**Purpose:**
To demonstrate the minimum and maximum PWM duty cycle capabilities of the AAT2405's constant current sinks.

**Background:**
LED string dimming is achieved by applying an external PWM signal to the AAT2405’s PWMIN input pin. The AAT2405 has an internal clock that self-synchronizes to the PWM dimming input signal. This function enables a synchronized feed-through of the PWM dimming control to the PWMOUT output pin so a common PWM signal can be used to drive as many cascaded AAT2405 backlight controllers as needed for a system. The period of the PWM signal control is based on the period of the input signal with in a 50Hz to 20kHz range.

The AAT2405 is capable of a wide PWM dimming signal duty cycle range. The maximum duty cycle is 100% PWM at which point the current sinks will be fully turned on to the current level set by the $R_{SET}$ resistor. The minimum duty cycle is bounded by the collective turn-on and turn-off slew rate of the PWM control signal along with the current sink and control circuit. The minimum slew rate boundary on/off time is typically 20μs, but this value can vary depending upon the gate charge specification of the external current sink MOSFET selected for use with the AAT2405. A typical 20μs on/off slew rate time will yield a minimum PWM duty cycle of 0.24% for a 120Hz control signal or 0.48% for a 240Hz control signal.

**Typical current sink control slew rate turn on/off specifications:**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{ON,CS}$</td>
<td>Current Sink Slew Rate Control OFF to ON</td>
<td>$V_{CS, Dx} = 1V, I_{CSx} = 100mA$</td>
<td>6</td>
<td></td>
<td></td>
<td>μs</td>
</tr>
<tr>
<td>$T_{OFF,CS}$</td>
<td>Current Sink Slew Rate Control ON to OFF</td>
<td>$V_{CS, Dx} = 1V, I_{CSx} = 100mA$</td>
<td>6</td>
<td></td>
<td></td>
<td>μs</td>
</tr>
</tbody>
</table>

**Additional Considerations**
1. The background statements sighted in the paragraph from the datasheet pertain to the current sink MOSFET gate control signal. The realized minimum PWM duty cycle for any given LED string must also take into account the switched LED string current magnitude and in some cases the gate charge specification of the current sink MOSFET.
   a. The selected MOSFETs used on the AAT2405 evaluation board have a low gate charge ($Q_G$) specification and do not contribute to the current sink on/off timing as the control signal slew rate timing is significantly greater.
   b. The current sink slew rate controlled turn on has an associated time constant and subsequent impedance ($\text{di} = \text{dv}/\text{dt}$). Since “dv” is a constant in this application, “dt” increases as $I_{LED}$ increases. Therefore, greater programmed current sink current levels will require a greater minimum PWM duty cycle “on” time.
2. Because the slew rate controlled turn-on and turn-off time is a fixed constant, the minimum PWM “on” time is independent of the applied PWM period. The fixed minimum “on” time only affects the minimum percent of the on time value that is related to the applied PWM period. [“A typical 20μs on/off slew rate time will yield a minimum PWM duty cycle of 0.24% for a 120Hz control signal or 0.48% for a 240Hz control signal”]. Therefore, the current sink control $T_{ON} + T_{OFF} = 20μs$ will remain constant regardless of the applied PWM period or duty cycle.
3. If the applied PWM control signal “on” time is less than 20μs, the current sink will simply not turn on or conduct current. The current sink channel will be perceived to be off.
4. The purpose of the slew rate turn on is to limit the LED string inrush current when each leading edge of the PWM control signal enables the 2405 external current sink MOSFET. Without a slew rate limited turn on, the total load transient current for the LED voltage supply would cause excessive peak currents in the boost supply inductor, reduce system efficiency and stability. Therefore the slew rate turn on/off function is necessary and should not be eliminated.
Measurement Setup

Equipment Used:
1. Tektronix DPO 4054 500MHz Digital Oscilloscope with Current Probe
2. Agilent 33220A 20MHz Function / Arbitrary Waveform Generator
3. Xantrex XDL 35-5 DC Power Supply (2 pcs)
4. Fluke 45 Digital Multimeter
5. Jet Labs RS-200 Resistance Decade Box (to adjust \( R_{SET} \))

AAT2405 Configuration:
- AAT2405 Evaluation Board is used for all measurements
- PD0 = PD1 = 1 (no phase delay applied)
- CH0 = CH1 = 0 (all current sink channels set for individual operation)
- \( V_{IN} = V_{EN} = 24\text{VDC} \)
- \( V_{LED} = 35\text{VDC} \)
- LED Array = 10S/6P; driven at 50mA and 100mA

Measured PWM Duty Cycle Data for \( F_{PWM} = 120\text{Hz} \) and \( 320\text{Hz} \)

Figure 1: Example of 50% Duty Cycle Operation for \( F_{PWM} = 120\text{Hz} \).

Figure 2: Example of 50% Duty Cycle Operation for \( F_{PWM} = 320\text{Hz} \).
AAT2405 PWM Control Duty Cycle Capabilities and Limitations

Figure 3: Example of 1% Duty Cycle Operation for $F_{PWM} = 120\text{Hz}$.

Figure 4: Example of 99% Duty Cycle Operation, $F_{PWM} = 320\text{Hz}$.

Figure 5: 1% PWM Duty Cycle for $F_{PWM} = 120\text{Hz}$, $I_{LED} = 100\text{mA}$.

Figure 6: 1% PWM Duty Cycle for $F_{PWM} = 320\text{Hz}$, $I_{LED} = 100\text{mA}$.
AAT2405 PWM Control Duty Cycle Capabilities and Limitations

Conclusion and Results

The AAT2405 is fully capable of supporting PWM dimming operation with in the range of Off to 1% to 99% and 100% duty cycles over a range of 120Hz to 480Hz.

- For PWM control frequencies above 500Hz, 1% PWM operation can not be supported as the PWM on time would be less than 20µs. At control frequencies above 500Hz, the minimum duty cycle then becomes a ratio of:

\[
\frac{T_{\text{ON(MIN)}}}{T_{\text{PWM}}} = \frac{DC}{100}
\]

Where:
- DC = PWM duty cycle value (%)
- \(T_{\text{ON(MIN)}} = 20\mu s\) (constant value set by design)
- \(T_{\text{PWM}} = \) Period of the applied PWM control signal(s)

For operation conditions where \(F_{\text{PWM}} < 480\text{Hz}\), the minimum duty cycle may be less than 1% of \(F_{\text{PWM}}\), but may not be less than 20µs in cases where \(I_{\text{LED}} \geq 75\text{mA}\). For applications where \(I_{\text{LED}} \geq 75\text{mA}\), the di/dt switched nature of the circuit becomes a factor and will increase the required minimum duty cycle “on” time.

- In the case of \(I_{\text{LED}} = 50\text{mA}\), a minimum on time of only 15µs was required.
  - For \(F_{\text{PWM}} = 120\text{Hz}\), 15µs equates to a 0.18% duty cycle
  - For \(F_{\text{PWM}} = 240\text{Hz}\), 15µs equates to a 0.36% duty cycle
  - For \(F_{\text{PWM}} = 320\text{Hz}\), 15µs equates to a 0.48% duty cycle
  - For \(F_{\text{PWM}} = 480\text{Hz}\), 15µs equates to a 0.72% duty cycle

- In the case of \(I_{\text{LED}} = 100\text{mA}\), a minimum on time of only 15µs was required.
  - For \(F_{\text{PWM}} = 120\text{Hz}\), 28.8µs equates to a 0.34% duty cycle
  - For \(F_{\text{PWM}} = 240\text{Hz}\), 28.8µs equates to a 0.69% duty cycle
  - For \(F_{\text{PWM}} = 320\text{Hz}\), 28.8µs equates to a 0.92% duty cycle
  - For \(F_{\text{PWM}} = 480\text{Hz}\), 28.8µs equates to a 1.38% duty cycle

- For LED string current levels above 100mA, the minimum on time requirement will increase and should be determined by the operation condition of the specific application.
APPLICATION NOTE

AAT2405 PWM Control Duty Cycle Capabilities and Limitations

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