ANGSEMI

Datasheet

Pb Free — ANGSemi Microelectronics Components

RoHS — Directive Compliance

Motor Driver ICs

Maximum 4.5A Full Bridge DC Motor Driver with PWM Control

AS5970

● General Description

The AS5970 device is a brushed-DC motor driver for printers, appliances, industrial equipment, and other small machines. Two logic inputs control the H-bridge driver, which consists of four N-channel MOSFETs that can control motors bidirectionally with up to 4.5A peak current. The inputs can be pulse width modulated (PWM) to control motor speed, using a choice of current-decay modes. Setting both inputs low enters a low-power sleep mode. Input terminals are provided for use in controlling the speed and direction of a DC motor with externally applied PWM control signals. Internal synchronous rectification control circuitry is provided to lower power dissipation during PWM operation.

The AS5970 device features integrated current regulation, based on the analog input VREF and the voltage on the ISEN pin, which is proportional to motor current through an external sense resistor. The ability to limit current to a known level can significantly reduce the system power requirements and bulk capacitance needed to maintain stable voltage, especially for motor startup and stall conditions.

The device is fully protected from faults and short circuits, including under-voltage (UVLO), over-current (OCP), over-temperature (TSD) and protection against shorted loads, or against output shorts to ground or supply. When the fault condition is removed, the device automatically resumes normal operation.

The AS5970 contain a thermal management system to protect the device; and a cycle-by-cycle current limit prevents damage to the AS5970. Built-in circuitry prevents excessive inrush current during start-up. The shutdown feature reduces quiescent current to less than 1.0μA.

The device is available in ePAD 8-pin SOP package and is rated over the -40°C to 125°C.

● Features

- Monolithic IC Using BiCD Process
- Input Voltage Range : 6.5V to 30V
- Total Driver H+L Rdson Typical: 0.5Ω
- Maximum 4.5A Current Drive
- Adjustable PWM Current Limit
- H-Bridge Motro Driver:
  - Drives One DC Motor, One Winding of A Stepper Motor, or Other Loads
- PWM Control Interface
- Integrated Current Regulation
- Low Power Sleep Mode
- Supporting 4 Operation Modes: Forward /Reverse/Brake/Stop (OFF)
- Sensorless Proprietary Back Electromotive Force (BEMF) Control Scheme
- Integrated Protection Features:
  - ✓ Over Current Protection (OCP)
  - ✓ Crossover Current Protection
  - ✓ VM Under voltage Lockout (UVLO)
  - ✓ Thermal Shut down (TSD)
  - ✓ Automatic Fault Recovery (AFR)
- Integrated Protection Features: (VM≤28V)
  - ✓ Motor Short Protection (SCP)
  - ✓ Motor Lead Short to Ground Protection
  - ✓ Motor Lead Short to Battery Protection
- Synchronous Rectification
- Small Solution Size
- Less than 1uA Shutdown Current
- RoHS and Green Compliant
- ePAD 8-pin, SOP Packages
- -40℃ to +125 ℃ Temperature Range

● Applications

- Home Appliance Cooling Fan
- Printers / Relay Drivers
- Solenoid Drivers
- Industrial Equipment
- Other Mecha-tronic Applications
- Instrumentation Fan
- DC Brush Motor Drive

Ordering Information

AS5970XXX

Package：
EM:SOP-8L-EP

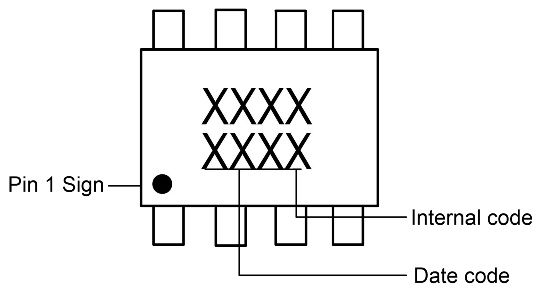
Packing：
R: Tape&Reel

Temperature Grade：
Y: -40°C~125°C

Part Number	Driver Capability	Package Type	Package Qty	Temperature	Eco Plan
AS5970EMRY	4.5A	SOP-8L-EP	13-in reel 4000pcs/reel	-40～125℃	Green

Marking Information

SOP-8L-ePAD:



Typical Application Circuit

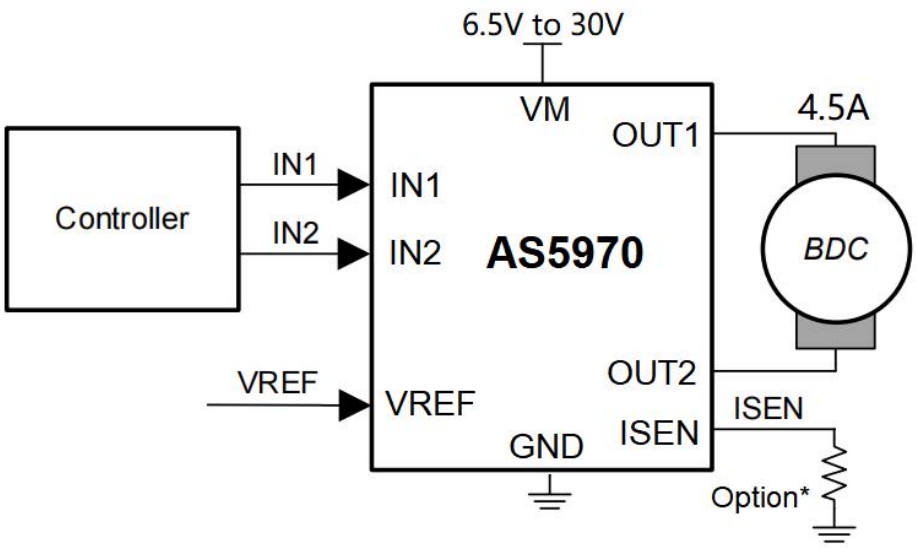


Figure 1, Typical Application Circuit of AS5970

Pin Configuration

SOP-8L-EP (Top View)

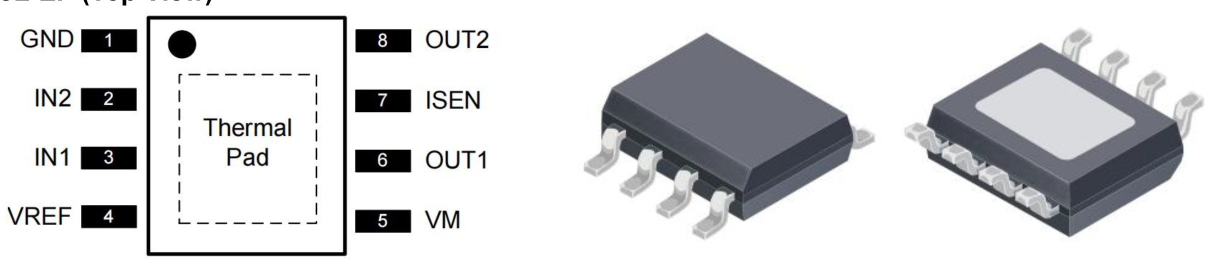


Figure 2, Pin Assignments of AS5970

Pin Name	Pin No. SOP-8L-EP	I/O	Pin Function
GND	1	P	Logic ground pin. Connected to board ground.
IN2	2	I	Logic inputs. Controls the H-bridge output. Has internal pull downs. See Table 1.
IN1	3	I	Logic inputs. Controls the H-bridge output. Has internal pull downs. See Table 1.
VREF	4	I	Analog input. Apply a voltage between 0.3 to 5V. For information on current regulation, see the ***Current Regulation*** section.
VM	5	P	6.5V to 30V power supply.
OUT1	6	O	H-bridge output. Connect directly to the motor or other inductive load.
ISEN	7	I/O	High-current ground path. If using current regulation, connect I_{SEN} to a resistor (low-value, high-power-rating) to ground. If not using current regulation, connect I_{SEN} directly to ground.
OUT2	8	O	H-bridge output. Connect directly to the motor or other inductive load.
PAD	EP	-	Thermal pad Connect to board ground. Use large ground planes on multiple layers, and multiple nearby vias connecting those planes.

■ Block Diagram

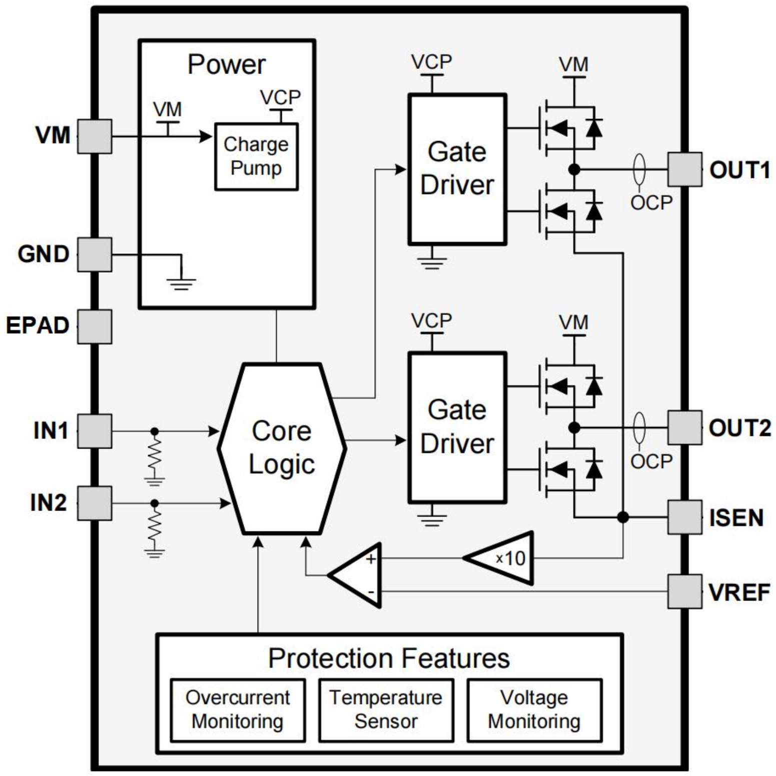


Figure 3, Block Diagram of AS5970

■ Absolute Maximum Ratings[1] (T_A=25°C, unless otherwise noted)

Parameter	Symbol	Rating	Unit
V_{VM} Pin to GND	V_{VM}	-0.3 to +45.0	V
Logic Input IN1 and IN2 Pins to GND	V_{IN*}	-0.3 to 7.0	V
Reference Input Pin VREF to GND	V_{REF}	-0.3 to 6.0	V
Output Voltage OUT1 and OUT2 to GND	V_{OUT*}	-0.3 to V_M + 0.7	V
Current Sense Input Pin Voltage to GND	V_{ISEN}	-0.5 to +0.5	V
Output Current (100% Duty Cycle)	I_{SEN}	0 to 4.5	A
Human Body Model, per ANSI/ESDA/JEDEC JS-001	HBM	4000	V
Storage Temperature Range	T_S	-55 to +150	℃
Operating Junction Temperature Range	T_J	-40 to +150	℃
Maximum Soldering Temperature (at leads, 10 sec)	T_{LEAD}	260	℃

Recommended Operating Conditions[2]

Parameter		Symbol	Rating	Unit
V_{VM} Pin Voltage to GND		V_{VM}	+6.5 to +30	V
VREF pin Voltage to GND		V_{REF}	0 to 5.0	V
Logic Input Voltage IN1 and IN2 to GND		V_{IN*}	0 to 5.5	V
Logic Input PWM Frequency		f_{PWM}	0 to 200	KHz
Peak Output Current		I_{PEAK}	0 to 4.5	A
Operating Temperature Range		T_{OP}	-40 to +125	℃
Maximum Thermal Resistance	SOP-8L-EP	Θ_{JA}	45	℃/W
Maximum Power Dissipation	T_A<25°C	P_D	2.2	W

Note: 1: Stresses above those listed in absolute maximum ratings may cause permanent damage to the device. Functional operation at conditions other than the operating conditions specified is not implied. Only one absolute maximum rating should be applied at any one time.

2: The device is not guaranteed to function outside of its operating conditions.

Electrical Characteristics

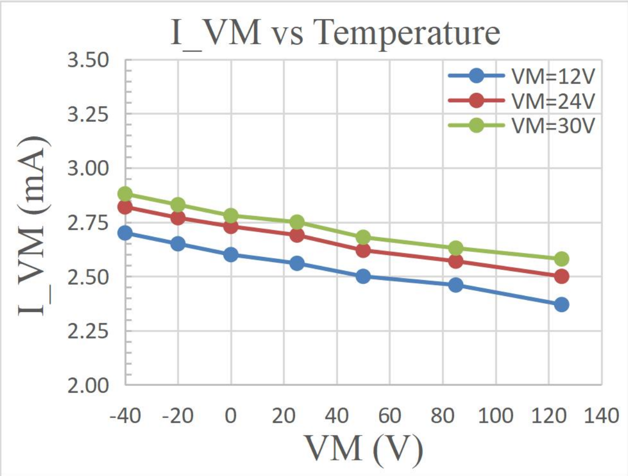
(T_A = -40 to +125℃ unless otherwise noted. Typical values are at T_A = +25℃, V_{VM} = 6.5 to 30V)

Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
Supply						
V_{VM}	VM Input Voltage		6.5	24	30	V
I_{VM}	VM Operation Supply Current	V_{VM} = 12V	-	2.5	6.0	mA
I_{SHDN}	VM Sleep Current	V_{VM} = 12V	-	-	10	μA
V_{UV}	VM Under Voltage Lockout	V_{IN} Rising	-	6.30	6.50	V
V_{UVLO}	Under Voltage Lockout Hysteresis		-	300		mV
t_{ON}	Turn-on Time	V_M>V_{UVLO} with IN1 or IN2 High	-	40	50	uS
Logic Input IN1 and IN2:						
V_{INL}	Input Logic Low Voltage Threshold	V_{EN} Falling	0	-	0.5	V
V_{INH}	Input Logic High Voltage Threshold	V_{EN} Rising	1.5	-	V_{IN}	V
$R_{IN1/2}$	Input Logic Pin Pull-down Resistor		-	350	-	kΩ
I_{IL}	Input Logic Low Current	V_{IN}=0V	-1.0	-	+1.0	uA
I_{IH}	Input Logic High Current	V_{IN}=3.3V	-	33	100	uA
f_{PWM}	Logic Input PWM Frequency		0	-	200	KHz
t_{PD}	Propagation Delay	INx to OUTx Change	-	0.7	1.0	uS
t_{SLEEP}	Time to Sleep	Inputs low to Sleep	-	1.0	1.5	mS
Motor Driver Output (OUT1 and OUT2)						
$R_{DS(ON)H}$	High Side Switch On-Resistance	VM=24V, I_{OUT}=1A, f_{PWM}=25KHz	-	200	-	mΩ
$R_{DS(ON)L}$	Low Side Switch On-Resistance		-	200	-	mΩ
t_{DEAD}	Output dead time		-	550	-	nS
I_{OCP}	Switch Current Limit		4.5	6.5	-	A
t_{OCP}	Over-current deglitch time		-	1.5	-	uS
t_{RETRY}	Over-current retry time		-	3.0	-	mS
V_{Diodes}	Body Diode Forward Voltage	I_{OUT}=1A	-	0.8	1.0	V
Current Regulation						
A_V	ISEN Gain	V_{REF}=2.5V	-	10.5	-	V/V
t_{OFF}	PWM Off-time		-	25	-	uS
t_{BLANK}	PWM Blanking Time		-	2	-	uS
Thermal Shutdown						
T_{TH}	Thermal Shutdown		150	170	-	℃
T_{HS}	Thermal Shutdown Hysteresis		-	40	-	℃

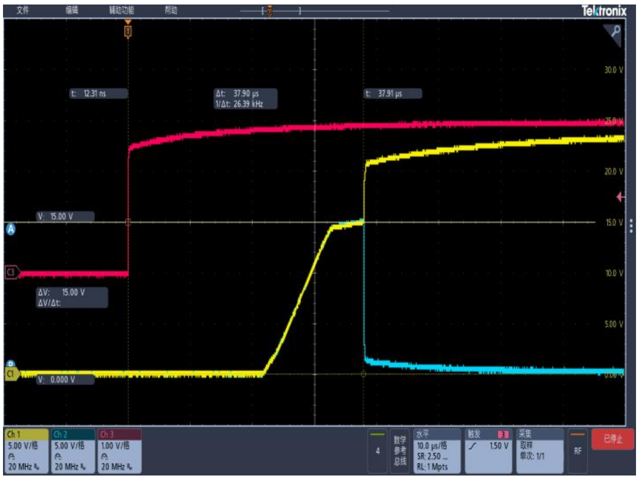
Typical Characteristics—AS5970

(T_A = -40 to +125℃ unless otherwise noted. Typical values are at T_A = +25℃, V_{VM} = 6.5 to 30V)

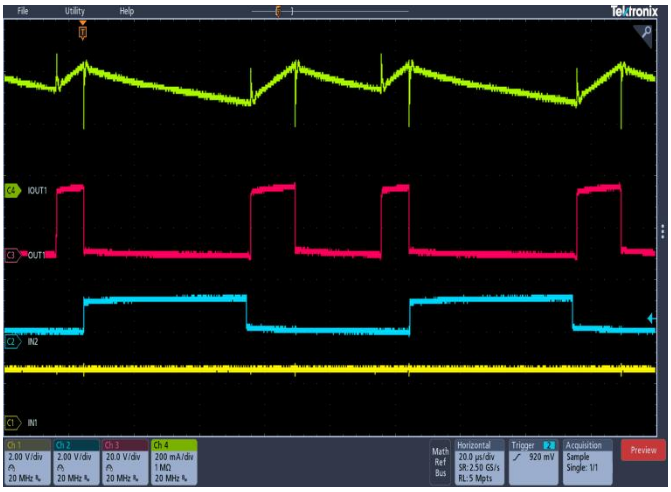
Quiescent Current vs Temperature



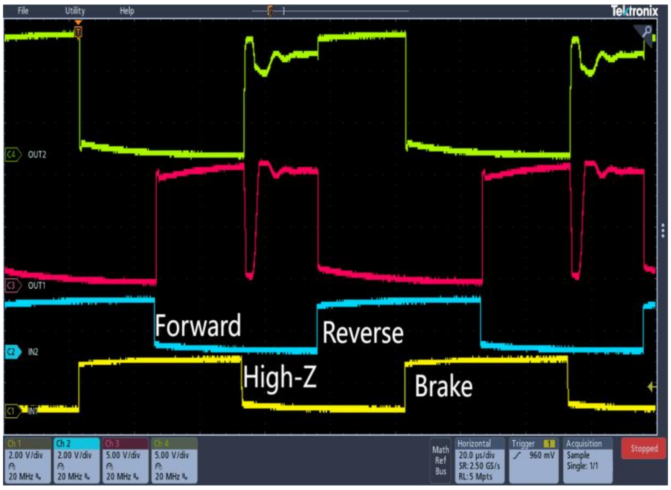
Power On Time



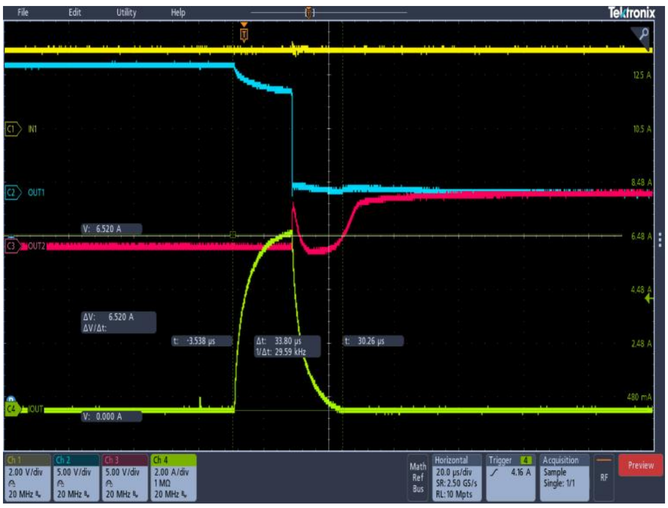
Current Ramp



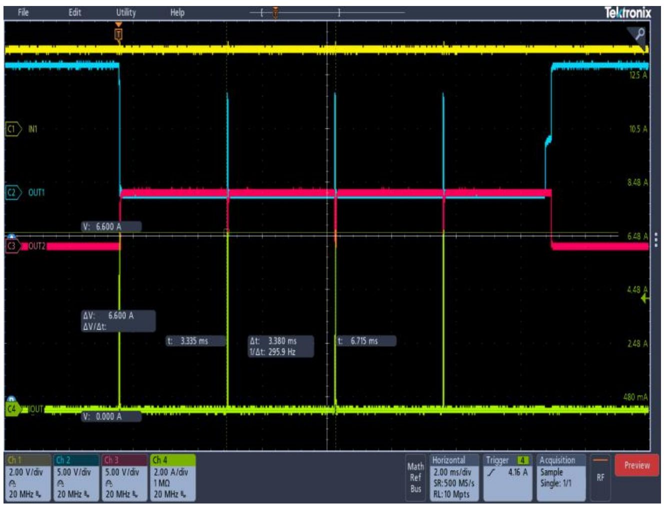
H-Bridge States



OCP Protection Waveform

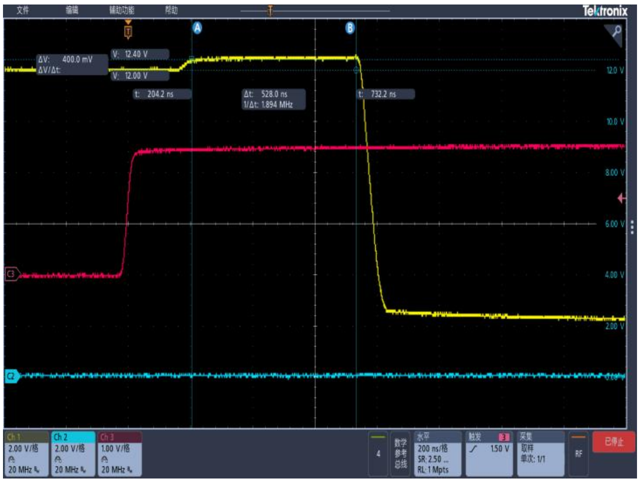
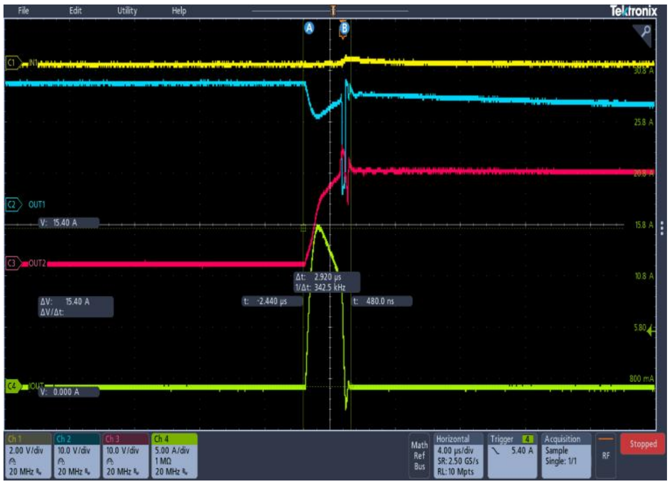


OCP Re-start Waveform



■ Typical Characteristics—AS5970

(T_A = -40 to +125℃ unless otherwise noted. Typical values are at T_A = +25℃, V_{VM} = 6.5 to 30V)

t_{PD}	**Output OUT1 Short to OUT2 Protection Waveform** (VM=24V, Vref and IN1 On)
	

Functional Description

The AS5970 device is a brushed-DC motor driver for printers, appliances, industrial equipment, and other small machines. Two logic inputs control the H-bridge driver, which consists of four N-channel MOSFETs that can control motors bidirectionally with up to 4.5A peak current. The inputs can be pulse width modulated (PWM) to control motor speed, using a choice of current-decay modes. Setting both inputs low enters a low-power sleep mode. Input terminals are provided for use in controlling the speed and direction of a DC motor with externally applied PWM control signals. Internal synchronous rectification control circuitry is provided to lower power dissipation during PWM operation.

The AS5970 device features integrated current regulation, based on the analog input VREF and the voltage on the ISEN pin, which is proportional to motor current through an external sense resistor. The ability to limit current to a known level can significantly reduce the system power requirements and bulk capacitance needed to maintain stable voltage, especially for motor startup and stall conditions.

The device is fully protected from faults and short circuits, including under-voltage (UVLO), over-current (OCP), over-temperature (TSD), and protection against shorted loads, or against output shorts to ground or supply. When the fault condition is removed, the device automatically resumes normal operation.

The AS5970 contain a thermal management system to protect the device; and a cycle-by-cycle current limit prevents damage to the AS5970. Built-in circuitry prevents excessive inrush current during start-up. The shutdown feature reduces quiescent current to less than 1.0μA.

Bridge Control

The AS5970 output consists of four N-channel MOSFETs that are designed to drive high current. These outputs are controlled by the two logic inputs IN1 and IN2 as listed in Table 1.

Table 1, H-Bridge Control

IN1	IN2	$10xV_S>V_{REF}$	OUT1	OUT2	Description
0	0	False	High-Z	High-Z	Coast, H-bridge disable to high-z (sleep entered after 1mS)
0	1	False	L	H	Reverse (Current OUT2 --> OUT1)
1	0	False	H	L	Forward (Current OUT1 --> OUT2)
0	1	True	H/L	L	Chop (Mixed decay), Reverse
1	0	True	L	H/L	Chop (Mixed decay), Forward
1	1	False	L	L	Brake, low side slow decay

The inputs can be set to static voltages for 100% duty cycle drive, or they can be pulse-width modulated (PWM) for variable motor speed. When using PWM, switching between driving and braking typically works best. For example, to drive a motor forward with 50% of the maximum RPM, IN1 = 1 and IN2 = 0 during the driving period, and IN1 = 1 and IN2 = 1 during the other period. Alternatively, the coast mode (IN1 = 0, IN2 = 0) for *fast current decay* is also available. The input pins can be powered before VM is applied.

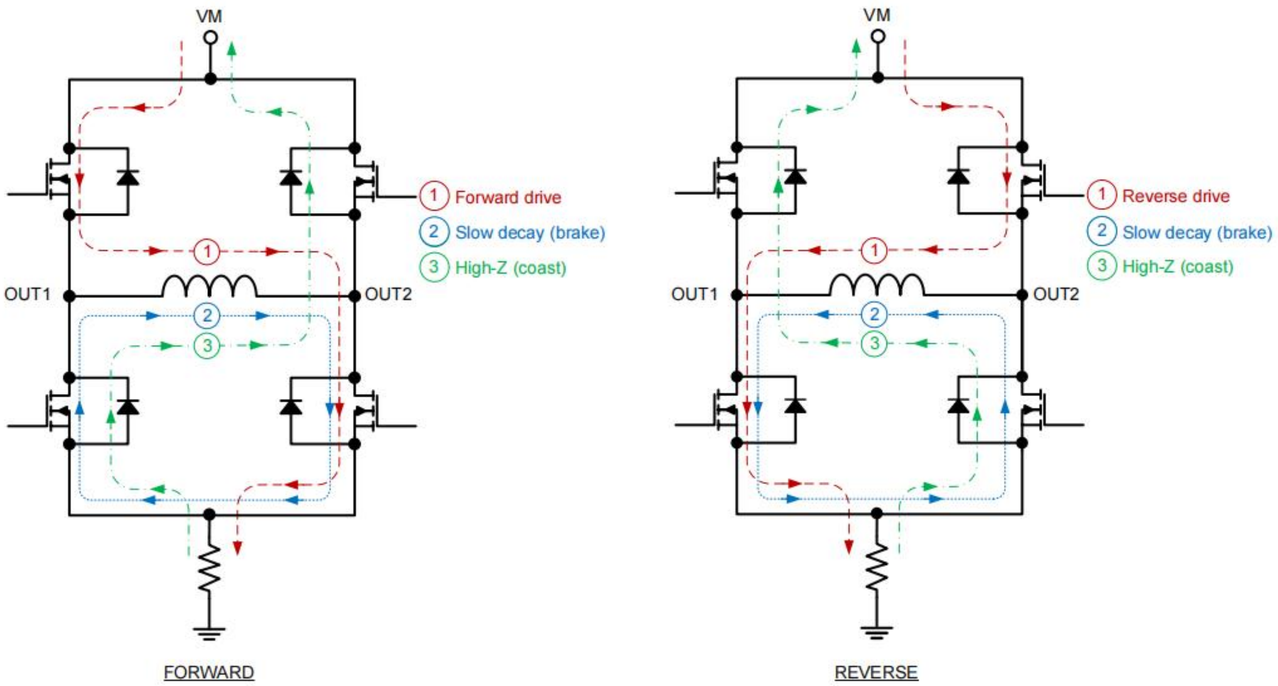


Figure 4, Block Diagram of AS5970

Sleep Mode:

When the IN1 and IN2 pins are both low for time t_{SLEEP} (typically 1 ms), the AS5970 device enters a low-power sleep mode, where the outputs remain High-Z and the device uses $I_{VMSLEEP}$ (μA) of current. If the device is powered up while both inputs are low, it immediately enters sleep mode. After the IN1 or IN2 pins are high for at least 5 μs, the device is operational 50μs (t_{ON}) later.

Current Regulation:

The AS5970 device limits the output current based on the analog input, VREF, and the resistance of an external sense resistor on the I_{SEN} pin according to Equation 1:

$$I_{TRIP}(A) = \frac{V_{REF}(V)}{A_V * R_{ISEN}(\Omega)} = \frac{V_{REF}(V)}{10 * R_{ISEN}(\Omega)}$$

For example, if V_{REF} = 3.3V and a R_{ISEN} = 0.15Ω, the AS5970 device limits motor current to 2.2A no matter how much load torque is applied. For guidelines on selecting a sense resistor, see the *Sense Resistor* section.

When I_{TRIP} is reached, the device enforces slow current decay by enabling both low-side FETs, and it does this for a time of t_{OFF} (typically 25μs).

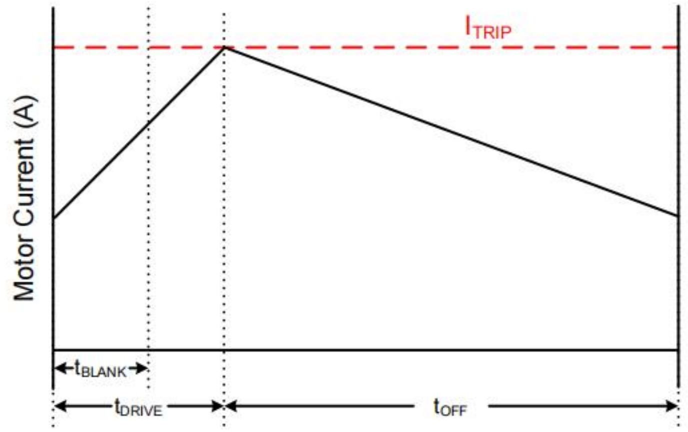


Figure 5, Current Regulation Time Periods of AS5970

After t_{OFF} elapses, the output is re-enabled according to the two inputs, INx. The drive time (t_{DRIVE}) until reaching another I_{TRIP} event heavily depends on the VM voltage, the back-EMF of the motor, and the inductance of the motor.

Dead Time:

When an output changes from driving high to driving low, or driving low to driving high, dead time is automatically inserted to prevent shoot-through. The t_{DEAD} time is the time in the middle when the output is High-Z. If the output pin is measured during t_{DEAD}, the voltage depends on the direction of current. If the current is leaving the pin, the voltage is a diode drop below ground. If the current is entering the pin, the voltage is a diode drop above VM. This diode is the body diode of the high-side or low-side FET.

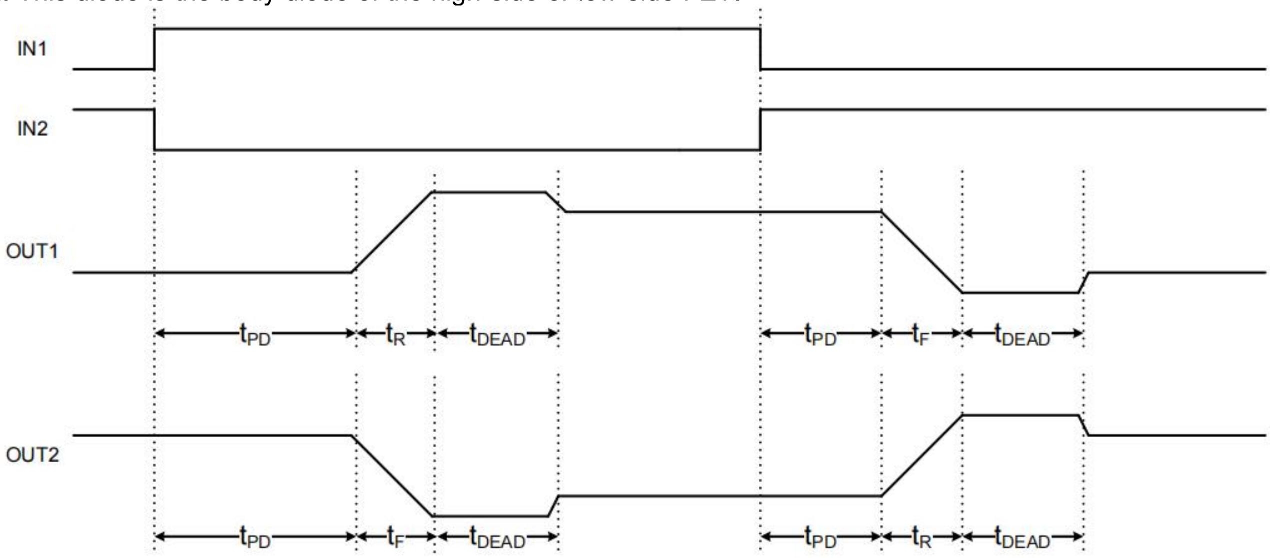


Figure 6, Propagation Delay Time

VM Under-voltage Lockout (UVLO):

If at any time the voltage on the VM pin falls below the under-voltage lockout threshold voltage, all FETs in the H-bridge will be disabled. Operation resumes when VM rises above the UVLO threshold.

Over-current Protection (OCP):

If the output current exceeds the OCP threshold, I_{OCP}, for longer than t_{OCP}, all FETs in the H-bridge are disabled for a duration of t_{RETRY}. After that, the H-bridge is re-enabled according to the state of the INx pins. If the over-current fault is still present, the cycle repeats; otherwise normal device operation resumes. The device is protected from short circuits, including protection against shorted loads, or against output shorts to ground or supply. When the fault condition is removed, the device automatically resumes normal operation.

Thermal Shutdown (TSD):

If the die temperature exceeds safe limits, all FETs in the H-bridge are disabled. After the die temperature has fallen to a safe level, operation automatically resumes.

Table 2, Protection Functionality

Fault	Condition	H-bridge Becomes	Recovery
VM Undervoltage Lockout (UVLO)	VM < V_{UVLO}	Disabled	VM > V_{UVLO}
Overcurrent Protection (OCP)	$I_{OUT} > I_{OCP}$	Disabled	t_{RETRY}
Thermal Shutdown (TSD)	$T_J > 150$℃	Disabled	$T_J > T_{SD} - T_{HYS}$

PWM With Current Regulation:

This scheme uses all of the capabilities of the device. The I_{TRIP} current is set above the normal operating current, and high enough to achieve an adequate spin-up time, but low enough to constrain current to a desired level. Motor speed is controlled by the duty cycle of one of the inputs, while the other input is static. Brake or slow decay is typically used during the off-time.

PWM Without Current Regulation:

If current regulation is not required, the I_{SEN} pin should be directly connected to the PCB ground plane. The V_{REF} voltage must still be 0.3 to 5V, and larger voltages provide greater noise margin. This mode provides the highest-possible peak current which is up to 4.5A for a few hundred milliseconds (depending on PCB characteristics and the ambient temperature). If current exceeds 4.5A, the device might reach over-current protection (OCP) or over-temperature shutdown (TSD). If that happens, the device disables and protects itself for about 3 ms (t_{RETRY}) and then resumes normal operation.

Static Inputs With Current Regulation:

The IN1 and IN2 pins can be set high and low for 100% duty cycle drive, and I_{TRIP} can be used to control the current of the motor, speed, and torque capability.

VM Control:

In some systems, varying VM as a means of changing motor speed is desirable. See the *Motor Voltage* section for more information.

Braking Control:

The braking function is implemented by driving the device in Slow Decay mode, which is done by applying a logic high to both inputs, after a bridge-enable Chop command (see PWM Control Truth Table). Because it is possible to drive current in both directions through the DMOS switches, this configuration effectively shorts-out the motor-generated BEMF, as long as the Chop command is asserted. The maximum current can be approximated by VBEMF / RL . Care should be taken to ensure that the maximum ratings of the device are not exceeded in worse case braking situations: high speed and high-inertia loads.

Application Information

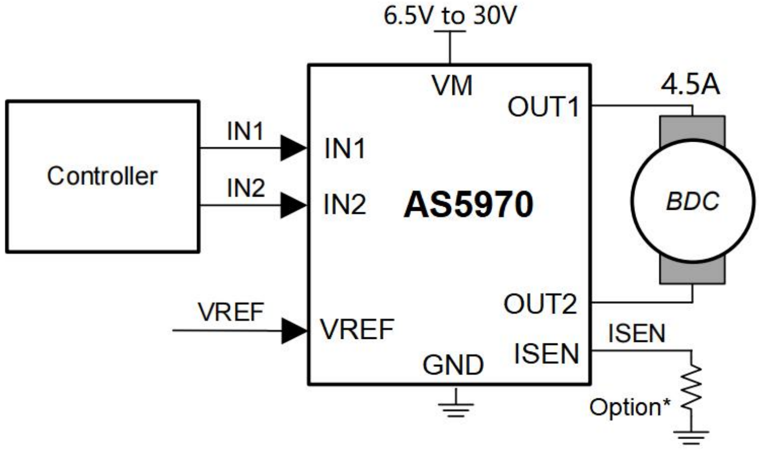


Figure 7, Typical Application Circuit of AS5970

Design Requirements:

Table 3, Design Parameters

Design Parameter	Reference	Example Value
Motor Voltage	V_M	24V
Motor RMS Current	I_{RMS}	0.8V
Motor Startup Current	I_{START}	2.0A
Motor Current Trip Point	I_{TRIP}	2.2A
VREF Voltage	VREF	3.3V
Sense Resistance	R_{ISEN}	0.15Ω
PWM Frequency	f_{PWM}	5KHz

Motor Voltage:

The motor voltage to use depends on the ratings of the motor selected and the desired RPM. A higher voltage spins a brushed DC motor faster with the same PWM duty cycle applied to the power FETs. A higher voltage also increases the rate of current change through the inductive motor windings.

Drive Current:

The current path is through the high-side sourcing DMOS power driver, motor winding, and low-side sinking DMOS power driver. Power dissipation losses in one source and sink DMOS power driver are shown in Equation 2.

$$P_D = I^2 (R_{DS(ON)Source} + R_{DS(ON)Sink})$$

The AS5970 device has been measured to be capable of 2-A RMS current at 25°C on standard FR-4 PCBs. The maximum RMS current varies based on the PCB design, ambient temperature, and PWM frequency. Typically, switching the inputs at 200kHz compared to 20kHz causes 20% more power loss in heat.

Sense Resistor:

For optimal performance, the sense resistor must have the following characteristics:

- Surface-mount
- Low inductance
- Rated for high enough power
- Placed closely to the motor driver

The power dissipated by the sense resistor equals $I_{RMS}^2 \times R$. For example, if peak motor current is 3A, RMS motor current is 1.5A, and a 0.2Ω sense resistor is used, the resistor dissipates 1.5 $A^2 \times 0.2\Omega = 0.45W$. The power quickly increases with higher current levels.

Resistors typically have a rated power within some ambient temperature range, along with a derated power curve for high ambient temperatures. When a PCB is shared with other components generating heat, the system designer should add margin. Measuring the actual sense resistor temperature in a final system is always best.

Because power resistors are larger and more expensive than standard resistors, using multiple standard resistors in parallel, between the sense node and ground, is common and distributes the current and heat dissipation.

Bulk Capacitance:

Having appropriate local bulk capacitance is an important factor in motor drive system design. Having more bulk capacitance is generally beneficial, while the disadvantages are increased cost and physical size.

The amount of local capacitance needed depends on a variety of factors, including:

- The highest current required by the motor system
- The capacitance of the power supply and ability to source current
- The amount of parasitic inductance between the power supply and motor system
- The acceptable voltage ripple
- The type of motor used (brushed DC, brushless DC, stepper)
- The motor braking method

The inductance between the power supply and motor drive system limits how the rate current can change from the power supply. If the local bulk capacitance is too small, the system responds to excessive current demands or dumps from the motor with a change in voltage. When adequate bulk capacitance is used, the motor voltage remains stable and high current can be quickly supplied.

The data sheet generally provides a recommended value, but system-level testing is required to determine the appropriate sized bulk capacitor.

The voltage rating for bulk capacitors should be higher than the operating voltage, to provide margin for cases when the motor transfers energy to the supply.

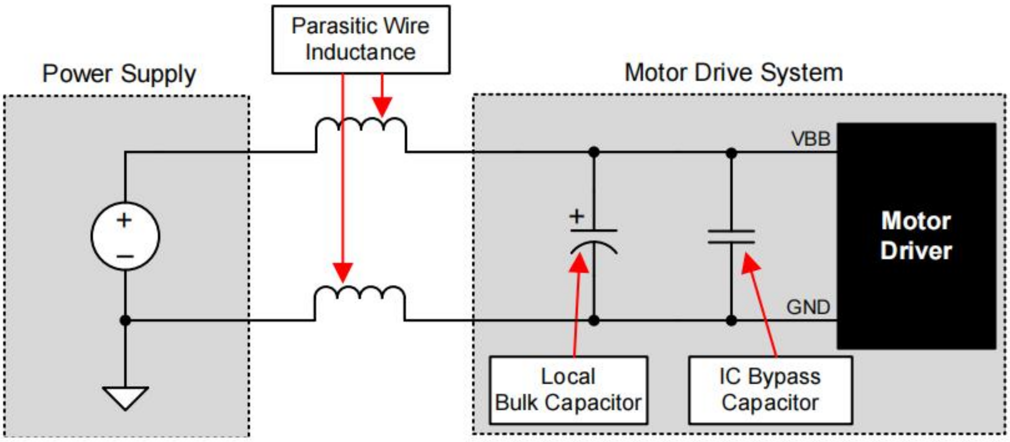


Figure 8, Example Setup of Motor Drive System With External Power Supply

Layout Considerations

The bulk capacitor should be placed to minimize the distance of the high-current path through the motor driver device. The connecting metal trace widths should be as wide as possible, and numerous vias should be used when connecting PCB layers. These practices minimize inductance and allow the bulk capacitor to deliver high current.

Small-value capacitors should be ceramic, and placed closely to device pins. The high-current device outputs should use wide metal traces.

The device thermal pad should be soldered to the PCB top-layer ground plane. Multiple vias should be used to connect to a large bottom-layer ground plane. The use of large metal planes and multiple vias help dissipate the $I^2 \times R_{DS(on)}$ heat that is generated in the device.

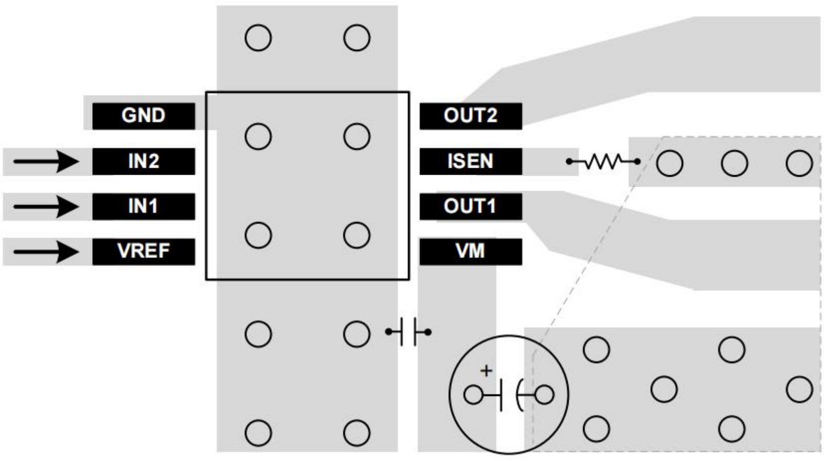


Figure 9, Layout Recommendation

Heat-sinking:

The PowerPAD package uses an exposed pad to remove heat from the device. For proper operation, this pad must be thermally connected to copper on the PCB to dissipate heat. On a multi-layer PCB with a ground plane, this connection can be accomplished by adding a number of vias to connect the thermal pad to the ground plane.

On PCBs without internal planes, a copper area can be added on either side of the PCB to dissipate heat. If the copper area is on the opposite side of the PCB from the device, thermal vias are used to transfer the heat between top and bottom layers.

Thermal Considerations

The AS5970 device has thermal shutdown (TSD) as described in the *Thermal Shutdown (TSD)* section. If the die temperature exceeds approximately 170°C, the device is disabled until the temperature drops below the temperature hysteresis level. Any tendency of the device to enter TSD is an indication of either excessive power dissipation, insufficient heat-sinking, or too high of an ambient temperature.

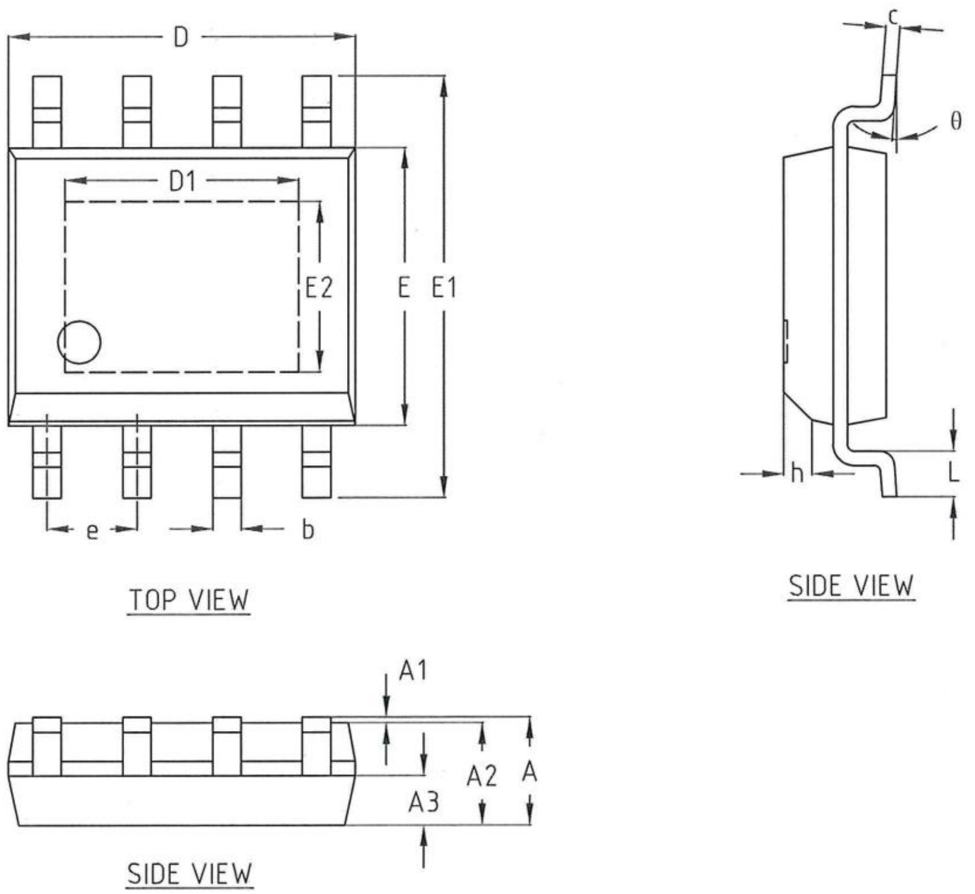
The maximum IC junction temperature should be restricted to 125°C under normal operating conditions. This restriction limits the power dissipation of the AS5970. Calculate the maximum allowable dissipation, $P_{D(max)}$, and keep the actual dissipation less than or equal to $P_{D(max)}$. The maximum-power-dissipation limit is determined using following equation:

$$P_{D(MAX)} = \frac{150^{\circ}\mathrm{C} - T_A}{R_{\theta JA}}$$

Where, T_A is the maximum ambient temperature for the application. $R_{\theta JA}$ is the thermal resistance junction-to-ambient given in Power Dissipation Table.

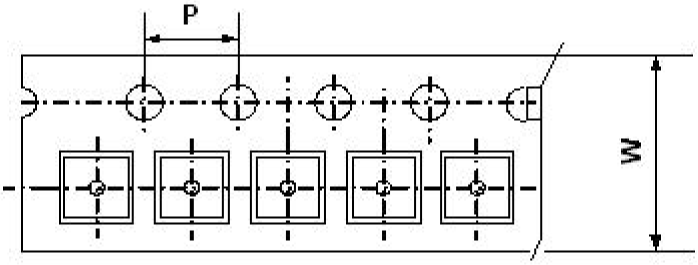
■ Package Information

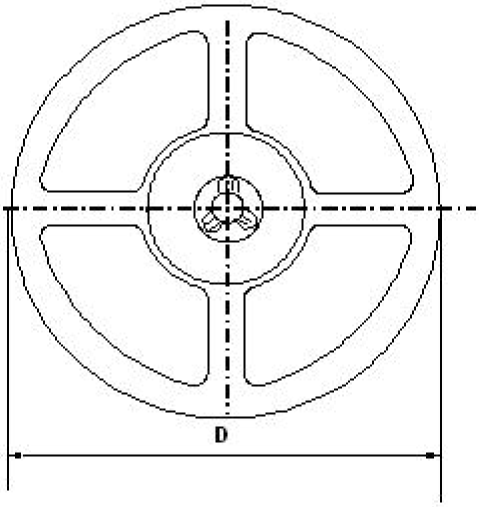
SOP-8L-EP:



Symbol	Dimensions In Millimeters			Dimensions In Inches		
	Min.	**Nom.**	**Max.**	**Min.**	**Nom.**	**Max.**
A	1.300	-	1.700	0.051	-	0.067
A1	-	-	0.250	-	-	0.010
A2	1.350	1.450	1.550	0.053	0.057	0.061
A3	0.650	0.700	0.750	0.026	0.028	0.030
b	0.330	0.420	0.510	0.013	0.017	0.020
c	0.170	0.210	0.250	0.006	0.008	0.010
D	4.700	4.900	5.100	0.185	0.192	0.200
D1	3.050	3.230	3.400	0.120	0.127	0.134
E	3.800	3.900	4.000	0.150	0.154	0.157
E1	5.800	6.000	6.200	0.228	0.236	0.244
E2	2.160	2.330	2.500	0.085	0.092	0.098
e	1.270 (BSC)			0.050 (BSC)		
h	0.300	-	0.500	0.012	-	0.020
L	0.400	0.835	1.270	0.016	0.033	0.050
θ	0°	-	8°	0°	-	8°

Packing Information





Package Type	Carrier Width(W)	Pitch(P)	Reel Size(D)	Packing Minimum
SOP-8L-EP	12.0±0.1 mm	4.0±0.1 mm	330±1 mm	4000pcs

Note: Carrier Tape Dimension, Reel Size and Packing Minimum