LM13700
Dual Operational Transconductance Amplifiers with Linearizing Diodes and Buffers

General 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 hence their output DC levels) are independent of \( I_{ABC} \). This may result in performance superior to that of the LM13600 in audio applications.

Features
- \( g_m \) adjustable over 6 decades
- Excellent \( g_m \) linearity
- Excellent matching between amplifiers
- Linearizing diodes
- High impedance buffers
- High output signal-to-noise ratio

Applications
- Current-controlled amplifiers
- Current-controlled impedances
- Current-controlled filters
- Current-controlled oscillators
- Multiplexers
- Timers
- Sample-and-hold circuits

Connection Diagram
**Absolute Maximum Ratings** (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

- **Supply Voltage**
  - LM13700: 36 V <sub>DC</sub> or ±18 V

- **Power Dissipation** (Note 2) <sub>T_A = 25˚C</sub>
  - LM13700N: 570 mW

- **Differential Input Voltage** ±5V

- **Diode Bias Current (I_D)** 2 mA

- **Amplifier Bias Current (I_ABC)** 2 mA

- **Output Short Circuit Duration** Continuous

- **Buffers Output Current** (Note 3) 20 mA

**Operating Temperature Range**
- LM13700N: 0˚C to +70˚C
- DC Input Voltage: +V_s to -V_s

**Storage Temperature Range** −65˚C to +150˚C

**Soldering Information**
- Dual-In-Line Package: Soldering (10 sec.) 260˚C
- Small Outline Package: Vapor Phase (60 sec.) 215˚C
- Infrared (15 sec.) 220˚C

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**Electrical Characteristics** (Note 4)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conditions</th>
<th>LM13700</th>
<th>Units</th>
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<tbody>
<tr>
<td>Input Offset Voltage (V_OS)</td>
<td>Over Specified Temperature Range</td>
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<tr>
<td>I_ABC = 5 µA</td>
<td>0.4</td>
<td>4</td>
<td>mV</td>
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<td></td>
<td>0.3</td>
<td>4</td>
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<td>V_OS Including Diodes</td>
<td>Diode Bias Current (I_D) = 500 µA</td>
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<td>Input Offset Change</td>
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<tr>
<td></td>
<td>Input Offset Current</td>
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<td>Over Specified Temperature Range</td>
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<td>6700</td>
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<td>Transconductance (g_m)</td>
<td>Over Specified Temperature Range</td>
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<td>g_m Tracking</td>
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<td>Peak Output Current</td>
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<td>RL = 0, Over Specified Temp Range</td>
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<td>Peak Output Voltage</td>
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<td></td>
<td>Negative</td>
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<td>Common Mode Range</td>
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<td>±13.5</td>
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<tr>
<td>Peak Buffer Output Voltage</td>
<td>(Note 5)</td>
<td>10</td>
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</tbody>
</table>

**Notes:**
1. “Absolute Maximum Ratings” indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits.
2. 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.
3. Buffer output current should be limited so as to not exceed package dissipation.
Electrical Characteristics (Note 4) (Continued)

**Note 4:** These specifications apply for $V_S = \pm 15V$, $T_A = 25^\circ C$, amplifier bias current ($I_{ABC}$) = 500 $\mu A$, pins 2 and 15 open unless otherwise specified. The inputs to the buffers are grounded and outputs are open.

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

**Schematic Diagram**

![Schematic Diagram](image)

**Typical Application**

![Typical Application](image)
Typical Performance Characteristics

- **Input Offset Voltage**
  - Graph showing voltage offset vs. amplifier bias current at different temperatures.

- **Input Offset Current**
  - Graph showing current offset vs. amplifier bias current at different temperatures.

- **Input Bias Current**
  - Graph showing bias current vs. amplifier bias current at different temperatures.

- **Peak Output Current**
  - Graph showing peak output current vs. amplifier bias current at different temperatures.

- **Peak Output Voltage and Common Mode Range**
  - Graph showing peak output voltage and common mode range vs. amplifier bias current at different temperatures.

- **Leakage Current**
  - Graph showing leakage current vs. ambient temperature.
Typical Performance Characteristics (Continued)

Input Leakage

![Input Leakage Graph]

Transconductance

![Transconductance Graph]

Input Resistance

![Input Resistance Graph]

Amplifier Bias Voltage vs. Amplifier Bias Current

![Amplifier Bias Voltage Graph]

Input and Output Capacitance

![Input and Output Capacitance Graph]

Output Resistance

![Output Resistance Graph]
Typical Performance Characteristics (Continued)

Distortion vs. Differential Input Voltage

Output Noise vs. Frequency

Voltage vs. Amplifier Bias Current

Unity Gain Follower

www.national.com
Circuit Description

The differential transistor pair Q₄ and Q₅ 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 \( I_4 \) and \( I_5 \) are the collector currents of transistors Q₄ and Q₅ respectively. With the exception of Q₁₂ and Q₁₃, all transistors and diodes are identical in size. Transistors Q₁ and Q₂ with Diode D₁ form a current mirror which forces the sum of currents \( I_4 \) and \( I_5 \) to equal \( I_{ABC} \):

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

For small differential input voltages the ratio of \( I_4 \) and \( I_5 \) approaches unity and the Taylor series of the \( \ln \) function can be approximated as:

\[ \ln \frac{I_5}{I_4} \approx \frac{kT}{q} \left( I_5 - I_4 \right) \quad (3) \]

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:

\[ \frac{kT}{q} \ln \frac{I_{ABC}}{2kT} = I_5 - I_4 \quad (4) \]

Linearizing Diodes

For differential voltages greater than a few millivolts, Equation (3) becomes less valid and the transconductance becomes increasingly nonlinear. Figure 1 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 \( I_5 \) can be written as follows:

\[ I_4 = \frac{I_{ABC}}{2} - \frac{I_{OUT}}{2}, \quad I_5 = \frac{I_{ABC}}{2} + \frac{I_{OUT}}{2} \]

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

\[ \frac{kT}{q} \ln \frac{I_D}{2} + I_S = \frac{kT}{q} \ln \frac{I_{ABC} + I_{OUT}}{2} \]

\[ \therefore I_{OUT} = I_S \left( \frac{2I_{ABC}}{I_D} \right) \quad \text{for } |I_S| < \frac{I_D}{2} \quad (6) \]

Notice that in deriving Equation (6) 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.

Applications

Voltage Controlled Amplifiers

Figure 2 shows how the linearizing diodes can be used in a voltage-controlled amplifier. To understand the input biasing, it is best to consider the 13 kΩ resistor as a current source and use a Thevenin equivalent circuit as shown in Figure 3. This circuit is similar to Figure 1 and operates the same. The potentiometer in Figure 2 is adjusted to minimize the effects of the control signal at the output.
Applications
Voltage Controlled Amplifiers

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 2) until the output distortion is below some 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 ($r_D$) 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.

**FIGURE 1. Linearizing Diodes**

**FIGURE 2. Voltage Controlled Amplifier**
Stereo Volume Control

The circuit of Figure 4 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 2 as being:

\[
\frac{V_O}{V_{IN}} = 940 \times I_{ABC}
\]

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 5, where:

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

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 6 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 \( I_O \).
Stereo Volume Control  (Continued)

FIGURE 4. Stereo Volume Control

FIGURE 5. Amplitude Modulator
Noting that the gain of the LM13700 amplifier of Figure 3 may be controlled by varying the linearizing diode current $I_D$ as well as by varying $I_{ABC}$, Figure 7 shows an AGC Amplifier using this approach. As $V_C$ reaches a high enough amplitude (3VBE) 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.

### Voltage Controlled Resistors

An Operational Transconductance Amplifier (OTA) may be used to implement a Voltage Controlled Resistor as shown in Figure 8. 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:

$$R_X = \frac{R + R_A}{g_m R_A}$$

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 9 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 10, where each “end” of the “resistor” may be at any voltage within the output voltage range of the LM13700.
Voltage Controlled Resistor

OTA's are extremely useful for implementing voltage controlled filters, with the LM13700 having the advantage that the required buffers are included on the IC. The VC Lo-Pass Filter of Figure 11 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 12 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 13 and the state variable filter of Figure 14. Due to the excellent $g_m$ tracking of the two amplifiers, these filters perform well over several decades of frequency.
Voltage Controlled Filters (Continued)

FIGURE 10. Floating Voltage Controlled Resistor

FIGURE 11. Voltage Controlled Low-Pass Filter
Voltage Controlled Filters (Continued)

![Diagram of Voltage Controlled Hi-Pass Filter](image1)

\[ f_0 = \frac{R_A Q_m}{(R + R_A) 2\pi C} \]

**FIGURE 12. Voltage Controlled Hi-Pass Filter**

![Diagram of Voltage Controlled 2-Pole Butterworth Lo-Pass Filter](image2)

\[ f_0 = \frac{R_A Q_m}{(R + R_A) 2\pi C} \]

**FIGURE 13. Voltage Controlled 2-Pole Butterworth Lo-Pass Filter**
Voltage Controlled Oscillators

The classic Triangular/Square Wave VCO of Figure 15 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 5V to prevent zenering the inputs.

A few modifications to this circuit produce the ramp/pulse VCO of Figure 16. When \( V_{C2} \) 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 \( V_{C2} \) is low, \( I_F \) goes to zero and the capacitor discharge current is set by \( I_C \).

The VC Lo-Pass Filter of Figure 11 may be used to produce a high-quality sinusoidal VCO. The circuit of Figure 16 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.
Voltage Controlled Oscillators (Continued)

FIGURE 15. Triangular/Square-Wave VCO

\[ f_{\text{osc}} = \frac{I_C}{4C \mu R_\text{A}} \]

FIGURE 16. Ramp/Pulse VCO

\[
\begin{align*}
V_{\text{PK}} &= \left( V^+ \pm 0.8V \right) \frac{R_2}{R_1 + R_2} \\
I_V &\approx \frac{2V_{\text{PK}}C}{I_F} \\
I_C &= \frac{2V_{\text{PK}}C}{I_F} \\
I_0 &\approx \frac{I_C}{2V_{\text{PK}}C} \text{ for } I_C < I_F
\end{align*}
\]
Additional Applications

Figure 19 presents an interesting one-shot which draws no power supply current until it is triggered. A positive-going trigger pulse of at least 2V 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.
The operation of the multiplexer of Figure 20 is very straightforward. When A1 is turned on it holds $V_O$ equal to $V_{IN1}$ and when A2 is supplied with bias current then it controls $V_O$. $C_C$ and $R_C$ serve to stabilize the unity-gain configuration of amplifiers A1 and A2. The maximum clock rate is limited to about 200 kHz by the LM13700 slew rate into 150 pF when the $(V_{IN1} - V_{IN2})$ differential is at its maximum allowable value of 5V.

The Phase-Locked Loop of Figure 21 uses the four-quadrant multiplier of Figure 6 and the VCO of Figure 18 to produce a PLL with a ±5% hold-in range and an input sensitivity of about 300 mV.
Additional Applications (Continued)

The Schmitt Trigger of Figure 22 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 23 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 \(C_f\) 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 \(C_f\) 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 24 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.
Additional Applications (Continued)

The Ramp-and-Hold of Figure 26 sources \( I_b \) into capacitor \( C \) whenever the input to \( A1 \) is brought high, giving a ramp-rate of about 1V/ms for the component values shown.

The true-RMS converter of Figure 27 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.
Additional Applications (Continued)

FIGURE 25. Sample-Hold Circuit

FIGURE 26. Ramp and Hold
The circuit of Figure 28 is a voltage reference of variable Temperature Coefficient. The 100 kΩ potentiometer adjusts the output voltage which has a positive TC above 1.2V, zero TC at about 1.2V, and negative TC below 1.2V. 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 29.

For generating I_ABC over a range of 4 to 6 decades of current, the system of Figure 30 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 0V, the output current of A1 is equal to \( I_3 = -\frac{V_C}{R_C} \).

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:

\[
V_{IN1} = -\frac{2kT}{qL_2} - \frac{2kT}{qL_2R_C}
\]

The voltage on the base of Q1 is then

\[
V_B1 = \frac{(R_1 + R_2) V_{IN1}}{R_1}
\]

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

\[
V_B1 = \frac{kT}{q} \ln \frac{I_{C2}}{I_{C1}} \approx \frac{kT}{q} \ln \frac{I_{ABC}}{I_1}
\]

Combining and solving for I_ABC yields:

\[
I_{ABC} = I_1 \exp \left( \frac{2(R_1 + R_2) V_C}{R_1 R_2} \right)
\]

This logarithmic current can be used to bias the circuit of Figure 4 to provide temperature independent stereo attenuation characteristic.
Additional Applications (Continued)

FIGURE 28. Delta VBE Reference

FIGURE 29. Pulse Width Modulator
Additional Applications  (Continued)

![Logarithmic Current Source Circuit](image)

\[
I_{\text{ABC}} = I_1 \exp \left( \frac{-Ct_3}{I_2} \right)
\]

**FIGURE 30. Logarithmic Current Source**
Physical Dimensions

S.O. Package (M)
Order Number LM13700M or LM13700MX
NS Package Number M16A

Molded Dual-In-Line Package (N)
Order Number LM13700N
NS Package Number N16A
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