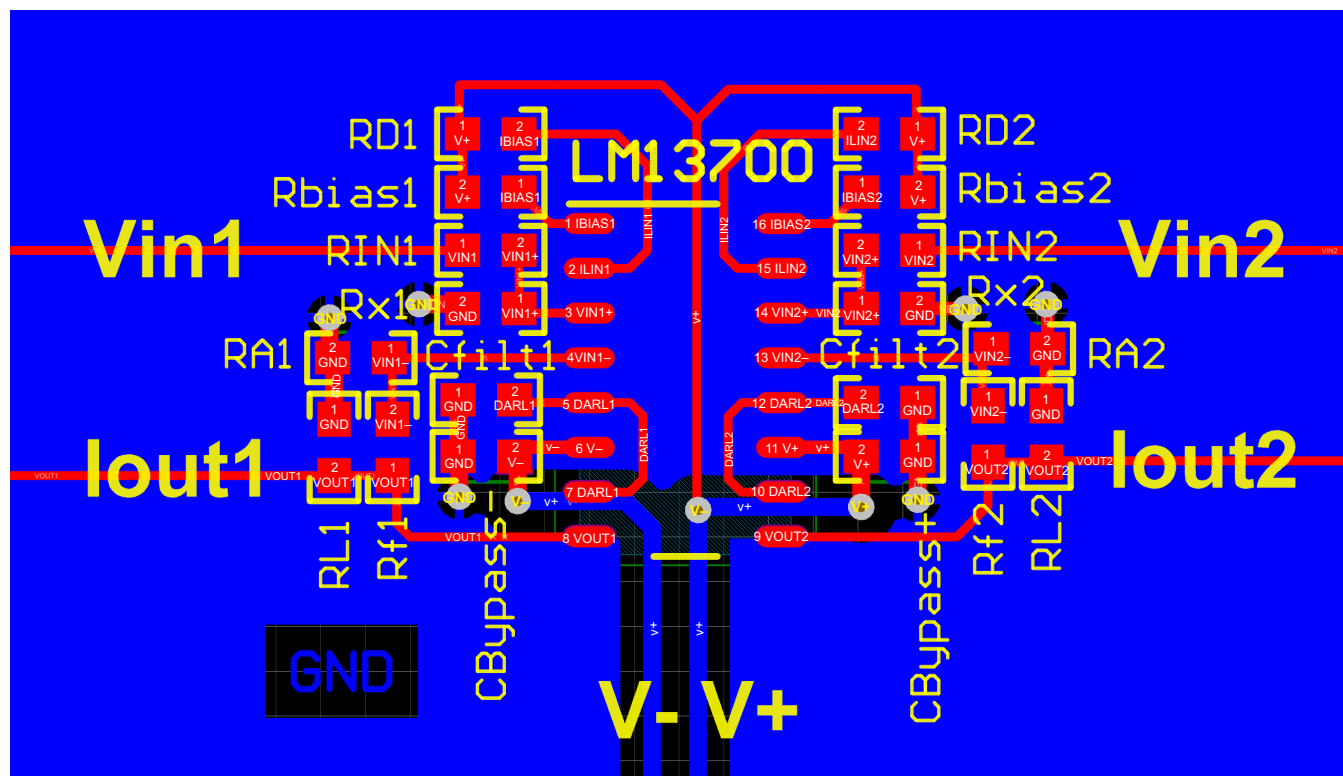


Figure 52. Layout Recommendation

## 11 Device and Documentation Support

### 11.1 Community Resources

The following links connect to TI community resources. Linked contents are provided "AS IS" by the respective contributors. They do not constitute TI specifications and do not necessarily reflect TI's views; see TI's [Terms of Use](#).

**TI E2E™ Online Community** *TI's Engineer-to-Engineer (E2E) Community*. Created to foster collaboration among engineers. At [e2e.ti.com](http://e2e.ti.com), you can ask questions, share knowledge, explore ideas and help solve problems with fellow engineers.

**Design Support** *TI's Design Support* Quickly find helpful E2E forums along with design support tools and contact information for technical support.

### 11.2 Trademarks

E2E is a trademark of Texas Instruments.  
All other trademarks are the property of their respective owners.

### 11.3 Electrostatic Discharge Caution



These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

### 11.4 Glossary

[SLYZ022](#) — *TI Glossary*.

This glossary lists and explains terms, acronyms, and definitions.

## 12 Mechanical, Packaging, and Orderable Information

The following pages include mechanical, packaging, and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.

## PACKAGING INFORMATION

| Orderable Device | Status<br>(1) | Package Type | Package<br>Drawing | Pins | Package<br>Qty | Eco Plan<br>(2)            | Lead/Ball Finish<br>(6) | MSL Peak Temp<br>(3) | Op Temp (°C) | Device Marking<br>(4/5) | Samples                 |
|------------------|---------------|--------------|--------------------|------|----------------|----------------------------|-------------------------|----------------------|--------------|-------------------------|-------------------------|
| LM13700M         | NRND          | SOIC         | D                  | 16   | 48             | TBD                        | Call TI                 | Call TI              | 0 to 70      | LM13700M                |                         |
| LM13700M/NOPB    | ACTIVE        | SOIC         | D                  | 16   | 48             | Green (RoHS<br>& no Sb/Br) | CU SN                   | Level-1-260C-UNLIM   | 0 to 70      | LM13700M                | <a href="#">Samples</a> |
| LM13700MX        | NRND          | SOIC         | D                  | 16   | 2500           | TBD                        | Call TI                 | Call TI              | 0 to 70      | LM13700M                |                         |
| LM13700MX/NOPB   | ACTIVE        | SOIC         | D                  | 16   | 2500           | Green (RoHS<br>& no Sb/Br) | CU SN                   | Level-1-260C-UNLIM   | 0 to 70      | LM13700M                | <a href="#">Samples</a> |
| LM13700N         | LIFEBUY       | PDIP         | NFG                | 16   | 25             | TBD                        | Call TI                 | Call TI              | 0 to 70      | LM13700N                |                         |
| LM13700N/NOPB    | ACTIVE        | PDIP         | NFG                | 16   | 25             | Pb-Free<br>(RoHS)          | CU SN                   | Level-1-NA-UNLIM     | 0 to 70      | LM13700N                | <a href="#">Samples</a> |

(1) The marketing status values are defined as follows:

**ACTIVE:** Product device recommended for new designs.

**LIFEBUY:** TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.

**NRND:** Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.

**PREVIEW:** Device has been announced but is not in production. Samples may or may not be available.

**OBSELETE:** TI has discontinued the production of the device.

(2) **RoHS:** TI defines "RoHS" to mean semiconductor products that are compliant with the current EU RoHS requirements for all 10 RoHS substances, including the requirement that RoHS substance do not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, "RoHS" products are suitable for use in specified lead-free processes. TI may reference these types of products as "Pb-Free".

**RoHS Exempt:** TI defines "RoHS Exempt" to mean products that contain lead but are compliant with EU RoHS pursuant to a specific EU RoHS exemption.

**Green:** TI defines "Green" to mean the content of Chlorine (Cl) and Bromine (Br) based flame retardants meet JS709B low halogen requirements of <=1000ppm threshold. Antimony trioxide based flame retardants must also meet the <=1000ppm threshold requirement.

(3) MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

(5) Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "~" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

(6) Lead/Ball Finish - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead/Ball Finish values may wrap to two lines if the finish value exceeds the maximum column width.

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**TAPE AND REEL INFORMATION**


\*All dimensions are nominal

| Device         | Package Type | Package Drawing | Pins | SPQ  | Reel Diameter (mm) | Reel Width W1 (mm) | A0 (mm) | B0 (mm) | K0 (mm) | P1 (mm) | W (mm) | Pin1 Quadrant |
|----------------|--------------|-----------------|------|------|--------------------|--------------------|---------|---------|---------|---------|--------|---------------|
| LM13700MX      | SOIC         | D               | 16   | 2500 | 330.0              | 16.4               | 6.5     | 10.3    | 2.3     | 8.0     | 16.0   | Q1            |
| LM13700MX/NOPB | SOIC         | D               | 16   | 2500 | 330.0              | 16.4               | 6.5     | 10.3    | 2.3     | 8.0     | 16.0   | Q1            |

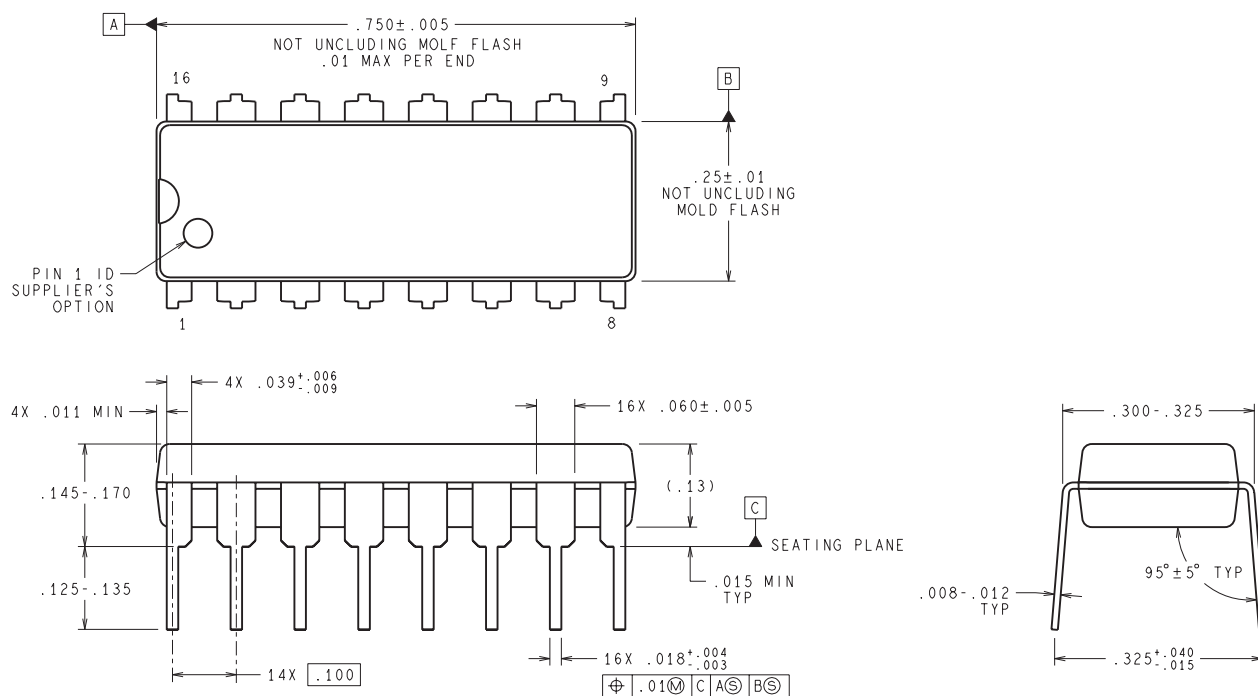
## TAPE AND REEL BOX DIMENSIONS



\*All dimensions are nominal

| Device         | Package Type | Package Drawing | Pins | SPQ  | Length (mm) | Width (mm) | Height (mm) |
|----------------|--------------|-----------------|------|------|-------------|------------|-------------|
| LM13700MX      | SOIC         | D               | 16   | 2500 | 367.0       | 367.0      | 35.0        |
| LM13700MX/NOPB | SOIC         | D               | 16   | 2500 | 367.0       | 367.0      | 35.0        |

NFG0016E

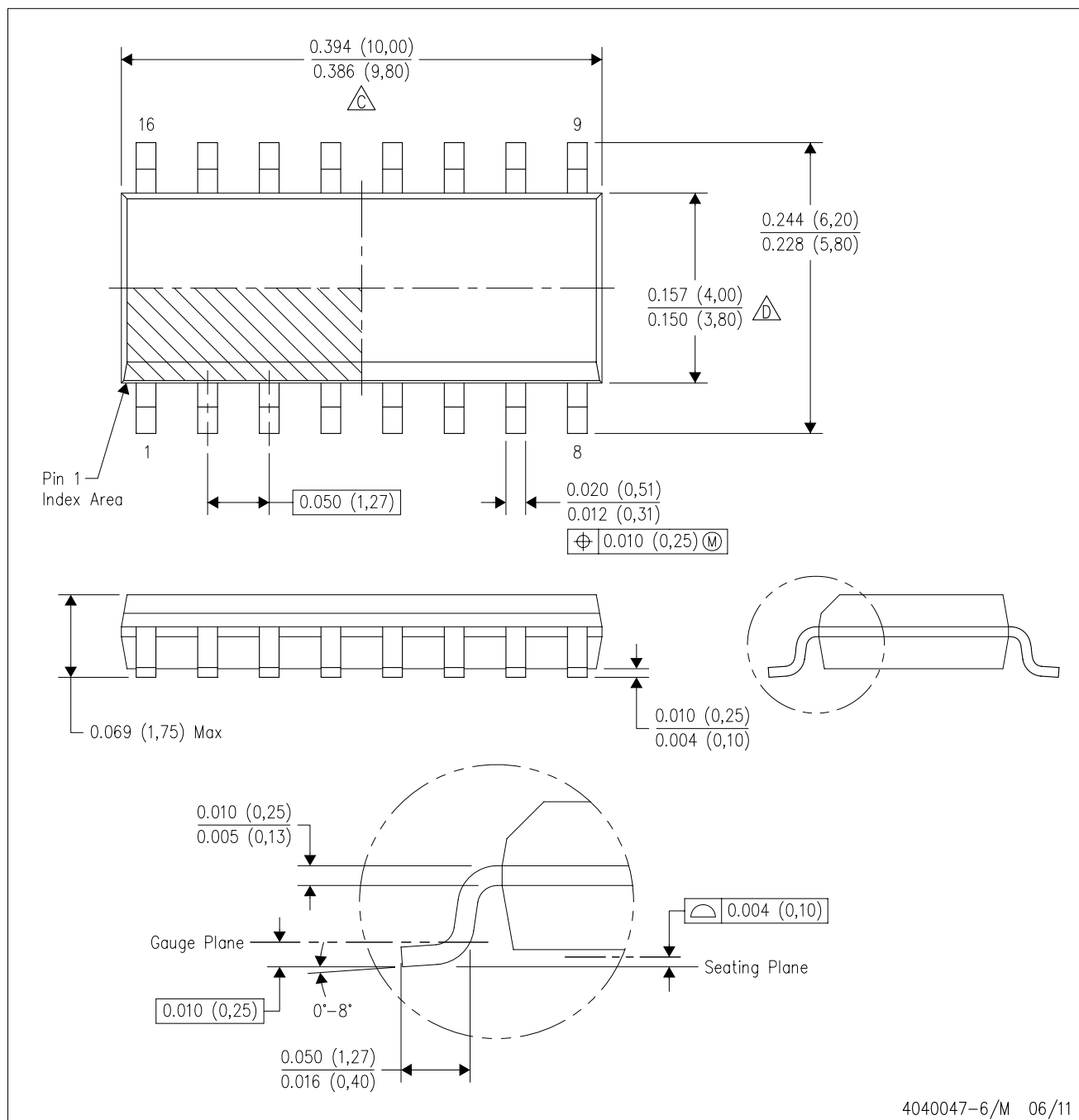


**DIMENSIONS ARE IN INCHES**  
DIMENSIONS IN ( ) FOR REFERENCE ONLY

N16E (Rev G)

## D (R-PDSO-G16)

## PLASTIC SMALL OUTLINE



- NOTES:
- A. All linear dimensions are in inches (millimeters).
  - B. This drawing is subject to change without notice.
  -  C. Body length does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.006 (0,15) each side.
  -  D. Body width does not include interlead flash. Interlead flash shall not exceed 0.017 (0,43) each side.
  - E. Reference JEDEC MS-012 variation AC.

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