**FEATURES**

32-position digital potentiometer  
10 kΩ, 50 kΩ, 100 kΩ end-to-end terminal resistance  
Simple manual up/down control  
Self-contained, requires only 2 pushbutton tactile switches  
Built-in adaptive debouncer  
Discrete step-up/step-down control  
Autoscan up/down control with 4 steps per second  
Pin-selectable zero-scale/midscale preset  
Low potentiometer mode tempco, 5 ppm/°C  
Low rheostat mode tempco, 35 ppm/°C  
Digital control compatible  
Ultralow power, $I_{DD} = 0.4 \mu A$ typ and $3 \mu A$ max  
Low operating voltage, 2.7 V to 5.5 V  
Temperature range, $-40°C$ to $+105°C$  
Compact thin SOT-23-8 (2.9 mm × 3 mm) Pb-free package

**APPLICATIONS**

Mechanical potentiometer and trimmer replacements  
LCD backlight, contrast, and brightness controls  
Digital volume control  
Portable device-level adjustments  
Electronic front panel-level controls  
Programmable power supply

**GENERAL DESCRIPTION**

The AD5228 is Analog Devices' latest 32-step-up/step-down control digital potentiometer emulating mechanical potentiometer operation. Its simple up/down control interface allows manual control with just two external pushbutton tactile switches. The AD5228 is designed with a built-in adaptive debouncer that ignores invalid bounces due to contact bounce commonly found in mechanical switches. The debouncer is adaptive, accommodating a variety of pushbutton tactile switches that generally have less than 10 ms of bounce time during contact closures. When choosing the switch, the user should consult the timing specification of the switch to ensure its suitability in an AD5228 application.

The AD5228 can increment or decrement the resistance in discrete steps or in autoscan mode. When the PU or PD button is pressed briefly (no longer than 0.6 s), the resistance of the AD5228 changes by one step. When the PU or PD button is held continuously for more than a second, the device activates the autoscan mode and changes four resistance steps per second.

The AD5228 can also be controlled digitally; its up/down features simplify microcontroller usage. The AD5228 is available in a compact thin SOT-23-8 (TSOT-8) package. The part is guaranteed to operate over the temperature range of $-40°C$ to $+105°C$.

The AD5228's simple interface, small footprint, and very low cost enable it to replace mechanical potentiometers and trimmers with typically 3× improved resolution, solid-state reliability, and faster adjustment, resulting in considerable cost saving in end users' systems.

Users who consider EEMEM potentiometers should refer to the recommendations in the Applications section.

**Table 1. Truth Table**

<table>
<thead>
<tr>
<th>PU</th>
<th>PD</th>
<th>Operation ¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>$R_{WB}$ Decrement</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>$R_{WB}$ Increment</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>$R_{WB}$ Decrement</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>$R_{WB}$ Does Not Change</td>
</tr>
</tbody>
</table>

¹The terms digital potentiometer and RDAC are used interchangeably.
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Changes to Table 2.......................................................................... 3  

4/04—Revision 0: Initial Version
### ELECTRICAL CHARACTERISTICS

10 kΩ, 50 kΩ, 100 kΩ versions: $V_{DD} = 3\, \text{V} \pm 10\%$ or $5\, \text{V} \pm 10\%$, $V_A = V_{DD}$, $V_B = 0\, \text{V}$, $-40\, ^\circ\text{C} < T_A < +105\, ^\circ\text{C}$, unless otherwise noted.

#### Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ¹</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC CHARACTERISTICS, RHEOSTAT MODE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistor Differential Nonlinearity²</td>
<td>R-DNL</td>
<td>$R_{WB, \ A \ terminal = no connect}$</td>
<td>-0.5</td>
<td>±0.05</td>
<td>+0.5</td>
<td>LSB</td>
</tr>
<tr>
<td>Resistor Integral Nonlinearity²</td>
<td>R-INL</td>
<td>$R_{WB, \ A \ terminal = no connect}$</td>
<td>-0.5</td>
<td>±0.1</td>
<td>+0.5</td>
<td>LSB</td>
</tr>
<tr>
<td>Nominal Resistor Tolerance³</td>
<td>$\Delta R_{AB}/R_{AB}$</td>
<td></td>
<td>-20</td>
<td>+20</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Resistance Temperature Coefficient</td>
<td>(Δ$R_{AB}/R_{AB}$) × 10⁴/ΔT</td>
<td></td>
<td>35</td>
<td></td>
<td></td>
<td>ppm/°C</td>
</tr>
<tr>
<td>Wiper Resistance</td>
<td>$R_W$</td>
<td>$V_{DD} = 2.7, \text{V}$</td>
<td>100</td>
<td>250</td>
<td></td>
<td>Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{DD} = 2.8, \text{V to 5.5, V}$</td>
<td>50</td>
<td>200</td>
<td></td>
<td>Ω</td>
</tr>
<tr>
<td>DC CHARACTERISTICS, POTENTIOMETER DIVIDER MODE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Specifications apply to all RDACs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>$N$</td>
<td></td>
<td></td>
<td>5</td>
<td></td>
<td>Bits</td>
</tr>
<tr>
<td>Integral Nonlinearity³</td>
<td>$INL$</td>
<td></td>
<td>-0.5</td>
<td>±0.05</td>
<td>+0.5</td>
<td>LSB</td>
</tr>
<tr>
<td>Differential Nonlinearity³, ⁵</td>
<td>$DNL$</td>
<td></td>
<td>-0.5</td>
<td>±0.05</td>
<td>+0.5</td>
<td>LSB</td>
</tr>
<tr>
<td>Voltage Divider Temperature Coefficient</td>
<td>(Δ$V_{W}/V_{W}$) × 10⁴/ΔT</td>
<td>Midscale</td>
<td>5</td>
<td></td>
<td></td>
<td>ppm/°C</td>
</tr>
<tr>
<td>Full-Scale Error</td>
<td>$V_{WFE}$</td>
<td>≥+15 steps from midscale</td>
<td>-1.2</td>
<td>-0.5</td>
<td>0</td>
<td>LSB</td>
</tr>
<tr>
<td>Zero-Scale Error</td>
<td>$V_{WZSE}$</td>
<td>≤−16 steps from midscale</td>
<td>0</td>
<td>0.3</td>
<td>0.6</td>
<td>LSB</td>
</tr>
<tr>
<td>RESISTOR TERMINALS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage Range⁶</td>
<td>$V_{A, B, W}$</td>
<td>With respect to GND</td>
<td>0</td>
<td>$V_{DD}$</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Capacitance⁴ A, B</td>
<td>$C_{A, B}$</td>
<td>$f = 1, \text{MHz, measured to GND}$</td>
<td>140</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>Capacitance⁴ W</td>
<td>$C_W$</td>
<td>$f = 1, \text{MHz, measured to GND}$</td>
<td>150</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>Common-Mode Leakage</td>
<td>$I_{CM}$</td>
<td>$V_A = V_B = V_W$</td>
<td>1</td>
<td></td>
<td></td>
<td>nA</td>
</tr>
<tr>
<td>PU, PD INPUTS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input High</td>
<td>$V_H$</td>
<td>$V_{DD} = 5, \text{V}$</td>
<td>2.4</td>
<td>5.5</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Input Low</td>
<td>$V_L$</td>
<td>$V_{DD} = 5, \text{V}$</td>
<td>0</td>
<td>0.8</td>
<td></td>
<td>µA</td>
</tr>
<tr>
<td>Input Current</td>
<td>$I_i$</td>
<td>$V_{IN} = 0, \text{V or 5, V}$</td>
<td>±1</td>
<td></td>
<td></td>
<td>µA</td>
</tr>
<tr>
<td>Input Capacitance⁴</td>
<td>$C_I$</td>
<td></td>
<td>5</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>POWER SUPPLIES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Supply Range</td>
<td>$V_{DD}$</td>
<td>$V_{DD} = 5, \text{V}$, $PU = PD = V_{DD}$</td>
<td>2.7</td>
<td>5.5</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Supply Standby Current</td>
<td>$I_{DD, STBY}$</td>
<td></td>
<td>0.4</td>
<td>3</td>
<td></td>
<td>µA</td>
</tr>
<tr>
<td>Supply Active Current⁷</td>
<td>$I_{DD, ACT}$</td>
<td>$V_{DD} = 5, \text{V}$, $PU$ or $PD$ = 0, \text{V}$</td>
<td>50</td>
<td>110</td>
<td></td>
<td>µA</td>
</tr>
<tr>
<td>Power Dissipation⁷, ⁸</td>
<td>$P_{DSS}$</td>
<td>$V_{DD} = 5, \text{V}$</td>
<td>17</td>
<td></td>
<td></td>
<td>µW</td>
</tr>
<tr>
<td>Power Supply Sensitivity</td>
<td>$PSSR$</td>
<td>$V_{DD} = 5, \text{V} \pm 10%$</td>
<td>0.01</td>
<td>0.05</td>
<td></td>
<td>%/%</td>
</tr>
</tbody>
</table>

Footnotes on next page.

---

¹ Typ values are at $T_A = +25\, ^\circ\text{C}$.
² $V_{DD} = 3\, \text{V} \pm 10\%$ or $5\, \text{V} \pm 10\%$.
³ $V_{DD} = 5\, \text{V}$.
⁴ Measured to GND.
⁵ Measured to $V_{DD}$.
⁶ With respect to GND.
⁷ Measured to $V_{DD}$.
⁸ Measured to $V_{DD} = 5\, \text{V}$. 

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Footnotes on next page.
## AD5228 Data Sheet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DYNAMIC CHARACTERISTICS 4, 9, 10, 11</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Built-in Debounce and Settling Time 12</td>
<td>tDB</td>
<td></td>
<td>6</td>
<td></td>
<td>12</td>
<td>ms</td>
</tr>
<tr>
<td>PU Low Pulse Width</td>
<td>tPU</td>
<td></td>
<td>12</td>
<td></td>
<td></td>
<td>ms</td>
</tr>
<tr>
<td>PD Low Pulse Width</td>
<td>tPD</td>
<td></td>
<td>12</td>
<td></td>
<td></td>
<td>ms</td>
</tr>
<tr>
<td>PU High Repetitive Pulse Width</td>
<td>tPU_REP</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>μs</td>
</tr>
<tr>
<td>PD High Repetitive Pulse Width</td>
<td>tPD_REP</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>μs</td>
</tr>
<tr>
<td>Autoscan Start Time</td>
<td>tAS_START</td>
<td>PU or PD = 0 V</td>
<td>0.6</td>
<td>0.8</td>
<td>1.2</td>
<td>s</td>
</tr>
<tr>
<td>Autoscan Time</td>
<td>tAS</td>
<td>PU or PD = 0 V</td>
<td>0.16</td>
<td>0.25</td>
<td>0.38</td>
<td>s</td>
</tr>
<tr>
<td>Bandwidth –3 dB</td>
<td>BW_10</td>
<td>RAB = 10 kΩ, midscale</td>
<td>460</td>
<td></td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td>Bandwidth –3 dB</td>
<td>BW_50</td>
<td>RAB = 50 kΩ, midscale</td>
<td>100</td>
<td></td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td>Bandwidth –3 dB</td>
<td>BW_100</td>
<td>RAB = 100 kΩ, midscale</td>
<td>50</td>
<td></td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td>Total Harmonic Distortion</td>
<td>THD</td>
<td>VA = 1 V rms, RAB = 10 kΩ, VB = 0 V dc, f = 1 kHz</td>
<td>0.05</td>
<td></td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Resistor Noise Voltage</td>
<td>eN_WB</td>
<td>RWB = 5 kΩ, f = 1 kHz</td>
<td>14</td>
<td></td>
<td></td>
<td>nV/√Hz</td>
</tr>
</tbody>
</table>

1. Typicals represent average readings at 25°C, VDD = 5 V.
2. Resistor position nonlinearity error, R-INL, is the deviation from an ideal value measured between the maximum resistance and the minimum resistance wiper positions. R-DNL measures the relative step change from ideal between successive tap positions. Parts are guaranteed monotonic.
3. INL and DNL are measured at VA with the RDAC configured as a potentiometer divider similar to a voltage output D/A converter. VA = VDD and VB = 0 V.
4. Guaranteed by design and not subject to production test.
5. DNL specification limits of ±1 LSB maximum are guaranteed monotonic operating conditions.
6. Resistor Terminals A, B, and W have no limitations on polarity with respect to each other.
7. PU and PD have 100 kΩ internal pull-up resistors, IDD_ACT = VDD/100 kΩ + IOSC (internal oscillator operating current) when PU or PD is connected to ground.
8. PDISS is calculated based on IDD_STBY × VDD only. IDD_ACT duration should be short. Users should not hold PU or PD pin to ground longer than necessary to elevate power dissipation.
9. Bandwidth, noise, and settling time are dependent on the terminal resistance value chosen. The lowest R value results in the fastest settling time and highest bandwidth. The highest R value results in the minimum overall power consumption.
10. All dynamic characteristics use VDD = 5 V.
11. Note that all input control voltages are specified with tR = tF = 1 ns (10% to 90% of VDD) and timed from a voltage level of 1.6 V. Switching characteristics are measured using VDD = 5 V.
12. The debouncer keeps monitoring the logic-low level once PU is connected to ground. Once the signal lasts longer than 11 ms, the debouncer assumes the last bounce is met and allows the AD5228 to increment by one step. If the PU signal remains at low and reaches tAS_START, the AD5228 increments again, see Figure 7. Similar characteristics apply to PD operation.

### INTERFACE TIMING DIAGRAMS

**Figure 2. Increment RWB in Discrete Steps**

**Figure 4. Decrement RWB in Discrete Steps**

**Figure 3. Increment RWB in Autoscan Mode**

**Figure 5. Decrement RWB in Autoscan Mode**
ABSOLUTE MAXIMUM RATINGS

Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDD to GND</td>
<td>−0.3 V, +7 V</td>
</tr>
<tr>
<td>VA, VB, VW to GND</td>
<td>0 V, VDD</td>
</tr>
<tr>
<td>PU, PD, PRE Voltage to GND</td>
<td>0 V, VDD</td>
</tr>
<tr>
<td>Maximum Current</td>
<td></td>
</tr>
<tr>
<td>IWB, IWA Pulsed</td>
<td>±20 mA</td>
</tr>
<tr>
<td>IWB Continuous (RWB ≤ 5 kΩ, A open)1</td>
<td>±1 mA</td>
</tr>
<tr>
<td>IWA Continuous (RWA ≤ 5 kΩ, B open)2</td>
<td>±1 mA</td>
</tr>
<tr>
<td>IKB Continuous (RKB = 10 kΩ/50 kΩ/100 kΩ)3</td>
<td>±500 μA/±100 μA/±50 μA</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td></td>
</tr>
<tr>
<td>Maximum Junction Temperature (TJ, max)</td>
<td>−40°C to +105°C</td>
</tr>
<tr>
<td>Maximum Junction Temperature (TJ, max)</td>
<td>150°C</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>−65°C to +150°C</td>
</tr>
<tr>
<td>Lead Temperature (Soldering, 10 s – 30 s)</td>
<td>245°C</td>
</tr>
<tr>
<td>Thermal Resistance2 θJA</td>
<td>230°C/W</td>
</tr>
</tbody>
</table>

1 Maximum terminal current is bounded by the maximum applied voltage across any two of the A, B, and W terminals at a given resistance, the maximum current handling of the switches, and the maximum power dissipation of the package. VDD = 5 V.

2 Package power dissipation = (TJ,max – TA) / θJA.

ESD CAUTION

Stresses at or above those listed under Absolute Maximum Ratings may cause permanent damage to the product. This is a stress rating only; functional operation of the product at these or any other conditions above those indicated in the operational section of this specification is not implied. Operation beyond the maximum operating conditions for extended periods may affect product reliability.

ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.
**Table 4. Pin Function Descriptions**

<table>
<thead>
<tr>
<th>Pin No.</th>
<th>Mnemonic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PU</td>
<td>Push-Up Pin. Connect to the external pushbutton. Active low. A 100 kΩ pull-up resistor is connected to VDD.</td>
</tr>
<tr>
<td>2</td>
<td>PD</td>
<td>Push-Down Pin. Connect to the external pushbutton. Active low. A 100 kΩ pull-up resistor is connected to VDD.</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>Resistor Terminal A. GND ≤ V_A ≤ VDD.</td>
</tr>
<tr>
<td>4</td>
<td>GND</td>
<td>Common Ground.</td>
</tr>
<tr>
<td>5</td>
<td>W</td>
<td>Wiper Terminal W. GND ≤ V_W ≤ VDD.</td>
</tr>
<tr>
<td>6</td>
<td>B</td>
<td>Resistor Terminal B. GND ≤ V_B ≤ VDD.</td>
</tr>
<tr>
<td>7</td>
<td>PRE</td>
<td>Power-On Preset. Output = midscale if PRE = GND; output = zero scale if PRE = VDD. Do not let the PRE pin float. No pull-up resistor is needed.</td>
</tr>
<tr>
<td>8</td>
<td>VDD</td>
<td>Positive Power Supply. 2.7 V to 5.5 V.</td>
</tr>
</tbody>
</table>
TYPICAL PERFORMANCE CHARACTERISTICS

Figure 7. R-INL vs. Code vs. Supply Voltages

Figure 10. R-DNL vs. Code vs. Temperature, $V_{DD} = 5\, \text{V}$

Figure 8. R-INL vs. Code vs. Temperature, $V_{DD} = 5\, \text{V}$

Figure 11. INL vs. Code vs. Supply Voltages

Figure 9. R-DNL vs. Code vs. Supply Voltages

Figure 12. INL vs. Code, $V_{DD} = 5\, \text{V}$
Figure 13. DNL vs. Code vs. Supply Voltages

Figure 14. DNL vs. Code, $V_{DD} = 5\, \text{V}$

Figure 15. Full-Scale Error vs. Temperature

Figure 16. Zero-Scale Error vs. Temperature

Figure 17. Supply Current vs. Temperature

Figure 18. Nominal Resistance vs. Temperature
Figure 19. Wiper Resistance vs. Temperature

Figure 20. Rheostat Mode Tempco $\Delta R_{wb}/\Delta T$ vs. Code

Figure 21. Potentiometer Mode Tempco $\Delta V_{wb}/\Delta T$ vs. Code

Figure 22. Gain vs. Frequency vs. Code, $R_{ab} = 10 \, k\Omega$

Figure 23. Gain vs. Frequency vs. Code, $R_{ab} = 50 \, k\Omega$

Figure 24. Gain vs. Frequency vs. Code, $R_{ab} = 100 \, k\Omega$
**Figure 25. PSRR**

**Figure 26. Basic Increment**

**Figure 27. Repetitive Increment**

**Figure 28. Autoscan Increment**

**Figure 29. Maximum Iwb vs. Code**
THEORY OF OPERATION

The AD5228 is a 32-position manual up/down digitally controlled potentiometer with selectable power-on preset. The AD5228 presets to midscale when the PRE pin is tied to ground and to zero-scale when PRE is tied to VDD. Floating the PRE pin is not allowed. The step-up and step-down operations require the activation of the PU (push-up) and PD (push-down) pins. These pins have 100 kΩ internal pull-up resistors that the PU and PD activate at logic low. The common practice is to apply external pushbuttons (tactile switches) as shown in Figure 30.

Because of the bounce mechanism commonly found in the switches during contact closures, a single pushbutton press usually generates numerous bounces during contact closure. Note that the term pushbutton refers specifically to a pushbutton tactile switch or a similar switch that has 10 ms or less bounce time during contact closure. Figure 31 shows the characteristics of one such switch, the KRS-3550 tactile switch. Figure 32 and Figure 33 show close ups of the initial bounces and end bounces, respectively.

The following paragraphs describes the PU incrementing operation. Similar characteristics apply to the PD decrementing operation.

The AD5228 features an adaptive debouncer that monitors the duration of the logic-low level of PU signal between bounces. If the PU logic-low level signal duration is shorter than 7 ms, the debouncer ignores it as an invalid incrementing command. Whenever the logic-low level of PU signal lasts longer than 11 ms, the debouncer assumes that the last bounce is met and therefore increments RWB by one step.

Repeatedly pressing the PU button for fast adjustment without missing steps is allowed, provided that each press is not shorter than tpu, which is 12 ms (see Figure 2). As a point of reference, an advanced video game player can press a pushbutton switch in 40 ms.

Figure 30. Typical Pushbutton Interface

Figure 31. Typical Tactile Switch Characteristics

Figure 32. Close-Up of Initial Bounces

Figure 33. Close-Up of Final Bounces
If the PU button is held for longer than 1 second, continuously holding it activates autoscan mode such that the AD5228 increments by four RWB steps per second (see Figure 3). Whenever the maximum RWB (RAB) is reached, RWB stops incrementing regardless of the state of the PU pin. Any continuous holding of the PU pin to logic-low simply elevates the supply current.

When both PU and PD buttons are pressed, RWB decrements until it stops at zero scale.

All the preceding descriptions apply to PD operation. Due to the tolerance of the internal RC oscillator, all the timing information given previously is based on the typical values, which can vary ±30%.

The AD5228 debouncer is carefully designed to handle common pushbutton tactile switches. Other switches that have excessive bounces and duration are not suitable to use in conjunction with the AD5228.

The end-to-end resistance, RB, has 32 contact points accessed by the wiper terminal, plus the B terminal contact if RWB is used. Pushing the PU pin discretely increments RWB by one step. The total resistance becomes Rs + Rw as shown in Figure 34. The change of RWB can be determined by the number of discrete PU executions provided that its maximum setting is not reached during operation. ∆RWB can, therefore, be approximated as

\[
ΔR_{WB} = \left( \frac{PU}{32} R_{AB} + R_W \right)
\]

where:

- PU is the number of push-up executions.
- PD is the number of push-down executions.
- RAB is the end-to-end resistance.
- RW is the wiper resistance contributed by the on-resistance of the internal switch.

Similar to the mechanical potentiometer, the resistance of the RDAC between the Wiper W and Terminal A also produces a complementary resistance, RWA. When these terminals are used, the B terminal can be opened or shorted to W. RWA can also be approximated if its maximum and minimum settings are not reached.

\[
ΔR_{WA} = \left( 32 - \frac{PU}{32} R_{AB} + R_W \right)
\]

Note that Equations 1 to 4 do not apply when PU and PD = 0 execution.

Because in the lowest end of the resistor string, a finite wiper resistance is present, care should be taken to limit the current flow between W and B in this state to a maximum pulse current of no more than 20 mA. Otherwise, degradation or possible destruction of the internal switches can occur.

The typical distribution of the resistance tolerance from device to device is process lot dependent, and ±20% tolerance is possible.
**Potentiometer Mode Operation**

If all three terminals are used, the operation is called potentiometer mode. The most common configuration is the voltage divider operation as shown in Figure 36.

The change of $V_{WB}$ is known provided that the AD5228 maximum or minimum scale has not been reached during operation. If the effect of wiper resistance is ignored, the transfer functions can be simplified as

\[
\Delta V_{WB} = \frac{PU}{32} V_A \tag{5}
\]

\[
\Delta V_{WB} = \frac{PD}{32} V_A \tag{6}
\]

Unlike in rheostat mode operation where the absolute tolerance is high, potentiometer mode operation yields an almost ratiometric function of $PU/32$ or $PD/32$ with a relatively small error contributed by the $R_W$ term. The tolerance effect is, therefore, almost canceled. Although the thin film step resistor $R_S$ and CMOS switch resistance, $R_W$, have very different temperature coefficients, the ratiometric adjustment also reduces the overall temperature coefficient effect to 5 ppm/°C except at low value codes where $R_W$ dominates.

Potentiometer mode operations include an op amp input and feedback resistors network and other voltage scaling applications. The A, W, and B terminals can be input or output terminals and have no polarity constraint provided that $|V_{AB}|, |V_{WA}|,$ and $|V_{WB}|$ do not exceed $V_{DD}$-to-GND.

**CONTROLLING INPUTS**

All $PU$ and $PD$ inputs are protected with a Zener ESD structure as shown in Figure 37.

$PU$ and $PD$ pins are usually connected to pushbutton tactile switches for manual operation, but the AD5228 can also be controlled digitally. It is recommended to add external MOSFETs or transistors that simplify the logic controls.

**TERMINAL VOLTAGE OPERATION RANGE**

The AD5228 is designed with internal ESD diodes for protection. These diodes also set the voltage boundary of the terminal operating voltages. Positive signals present on Terminal A, B, or W that exceed $V_{DD}$ are clamped by the forward-biased diode. There is no polarity constraint between $V_A, V_W,$ and $V_B$, but they cannot be higher than $V_{DD}$ or lower than GND.

![Figure 36. Potentiometer Mode Configuration](image1)

![Figure 37. Equivalent ESD Protection in PU and PD Pins](image2)

![Figure 38. Digital Control with External MOSFETs](image3)

![Figure 39. Maximum Terminal Voltages Set by VDD and GND](image4)
POWER-UP AND POWER-DOWN SEQUENCES

Because of the ESD protection diodes that limit the voltage compliance at Terminals A, B, and W (Figure 39), it is important to power on VDD before applying any voltage to Terminals A, B, and W. Otherwise, the diodes are forward-biased such that VDD is powered on unintentionally and can affect other parts of the circuit. Similarly, VDD should be powered down last. The ideal power-on sequence is in the following order: GND, VDD, and VA/B/W. The order of powering VA, VB, and VW is not important as long as they are powered on after VDD. The states of the PU and PD pins can be logic high or floating, but they should not be logic low during power-on.

LAYOUT AND POWER SUPPLY BIASING

It is always a good practice to use compact, minimum lead length layout design. The leads to the input should be as direct as possible with a minimum conductor length. Ground paths should have low resistance and low inductance. It is also good practice to bypass the power supplies with quality capacitors. Low ESR (equivalent series resistance) 1 μF to 10 μF tantalum or electrolytic capacitors should be applied at the supplies to minimize any transient disturbance and to filter low frequency ripple. Figure 39 illustrates the basic supply bypassing configuration for the AD5228.
APPLICATIONS

MANUAL ADJUSTABLE LED DRIVER

The AD5228 can be used in many electronics-level adjustments such as LED drivers for LCD panel backlight controls. Figure 41 shows a manually adjustable LED driver. The AD5228 sets the voltage across the white LED D1 for the brightness control. Since U2 handles up to 250 mA, a typical white LED with Vf of 3.5 V requires a resistor, R1, to limit U2 current. This circuit is simple but not power efficient. The U2 shutdown pin can be toggled with a PWM signal to conserve power.

ADJUSTABLE CURRENT SOURCE FOR LED DRIVER

Because LED brightness is a function of current rather than of forward voltage, an adjustable current source is preferred as shown in Figure 42. The load current can be found as the VWB of the AD5228 divided by RSET.

\[ I_{LED} = \frac{V_{W}}{R_{SET}} \]  

(7)

The U1 ADP333ARM-1.5 is a 1.5 V LDO that is lifted above or lowered below 0 V. When V_{WB} of the AD5228 is at its minimum, there is no current through D1, so the GND pin of U1 is at –1.5 V if U3 is biased with the dual supplies. As a result, some of the U2 low resistance steps have no effect on the output until the U1 GND pin is lifted above 0 V. When V_{WB} of the AD5228 is at its maximum, VOUT becomes VL + VAB, so the U1 supply voltage must be biased with adequate headroom. Similarly, PWM signal can be applied at the U1 shutdown pin for power efficiency.

ADJUSTABLE HIGH POWER LED DRIVER

The previous circuit works well for a single LED. Figure 43 shows a circuit that can drive three to four high power LEDs. The ADP1610 is an adjustable boost regulator that provides the voltage headroom and current for the LEDs. The AD5228 and the op amp form an average gain of 12 feedback network that serves the RSET voltage and the ADP1610 FB pin 1.2 V band gap reference voltage. As the loop is set, the voltage across RSET is regulated around 0.1 V and adjusted by the digital potentiometer.

\[ I_{LED} = \frac{V_{W}}{R_{SET}} \]  

(8)

RSET should be small enough to conserve power but large enough to limit maximum LED current. R3 should also be used in parallel with AD5228 to limit the LED current within an achievable range. A wider current adjustment range is possible by lowering the R2 to R1 ratio as well as changing R3 accordingly.
AUTOMATIC LCD PANEL BACKLIGHT CONTROL

With the addition of a photocell sensor, an automatic brightness control can be achieved. As shown in Figure 44, the resistance of the photocell changes linearly but inversely with the light output. The brighter the light output, the lower the photocell resistance and vice versa. The AD5228 sets the voltage level that is gained up by U2 to drive N1 to a desirable brightness. With the photocell acting as the variable feedback resistor, the change in the light output changes the R2 resistance, therefore causing U2 to drive N1 accordingly to regulate the output. This simple low cost implementation of an LED controller can compensate for the temperature and aging effects typically found in high power LEDs. Similarly, for power efficiency, a PWM signal can be applied at the gate of N2 to switch the LED on and off without noticeable effect.

Figure 44. Automatic LCD Panel Backlight Control

AUDIO AMPLIFIER WITH VOLUME CONTROL

The AD5228 and SSM2211 can form a 1.5 W audio amplifier with volume control that has adequate power and quality for portable devices such as PDAs and cell phones. The SSM2211 can drive a single speaker differentially between Pins 5 and 8 without any output capacitor. The high-pass cutoff frequency is $f_{H1} = 1/(2 \times \pi \times R1 \times C1)$. The SSM2211 can also drive two speakers as shown in Figure 45. However, the speakers must be configured in single-ended mode, and output coupling capacitors are needed to block the dc current. The output capacitor and the speaker load form an additional high-pass cutoff frequency as $f_{H2} = 1/(2 \times \pi \times R5 \times C3)$. As a result, C3 and C4 must be large to make the frequency as low as $f_{H1}$.
CONSTANT BIAS WITH SUPPLY TO RETAIN RESISTANCE SETTING

Users who consider EEMEM potentiometers but cannot justify the additional cost and programming for their designs can consider constantly biasing the AD5228 with the supply to retain the resistance setting as shown in Figure 46. The AD5228 is designed specifically with low power to allow power conservation even in battery-operated systems. As shown in Figure 47, a similar low power digital potentiometer is biased with a 3.4 V 450 mA/hour Li-Ion cell phone battery. The measurement shows that the device drains negligible power. Constantly biasing the potentiometer is a practical approach because most of the portable devices do not require detachable batteries for charging. Although the resistance setting of the AD5228 is lost when the battery needs to be replaced, this event occurs so infrequently that the inconvenience is minimal for most applications.
OUTLINE DIMENSIONS

Figure 48. 8-Lead Small Outline Transistor Package (TSOT) (UJ-8)
Dimensions shown in millimeters

ORDERING GUIDE

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<th>Temperature Range</th>
<th>Package Description</th>
<th>Package Option</th>
<th>Ordering Quantity</th>
<th>Branding</th>
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<td>8-Lead TSOT</td>
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</table>

1 The end-to-end resistance RAAB is available in 10 kΩ, 50 kΩ, and 100 kΩ. The final three characters of the part number determine the nominal resistance value, for example, 10 kΩ = 10.

2 Z = RoHS Compliant Part.

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