Mechatronics & Embedded Microcomputer Control
ME E4058 Fall 2013

Case Study # 6: DC Motor Control

Motors are often used mechatronic systems to precisely position a load or to move a load at a precise velocity. Mechatronic systems which involve the motion of mechanical components are often called motion control systems. Stepper motors, the topic of the previous case study, are often used for controlling the angular displacement of a load, or the linear displacement via a mechanism. DC (Direct Current) motors are more often used for precision velocity control. Since both motors are capable of applying torque to achieve rotational motion of a load, either can be used for position or velocity applications. The major difference between stepper motors and DC motors is that while the former can be considered a digital device, the latter is clearly an analog system. This case study involves DC motor control and the application of a variety of sensors.

Background Information – DC Motors

Modern multidisciplinary products often depend on a feedback control system for their optimum functioning. Today, control systems are an integral part of the overall system rather than afterthought "add-ons" and thus are considered from the very beginning of the design process. Both the digital control (solenoid) and the stepper motor case studies involved some form of feedback. The solenoid system included a reflective optical sensor which indicated whether or not the solenoid completed its motion. The stepper motor system included four optical interrupters which indicated when the two motors completed 90^0 of motions. The DC motor system of this case study contains numerous feedback sensors. These sensors will do much more than indicate successful completion of the required operation. Continuous feedback control of the entire time response will be required to successfully complete the requirements of this case study.

In order to control a dynamic motion control system, one must be able to influence the response of the system. The device that does this is the *actuator*. In this course, you will have experience controlling a solenoid, stepper motors and a DC motor. Any one or combination of these can be used in a motion control system. Before a specific actuator is selected, one must consider which variables can be influenced. Another important consideration is which variables can be physically measured, both for control purposes and for disturbance detection. The device that does this is the *sensor*. You will also have experience working with numerous sensors.

Some general considerations in *actuator selection* are:

- Underlying Technology: electro-magnetic, magnetic, electric, hydraulic, pneumatic, thermal, other

- Functional Performance: maximum force or torque possible, extent of the linear range, maximum speed possible, accuracy, repeatability, power, efficiency

- Physical properties: weight, size, strength

- Quality Factors: reliability, durability, maintainability, similarity to actuators used in existing products

- Cost: expense, availability, facilities for testing and maintenance

Some considerations in *sensor selection* are:

- Technology: electric or magnetic, mechanical, electromechanical, electro-optical, piezoelectric, thermal

- Functional Performance: linearity, bias, accuracy, repeatability, precision, response speed, dynamic range, noise performance

- Physical properties: weight, size, strength

- Quality Factors: reliability, durability, maintainability, similarity to sensors used in existing products

- Cost: expense, availability, facilities for testing and maintenance

The actuator is the device that drives a dynamic system. Proper selection of an actuator for a particular application is of utmost importance in the design of a dynamic system. Many actuators used in applications are continuous-drive actuators, for example, direct-current (DC) motors, alternating-current (AC) motors, hydraulic and pneumatic actuators. Stepper motors are incremental-drive actuators and it is reasonable to treat them as digital actuators. Unlike continuous-drive actuators, stepper motors are driven in fixed angular steps (increments). Each step of rotation (a predetermined, fixed increment of displacement) is the response of the motor rotor to an input pulse (or a digital command). In this manner, the step-wise rotation of the rotor can be synchronized with pulses in a command-pulse train, assuming, of course, that no steps are missed. The motor responds faithfully to the input signal (pulse sequence) in an open-loop manner. Solenoids are on/off devices. They are typically used in motion control systems where only two positions are required but more complicated arrangements of solenoids can achieve multiple positions. Like a conventional continuous-drive motor, the stepper motor and solenoid are electromagnetic actuators, in that they convert electromagnetic energy into mechanical energy to perform mechanical work.

In the early days of control, servo-actuators (actuators that automatically use output signals from a process with feedback to correct the operation of the process) were exclusively continuous-drive devices. Since the control signals in this early generation of control systems generally were not discrete pulses, the use of pulse-driven digital actuators was not feasible in those systems. DC servo-motors and servo-valve-driven hydraulic and pneumatic actuators were the most widely used types of actuators in industrial control systems, particularly because digital microcomputers were not invented. Furthermore, the control of AC actuators was a difficult task at that time. Today, AC motors are widely used as servo-motors, employing modern methods of phase-voltage control (vector control) and variable frequency control through microelectronic drive systems and using field-feedback compensation with digital signal processing (DSP) chips. It is interesting to note that actuator control using pulse signals is no longer limited to digital actuators. Microcomputer generated pulse-width-modulated (PWM) signals are increasingly being used to drive continuous actuators such as DC servo-motors, hydraulic and pneumatic servos, and AC motors. It is also interesting to note that electronic-switching commutation in brushless DC motors is quite similar to the method of phase switching used to drive stepper motors.

Although the cost of sensors and transducers is a deciding factor in low-power applications and in situations where precision, accuracy, and resolution are of primary importance, the cost of actuators can become crucial in moderate-to-high-power control applications. It follows that the proper design and selection of actuators can have a significant economical impact in many applications of industrial control. Since the cost of microcomputers and other electronic components is often insignificant, actuator cost can dominate the cost of motion control systems.

Measurement of system outputs is essential for feedback control, and is also useful for performance evaluation of a process. Input measurements are needed in feedforward control. It is evident, therefore, that the measurement subsystem is an important part of a control system. The measurement subsystem in a control system contains sensors and transducers that detect measurands and convert them into acceptable electronic signals (typically voltages). These signals are then appropriately modified using signal-conditioning hardware such as filters, amplifiers, demodulators, etc. The signals are then input to a microcomputer using analog-to-digital (A/D) converters. Impedance matching might be necessary to connect sensors and transducers to signal-conditioning hardware.

The accuracy, precision and repeatability of sensors, transducers, and their associated signal-conditioning devices is important in control system applications for two main reasons:

1. The measurement system in a feedback control system is situated in the feedback path of the control system. Measurements are used to compensate for the poor performance of the open-loop system, but any errors in the measurements themselves will enter directly into the system response and cannot be corrected if they are unknown.

2. It can be shown that sensitivity of a control system to parameter changes in the measurement system is direct. This sensitivity cannot be reduced by increasing the loop gain, unlike in the case of sensitivity to the open-loop components. Accordingly, the design strategy for closed-loop (feedback) control is to make the measurements very accurate and to employ a suitable controller to reduce all other types of errors.

The difference between accuracy and precision of sensors is illustrated in Figure 1.

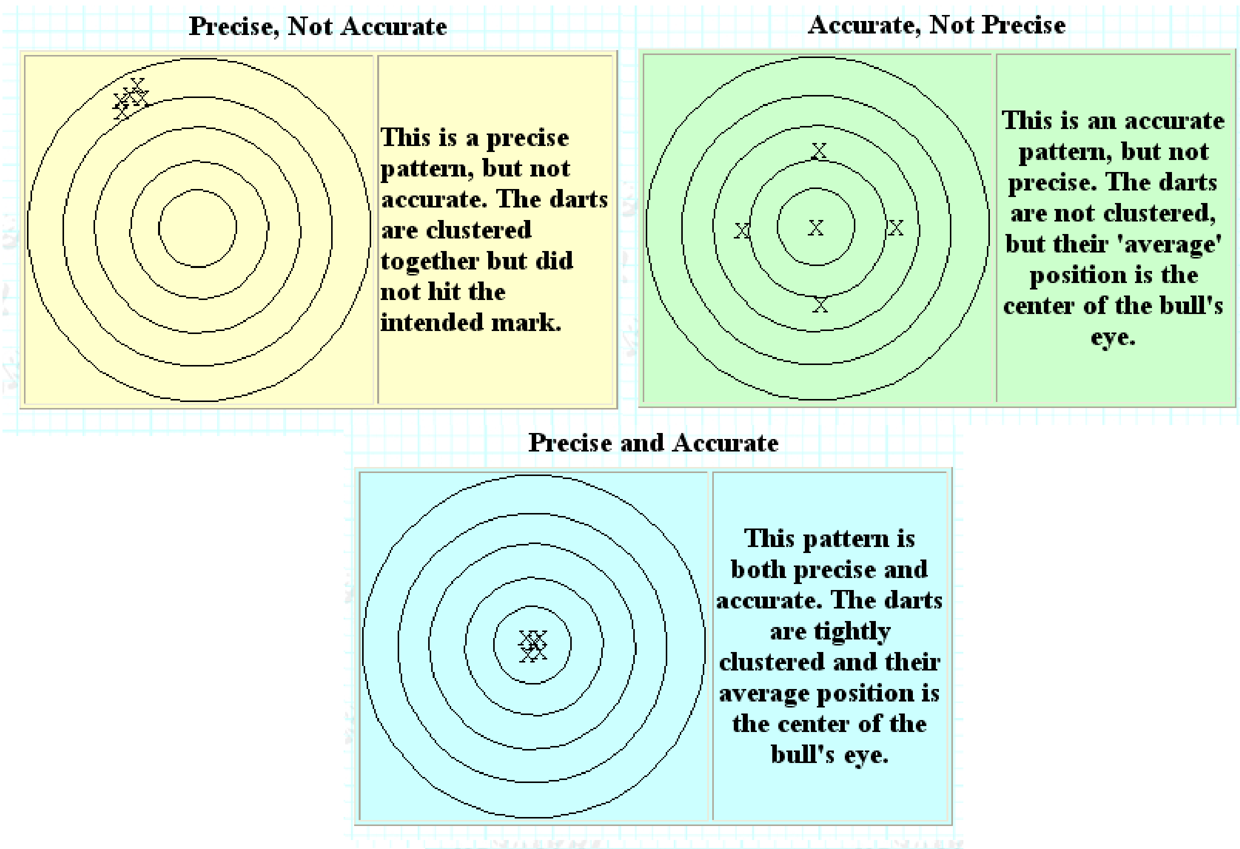


Figure1. Accuracy and Precision

Many sensor-transducer devices used in feedback control applications are analog components that generate continuous analog output signals. This is the case even in real-time direct digital control systems. When analog transducers are used in digital control applications, however, some type of A/D conversion is needed to obtain a digital representation of the measured signal. Prior to A/D conversion, some analog processing of the signals may be required. The analog signal is amplified and offset so that it adequately spans the range of the A/D converter for minimal code error. The signal is also filtered to reduce noise and avoid the effects of aliasing. The resulting digital signal is subsequently conditioned and processed using digital means. At the sensor, the physical signal being measured is indicated by the response of the sensor element. This is converted by the transducer into the transmitted (or measured) quantity. In this respect, the output of a measuring device can be interpreted as the response of the transducer. In control system applications, this output is typically (and preferably) an electrical signal (a voltage or current). This case study is a dynamic system investigation of a DC motor using an analog tachometer as a speed sensor. The tachometer is integral to the DC motor used in this case study (in fact, it is constructed of secondary windings on the same rotor poles as the motor windings). The DC motor system also contains an integral optical encoder which will be used for motor position measurement and an inductive sensor which will be used to indicate an index position of the shaft output. Optical encoders can also be used for speed measurement by measuring either the number of encoder pulses that occur in a measured period of time or by measuring the time between encoder pulses. The three sensors are discussed in more detail below. Figure 2 is a schematic of the DC motor system.

Case Study DC Motor System

A DC motor converts direct-current (DC) electrical energy into rotational mechanical energy. A major fraction of the torque generated by the rotor (armature) of the motor is available to drive an external load. DC motors are widely used in numerous control applications because of features such as high torque, speed controllability over a wide range, portability, well-behaved speed-torque characteristics, and adaptability to various types of control methods. DC motors are typically classified as either integral-horsepower motors ($\geq$ 1 hp) or fractional-horsepower motors (< 1 hp). Within the class of fractional-horsepower motors, a distinction can be made between those that generate the magnetic field with field windings (an electromagnet) and those that use permanent magnets. In heavy industrial DC motor products, the magnetic field is usually generated by field windings, while DC motors used in instruments, business machines or consumer products normally have a permanent magnet field.

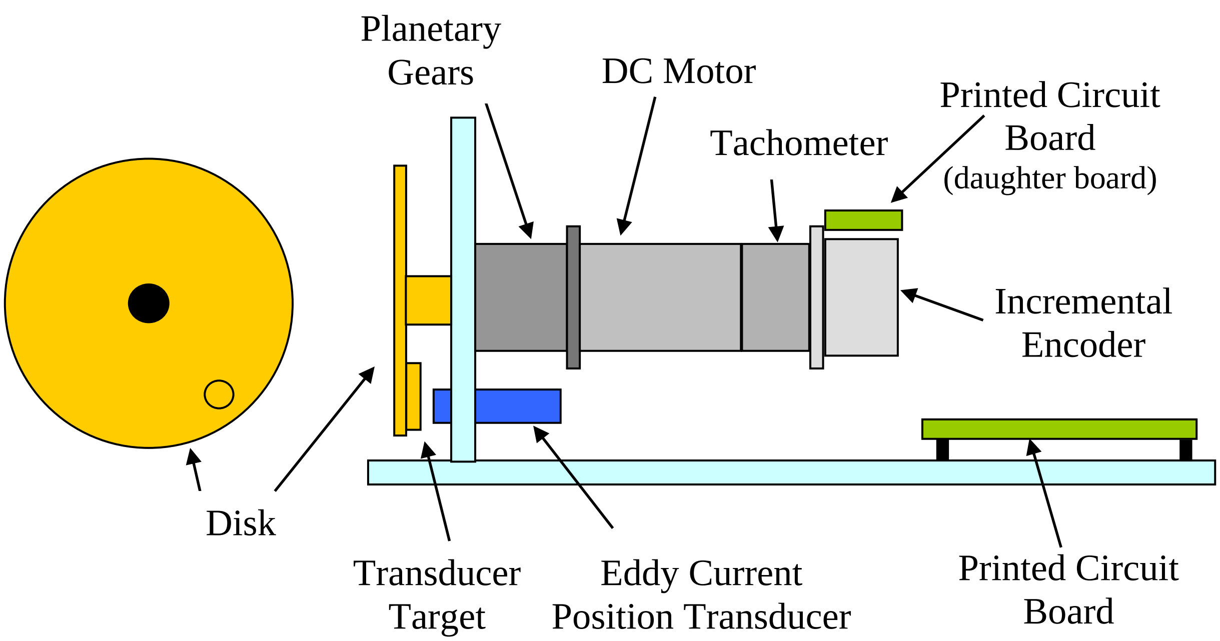


Figure 2. Schematic of the DC Motor System.

The physical system, shown in Figure 3 and typical of commonly used motors; is a fractional-horsepower, permanent-magnet, DC motor in which the commutation is performed with brushes. The load on the motor is a solid brass disk with a radius r = 2.25 inches (0.0572 m) and a thickness h = 0.125 inches (0.0032 m) connected to a solid brass hub with a radius r_h = 0.5 inches (0.0127 m) and a thickness h_h = 0.75 inches (0.019 m). In addition, a brass target for the eddy current transducer is attached to the disk. The target, a 1 inch (0.0254 m) disk 0.25 inches (0.0064 m) thick, is attached at a radius 1.75 inches (0.0445 m) from the axis of rotation. The moment of inertia of the disk and hub about the axis of rotation is calculated as $J_{disk} = ½\ m\ r^2$ (where mass $m = \rho\ \pi\ r^2\ h$ and density ρ = 8550 kg/m^2) which equals 4.67 e^{-4} kg – m^2. The moment of inertia of the target is calculated using the parallel axis theorem ($J_{target} = J_{cm} + m\ d^2$ where J_{cm} is the moment of inertia about the center of mass and d is the distance between the center of mass and the center of rotation of the disk). Thus, J_{target} is 6.16 e^{-5} kg – m^2 and J_{load} is 5.29 e^{-4} kg – m^2. Since the DC motor is connected to a 5:1 gear train, the moment of inertia of the motor rotor is reduced by a factor of 25. From the motor data sheet, the moment of inertia of the motor armature is greater than 1.0 e^{-6} kg – m^2. Thus, J_{total} , the total inertia that the motor must turn is 2.2 e^{-5} kg – m^2. The system is driven by a pulse-width-modulated (PWM) power amplifier connected to the microcomputer. Motor speed is measured using an analog tachometer. Motor angular displacement is measured with an incremental encoder. An exploded view of the DC motor components are shown in Figure 4.

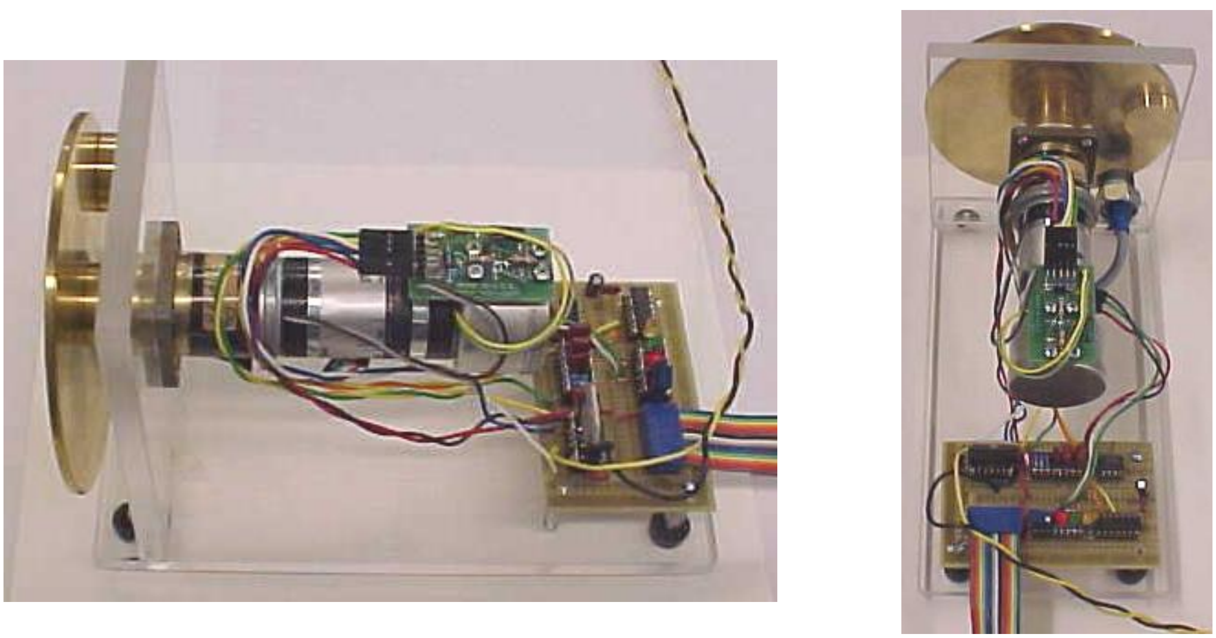


Figure 3. Physical System

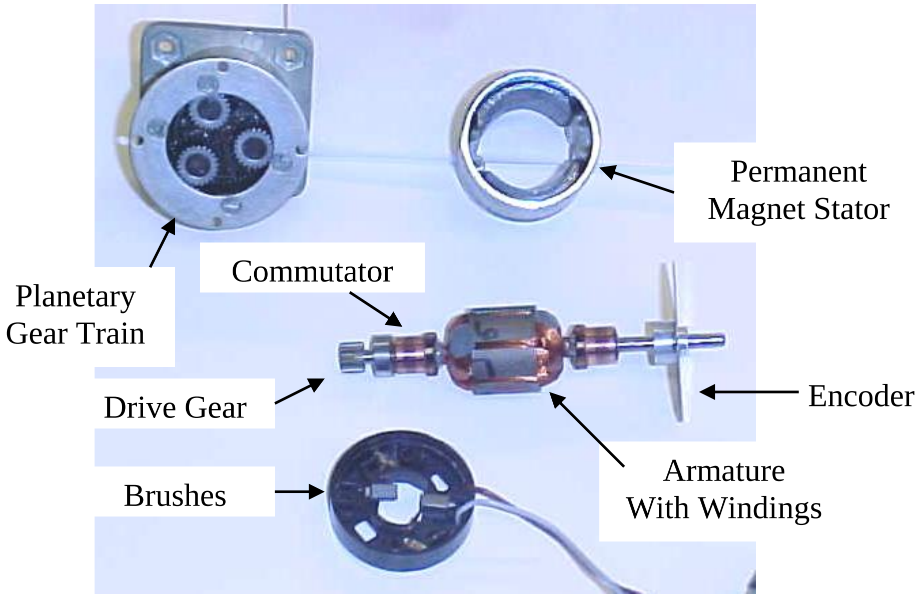


Figure 4. Motor Components

The DC motor/tachometer control system has a single input and a single output. The input is the voltage applied across the two motor terminals. The output is the voltage measured across the two tachometer terminals. The principle of operation of a DC motor is illustrated in Figure 5. Consider an electric conductor placed in a steady magnetic field (such as from a permanent magnet) and perpendicular to the direction of the magnetic field. The magnetic field flux density *B* is assumed constant. A DC current *i* is passed through the conductor and a circular magnetic flux around the conductor due to the current is produced. Consider a plane through the conductor parallel to the direction of flux of the magnet. On one side of this plane, the current flux and field flux are additive; on the opposite side, they oppose each other. The result is an imbalance magnetic force *F* on the conductor perpendicular to this plane. This force is given by:

$$\overrightarrow{F} = \oint \overrightarrow{i} \bullet \overrightarrow{d\ell} \times \overrightarrow{B}$$

$$F = B\,\ell\,i = K_\tau\,i$$

where

B = flux density of the original steady magnetic field
i = current through the conductor
ℓ = length of the conductor
K_τ = the torque constant

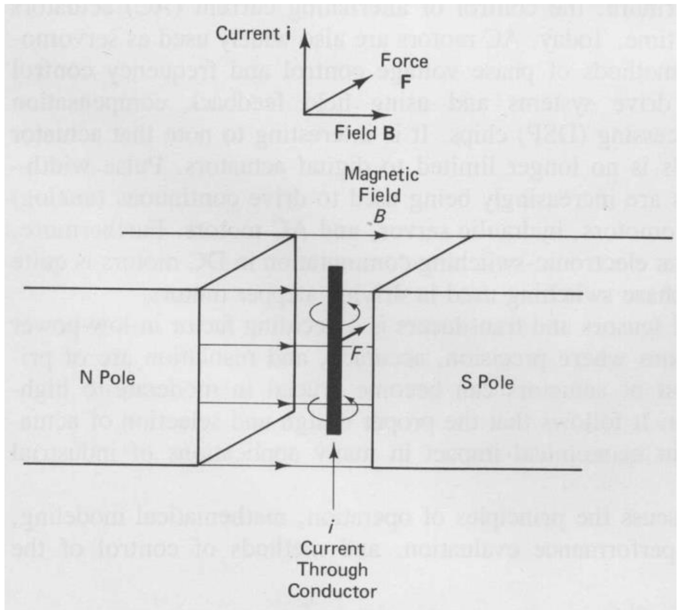


Figure 5. Operating Principle of a DC Motor

The active components of *B*, *i*, and *F* are mutually perpendicular and form a right-handed triad (thus the direction of the resulting force is determined from the right hand rule). If the conductor is free to move, the force will move it at some velocity *v* in the direction of the force. As a result of this motion in the magnetic field *B*, a voltage e_b is induced in the conductor. This voltage is known as the back electromotive force or back e.m.f. and is given by:

$$\overrightarrow{e_b} = \int \overrightarrow{v} \times \overrightarrow{B} \bullet \overrightarrow{d\ell}$$

$$e_b = B \ \ell \ v = K_v \ v$$

The flux due to the back e.m.f. will oppose the flux due to the original current through the conductor (Lenz's Law), thereby trying to stop the motion. This is the cause of electrical damping in motors. Saying this another way, the back e.m.f voltage tends to oppose the voltage which produced the original current. (Note that in SI units, K_i (in N / A) numerically equals K_v (in V / rad/sec).)

In somewhat more detail, Figure 6 shows the elements of a simple permanent magnet DC motor. It consists of a loop, usually of many turns of wire, called an armature which is immersed in the uniform magnetic field of a permanent magnet. The armature is connected to a commutator which is a divided slip ring. The purpose of the commutator is to reverse the current at the appropriate phase of rotation so that the torque on the armature always acts in the same direction. The current is supplied through a pair of springs or brushes which rest against the commutator.

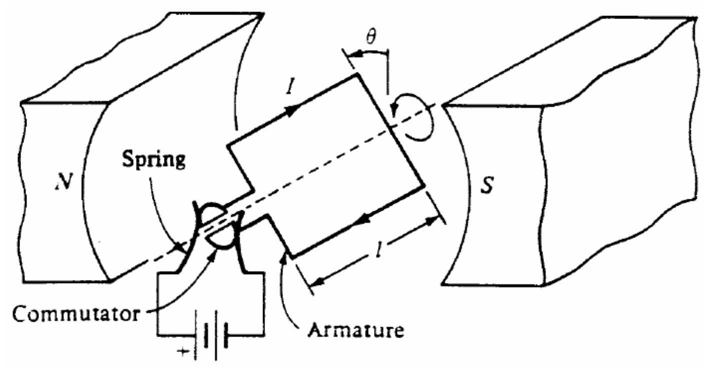


Figure 6. Elements of a Simple DC Motor

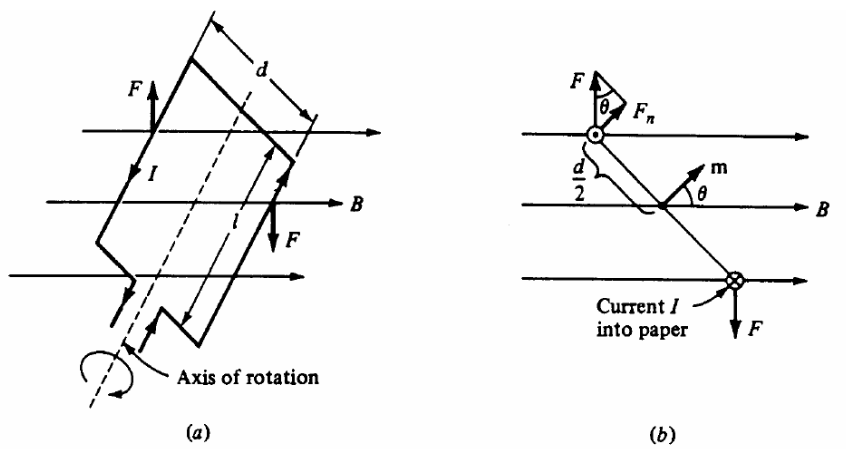


Figure 7. Rectangular Loop of Current-Carrying Wire in a Magnetic Field

Figure 7(a) shows a rectangular loop of wire of area A = d*l* carrying a current *i* (*I* in the figure) and Figure 7(b) shows a cross-section of the loop.

From Figure 7(b), the torque of the motor is given by:

$$T = 2\,F_N \left(\frac{d}{2}\right) N = \left(i\ B\ \ell\ \sin\theta\right) dN = i\,A\,B\,N\sin\theta = m\,B\,N\ \sin\theta$$

$$\overrightarrow{T} = N\left[\overrightarrow{m} \times \overrightarrow{B}\right]$$

where

N is the number of turns of the armature
A = dl is the area of the armature
$d/2$ is the moment arm of the force F_N on one side of a single turn of wire and
m = i A is the magnetic moment (a vector with a direction normal to the area A) (i.e., a vector with the direction determined by the right-hand rule applied to the direction of the current).

Schematic diagrams of a DC motor are shown in Figures 8 and 9.

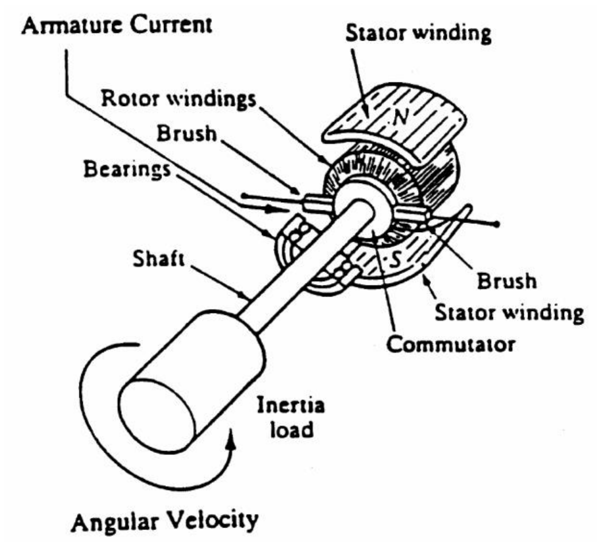


Figure 8. Schematic Diagram of a DC Motor

The motor used in this system is the TRW 4-5A6065 DC Motor with Tachometer.

The permanent-magnet DC velocity sensor (DC tachometer) is simply a motor operated as a generator (that is, it is mechanically rotated and a voltage is produced). Like the motor, it has a permanent magnet to generate a uniform and steady magnetic field. A relative motion between the magnetic field and an electrical conductor induces a voltage that is proportional to the speed at which the conductor crosses the magnetic field (the back e.m.f. effect). In a tachometer, no current is applied to the armature and the back e.m.f. (the voltage) is measured as an indication of motor speed. This is illustrated in Figure 10. Note that tachometers are passive transducers because the energy for the output signal is derived from the motion (measured signal) itself. The entire device is usually enclosed in a steel casing to isolate it from the motor magnetic fields. In the motor system for this case study, the tachometer windings are on the same rotor poles as the drive windings. Thus there is no isolation. This makes the tachometer signal very noisy.

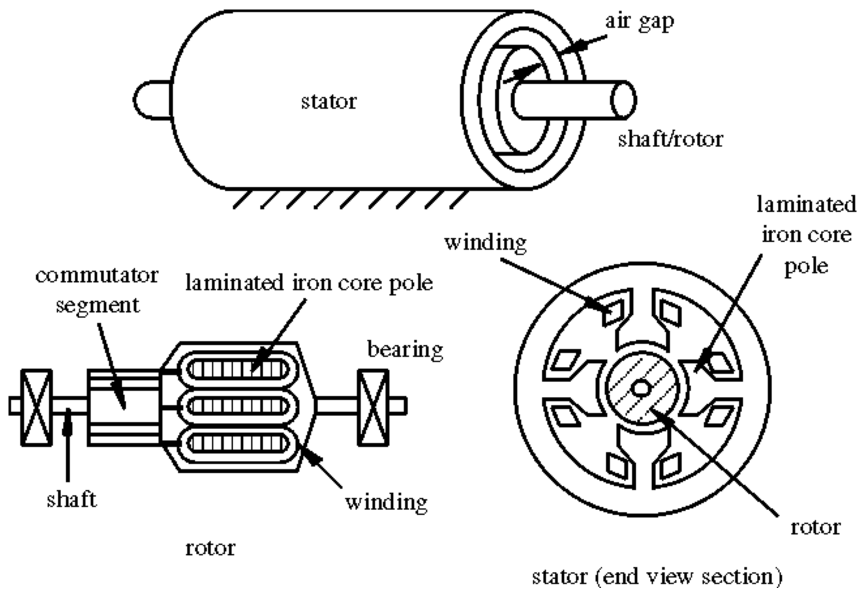


Figure 9. Schematic Diagram of a DC Motor Showing Construction

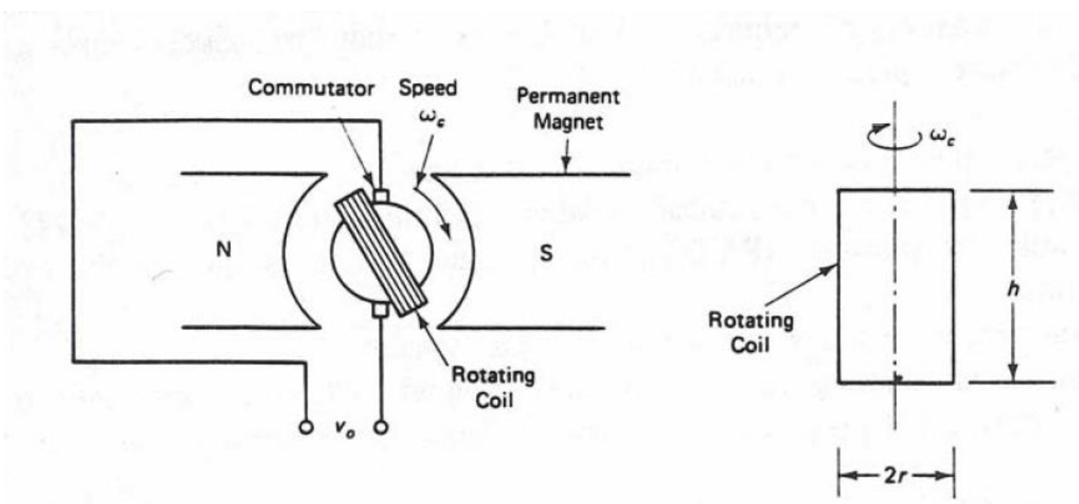
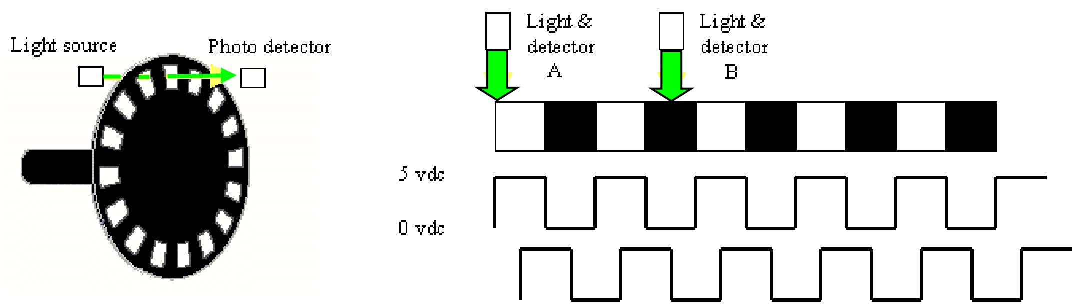


Figure 10. Permanent-Magnet Tachometer

In the DC motor used for this case study, there are circuit issues associated with the fact that the tachometer consists of a secondary set of windings on the same poles as the motor windings. The tachometer voltage is brought out on a second commutator and set of brushes and this arrangement produces a very compact motor design but, as stated, results in a very noisy tachometer signal. Switching signals in the motor coils are directly coupled into the tachometer coils by a transformer effect. The tachometer signal must be filtered to remove this noise. Since the motor speed measured by the tachometer has very low frequency components and the switching frequency of the motor coils is high, this filtering is possible. To use the tachometer signal, it must be low pass filtered (in an analog OpAmp circuit) and averaged in the microcomputer code.

In addition to the DC tachometer, a 20 count per revolution incremental encoder is attached to the motor. The encoder is illustrated in Figure 11a. It is the same as the sensor used for the stepper motor case study except that the disk has many more cutouts. Thus, multiple pulses are produced as the disk rotates. The encoder produces 20 pulses for each rotation of the motor and thus 100 pulses (after the 5:1 gear train) for every rotation of the output inertial load. The cutouts are equally spaced so each count represents 3.6^0 of rotation of the output load.



(a) operation (b) quadrature

Figure 11. Illustration of an Optical Encoder

Although not used for this case study, the encoder on the motor is a “quadrature” encoder. A quadrature encoder has one additional detector. Note that in Figure 11 (b), detector A is pointed at the start of a white sector (cutout) and detector B is pointed to the center of a black sector (solid disk). This offset provides the additional information. If the black/white strip is passing from right to left (moving left), the processor will get a pulse to count from detector A as it reaches the beginning of a white strip (in the position shown). At that time, detector B is looking at a black strip and is putting out a 0 logic signal. If the black/white strip is moving to the right instead, when the A detector encounters the beginning of a white strip, detector B will be in the middle of a white strip. Hence, the direction of motion when detector A gets a pulse can be determined by looking at the status of detector B. Note that in the motor quadrature encoder, the A and B detectors are not measuring the same light strip (that is, right next to each other), they are displaced around the wheel but have the same offset of one half the width of a black or white strip. Figure 12 illustrates a quadrature optical encoder using two patterns on the encoder disk.

The final sensor in the DC system is an eddy current sensor which measures the index position of the inertial load. Motion transducers, like the eddy current sensor, that employ the principle of electromagnetic induction are termed variable-inductance transducers. The sensor is basically a flat coil of wire. When you excite this coil and bring it close to a conducting surface, eddy currents are generated in the surface. These eddy currents change the impedance of the coil. A flux linkage in the conducting surface (defined as the magnetic flux density times the number of turns in the surface which is one) is produced by the eddy currents. The magnitude of the flux density depends on the permeability and resistivity of the surface and the diameter of the current path. This, in turn, generates a magnetic field that opposes the primary field from the flat coil. As the flat coil is brought closer to the conducting surface, greater eddy currents are generated and the impedance of the flat coil changes to a greater degree. Note that in these devices, the change in flux linkage is caused by mechanical motion, and mechanical-to-electrical energy transfer takes place under near-ideal conditions. The induced voltage, change in effective resistance or change in effective inductance may be used as a measure of displacement. The transducers are typically excited with a high frequency (on the order of 1 MHz) voltage and the current is measured (typically through a sense resistor). The motion is determined by processing (demodulating) the measured current. Like Hall effect devices, variable inductance transducers are used in dirty environments. Unlike Hall effect devices, no permanent magnet is needed since the transducer detects the presence of a conductor.

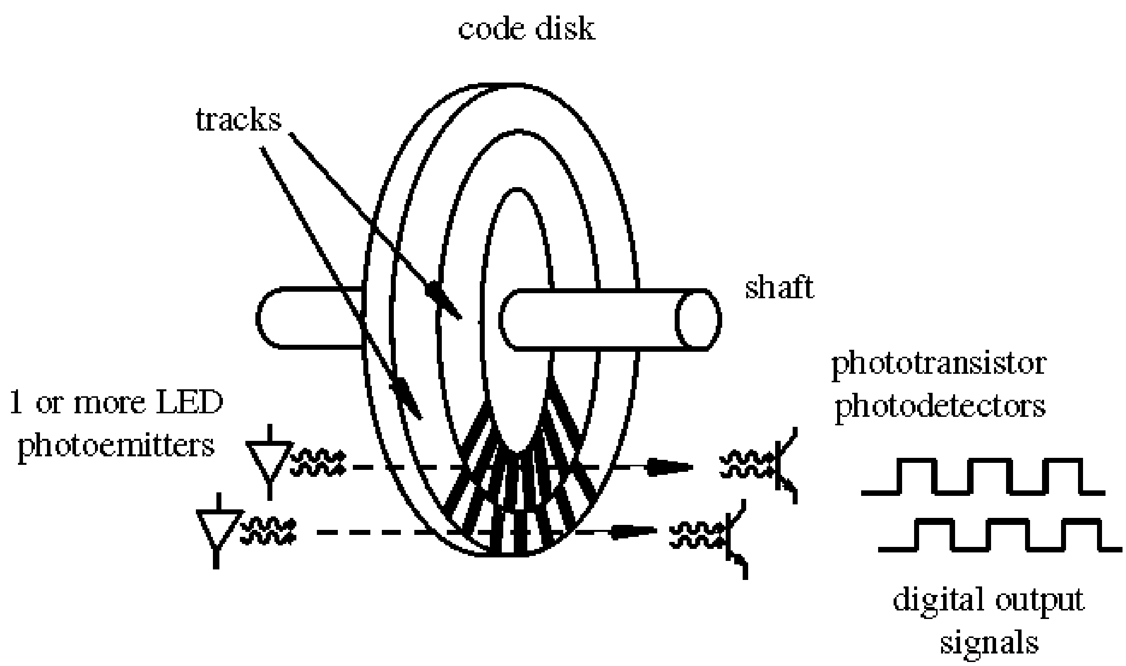


Figure 12. Illustration of a Quadrature Optical Encoder

Modeling a DC Motor System

A brushed permanent magnet DC motor is modeled in Figure 13. The wound armature is modeled as a series resistance and inductance. The current i_A from by the applied voltage V_i produces a torque proportional to the current (with K_τ as the proportionality constant). In addition, the rotational motion of the armature produces a back e.m.f voltage which opposes the applied voltage and is proportional to the rotational velocity (with K_v as the proportionality constant). The motor typically has both viscous friction (proportional to angular velocity) and Coulomb friction. Viscous friction comes from windage losses in the armature and drag in the bearings. For the motor system in this case study, the load inertia is reflected through the gear train. Additional frictional loss comes from the gears.

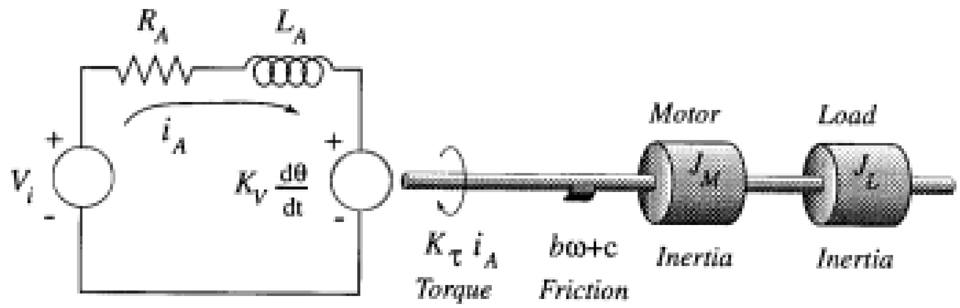


Figure 13. Model of DC Motor System

Brushed permanent magnet DC motors also have a very simple speed/torque curve shown in Figure 14. As the speed increases, the torque reduces proportionally giving the linear characteristic. The "stall torque" and "no-load speed" is often provided by motor manufacturers.

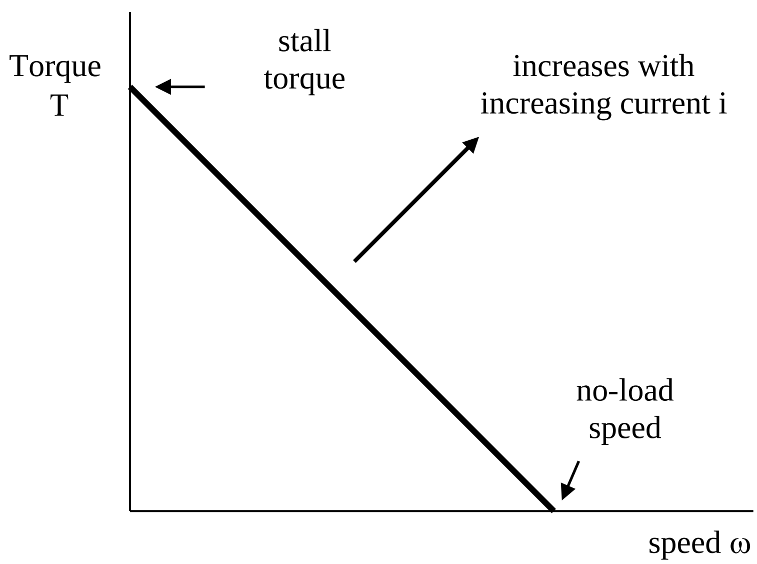


Figure 14. Speed / Torque Characteristic for a Brushed Permanent Magnet DC Motor

Pulse Width Modulation (PWM)

The DC motor system will be controlled with Pulse Width Modulation (PWM) using an electronic power bridge amp. PWM is a technique to control systems using a digital signal at a relatively high frequency to effectively produce an analog signal. This is illustrated in Figure 15. The PWM digital voltage signal is output at a fixed frequency and the width of the pulses are adjusted to produce more or less current in the motor. The high frequency voltage signal is filtered by the series resistance and inductance of the motor. The average current in the motor is high if the pulse width is long and the average current in the motor is low if the pulse width is short. The MicroChip microcomputer has an internal PWM module that makes outputting a PWM signal, simple.

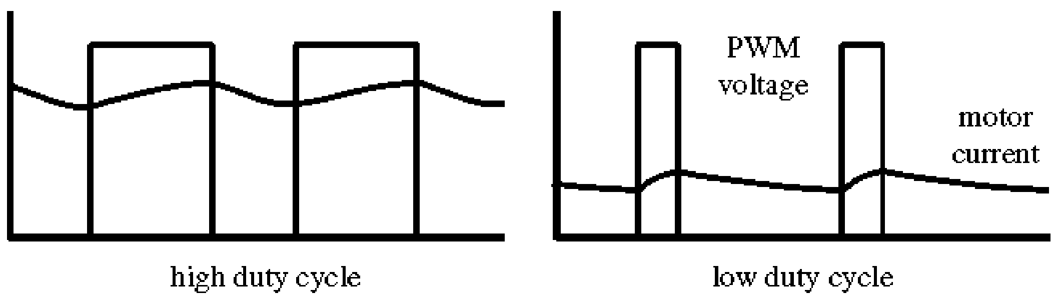


Figure 15. PWM Signals

An electronic bridge amplifier will be used to drive the motor. A bridge amp was also used for the bipolar stepper motor in the previous case study. The general configuration is shown in Figure 16.

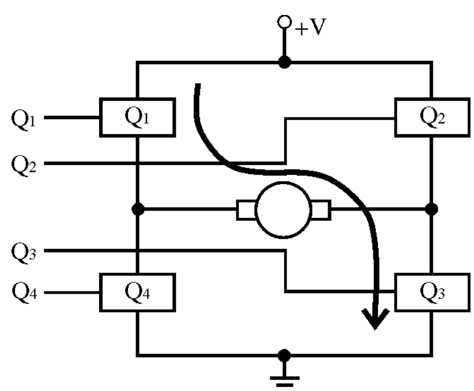


Figure 16. Bridge Amplifier for DC Motor

Laboratory Procedure

Circuit schematics for the DC motor case study are provided. No circuits have to be constructed and the motor circuit is connected to the microcomputer board with the upper ribbon cable connector. You will have to calibrate the tachometer signal for zero speed.

The microcomputer program will only have to perform one function: to control the DC motor system in a controlled velocity move. Several different control compensators will be programmed, however. Different compensators are chosen with the mode switch.

Consider the following design problem. A certain move of the DC motor system is transmitted from a control program running on a PC. The PC program does not control the motor, it simply communicates how far the motor must move. For example, the PC can be a user interface for a CNC (Computer Numerical Control) mill and the move is part of a cutting sequence. The microcomputer controls the motor. This means that the microcomputer must both plan the motion profile and control the velocity of the motor during the move. The motion profile that will be used is a trapezoidal function. This is the most typically profile used in industry. It means that the motor is first accelerated at a constant rate (so the motor velocity increases linearly with time and rotational distance). After a certain rotational distance is reached, the motor velocity is held constant for another (greater) distance. Finally, the motor is decelerated at a constant rate (so the motor velocity decreases linearly with time and rotational distance) until the motor stops.

In addition to determining the velocity profile, the microcomputer will also control the velocity of the motor using feedback. It will measure the analog velocity signal from the tachometer via the A/D converter. It will average these measurements to reduce noise. It will then compare (subtract) this velocity signal from the desired velocity determined in the profile. If the measured velocity is too slow, the motor will be accelerated. If the measured velocity is too fast, the motor will be decelerated. Several different control compensators will be used.

For simplicity, a proportional control compensator is often chosen. That is, once the velocity error is calculated, the signal to the motor (the voltage) will be proportional to the error. It is well known in feedback theory that proportional control results in a steady-state error. This means that a constant error is required to keep the motor running. If the error is zero, then the voltage applied to the motor, which is proportional to this error is also zero. When the mode switch is set to 0, the control compensator will be proportional.

To reduce the steady-state error problem which occurs with proportional control, one technique is to add a bias to the input signal. This bias is meant to be small enough so that it is sufficient to move the motor in spite of its friction. In this way, the proportional control is only required to correct for any velocity errors about this nominal condition of just running. When the mode switch is set to 1, the control compensator will be proportional with this added bias.

When the mode switch is set to 2, the control compensator will be proportional-derivative.

When the mode switch is set to 3, the control compensator will be proportional-integral-derivative.

If your program is working correctly, the velocity profile shown in Figure 17 should be produced (we will measure this with the oscilloscope). In addition, if you try to slow the motor by hand, the signal to the motor should increase. (The system should fight you if you try to slow it down.) We will also look at this with the oscilloscope. You will display the error on Port B of the microcomputer as the motor is running. You should expect that the error in mode 1 will be less than the error in mode 0. The error in mode 2 should have less oscillation than mode 0. The error in mode 3 should be much smaller than mode 0.

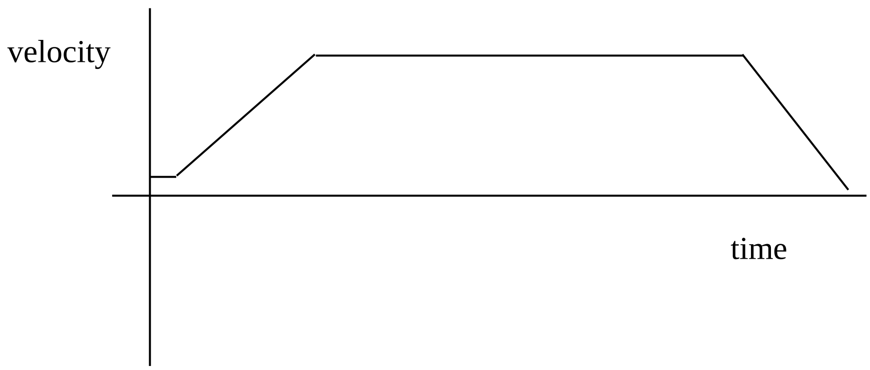


Figure 17. Desired Velocity Profile

Finally, the inductive position sensor on the load will be used to initialize the motor. To start, you will move the motor using some low constant speed until you see the sensor go high four times (indicating that the target has passed the sensor three times and is now in front of the sensor). The multiple passes are needed so that an adequate signal can be produced to overcome the substantial Coulomb friction at startup.

Summary of the Case Study Requirements

The program operation will be as follows:

1. Initialize the ports as required for the circuit. Digital inputs and outputs are connected to Port C. The analog tachometer is connected to pin 1 of Port A. In addition, you will use the black button connected to Port A pin 4 and the LEDs connected to Port B.

2. Initialize the A/D converter to measure the analog tachometer. The A/D converter should operate at the maximum possible frequency. The clock oscillator for the Microcomputer

Control Board is 20 MHz. You should read through the A/D converter section of the MicroChip PIC16F73 datasheet to determine how to set the frequency. The tachometer signal is connected to analog channel AN1. (Note: the time that you wait for the A/D to settle will also have to be adjusted from your previous case studies because of the faster clock.)

3. Set-up the PWM signal to produce a frequency of approximately 10 – 20 kHz using the system oscillator at the maximum PWM resolution. You should read through the PWM section of the MicroChip PIC16F73 datasheet to determine how to set up the PWM.

4. Adjust the potentiometer on the motor control board to calibrate the tachometer signal so that 2.5 V is produced on Port A pin 1 (there is also a testpoint on the control board) when the motor is not rotating. This will mean that the A/D converter in the microcomputer will read 128 (80 hex) when the motor is not rotating. A negative (counterclockwise) rotation will produce a reading less than 128; a positive (clockwise) rotation will produce a reading greater than 128.

5. Rotate the motor with a proportional control closed loop velocity so that it rotates slowly until the eddy current sensor indicates a high voltage four times (i.e. until the target on the inertial disk passes the sensor 3 times and is now aligned with the sensor). You will need to determine this velocity reference, which must be sufficient to overcome friction but should not rotate the motor too fast. (The value must be greater than 128.) (Note: when the direction signal to the PWM amp is hi, the motor will rotate clockwise.) You should read through the datasheet for the PWM amp to determine how to set the direction and brake signals.

6. Read the mode switch to determine which control compensator will be used.

7. When the black button is pressed and released, perform the following motion profile:

    a. Start the motor rotating at the closed loop velocity determined in step 5. Measure and average 64 readings of the tachometer voltage and store this reading. This is your baseline velocity measurement.

    b. After each load rotation, determined by measuring 100 counts from the incremental encoder, increase the desired velocity reference from the baseline value by 1 unit.

    c. Control the motor at this velocity value by measuring and averaging 64 readings of the tachometer voltage via the A/D, subtracting this value from the velocity reference and multiplying the result by the compensator. For the proportional control, you should determine an appropriate gain but a value of 10 is a good start. This is the new duty cycle for the PWM. (Note: you do not have to apply negative torque to this motor to slow it down since it has a very high Coulomb friction. Thus if the value that you want to send to the PWM is negative, you should just set it to zero. Also, it is sufficient to just use the upper byte of the PWM signal. Thus if the value that you want to send to the PWM is greater than 255, you should just set it to 255.

d. Output the velocity error on the LEDs connected to Port B.

e. When the motor reference reaches a value of 190 decimal (which corresponds to ½ max motor speed), control at this velocity for 60 load revolutions (i.e. 6000 encoder counts).

f. Following this, after each load rotation (determined by measuring 100 counts from the incremental encoder) decrease the desired velocity reference by 1 unit.

g. When the tachometer indicates that the motor has stopped (decimal value below 140 approximately in proportional control), turn off the PWM signal and turn on the brake.

h. Turn off or flash the LEDs to indicate finished.

If you view the tachometer voltage on an oscilloscope, you should see signal in Figure 17.

In addition, if you try to slow the motor by hand, you should see the pulse widths of the PWM signal increase. We will also look at this on the oscilloscope.

Mode 0

For mode 0, you will control the motor using a proportional controller. That is, the PWM signbal to the motor will be proportional to the velocity error (the difference between the velocity reference that you calculated from the encoder counts and the measured average velocity from the tachometer). Remember that if the value that you want to send to the PWM is negative, you should just set it to zero and, if the value that you want to send to the PWM is greater than 255, you should just set it to 255.

Mode 1

For mode 1, you will add a bias to the input to the motor. The PWM duty cycle that you use in the initialization (step 5) is a good starting point for the bias voltage applied to the motor but you can also experiment with this value. The digital outputs on Port B will give an indication of how well you are doing. Store this value (would have to be prior to reading mode switch). You will compute the control signal using a proportional compensator as in step 7c. You will reduce the steady state error by adding the result of the proportional controller to the stored bias. Again remember that if the value that you want to send to the PWM is negative, you should just set it to zero and, if the value that you want to send to the PWM is greater than 255, you should just set it to 255.

Mode 2

For mode 2, you will use a proportional-derivative controller. The controller equation can use a first difference or a discrete difference equation to compute the derivative value.

Mode 3

For mode 3, you will use a proportional-integral-derivative controller. The controller equation can use a first difference to compute the derivative value and a sum for the integral value. It can also use a discrete difference equation.

If you do not see a difference in the error between mode 3 and mode 0, your integral gain is probably too low. In general, however, integral gains are lower than proportional gains.

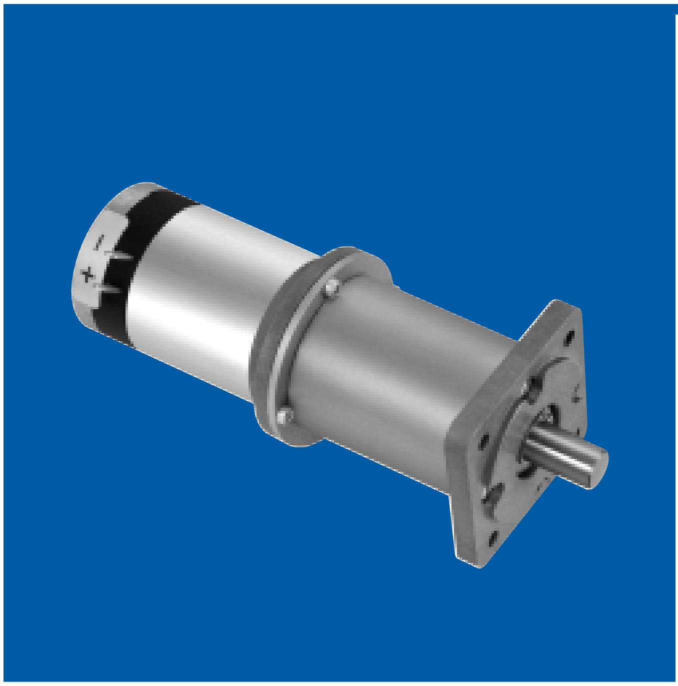
Questions:

a) A trapezoidal velocity profile is chosen for most motion control systems (including those that use a stepper motor or AC motor). Why do you think that this profile is preferred?
b) Why does the motor stop before the PWM signal reaches zero?
c) If you stepped the applied voltage to the motor with the rotor prevented from moving, what would you expect the current signal versus time to look like? Sketch the response. In words, describe how the response would change if the rotor were allowed to rotate.
d) Draw a free body diagram for the DC motor system in Figure 13 (you can lump the motor and load inertia into a single element). If you were able to step the current in the motor, what would you expect the velocity signal versus time to look like? When do you think that lumping the motor and load inertia into a single element is not appropriate?
e) What else can the back e.m.f. voltage of a DC motor be used for?
f) List five examples of DC motor control applications in consumer products or industrial processes which would use a trapezoidal velocity profile like the one that you generated.

IM-13 GEARMOTORS

DC Ceramic Permanent Magnet Planetary Gearmotors

E-2130



torque rating: Up to 1,250 oz. in.

weight: 12 to 17 ounces depending on ratio and motor

gears: Precision manufactured and heat treated for reliable performance and long life

shaft: Precision-ground No. 416 nitrided stainless steel. Options: length, smaller diameter, flats, pinions, gears, holes (through or tapped), threaded ends and tapers. Shaft material may change depending upon options selected

backlash: Varies with ratio, but average backlash is 3°

gear inertia: 1.2 x 10^{-5} oz. in. sec.^{2} @ input max

bearings: Motor output shaft is supported by life-lubricated sleeve bearings (ball bearing option available); gear train output shaft is supported by life-lubricated sleeve bearing

cables/leads: 8" min. #22 AWG 2 leads UL style 1180

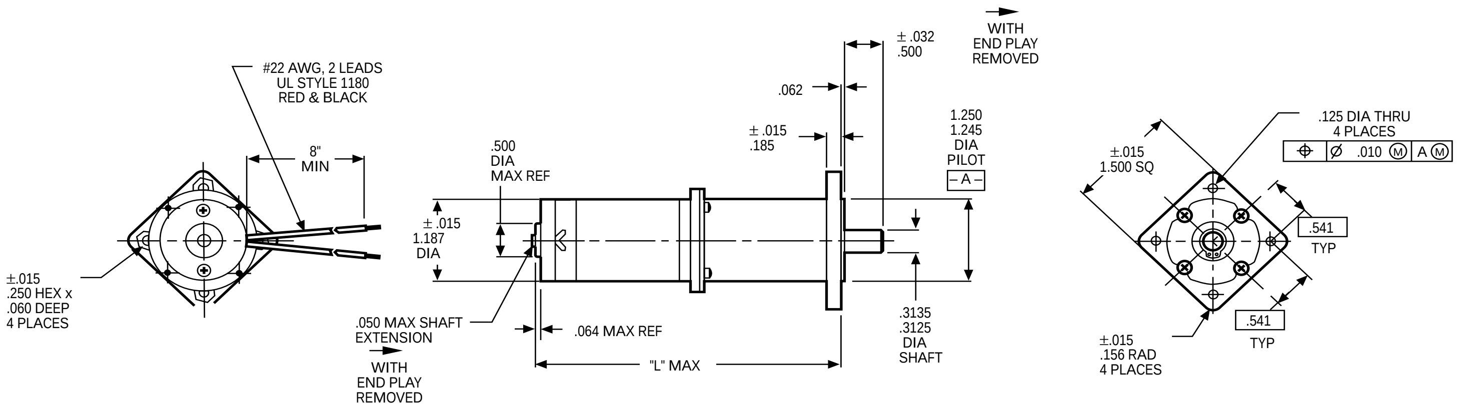
gearbox cover: Corrosion-resistant steel housing

mounting flange: Die-cast zinc

end bell: Die-cast zinc

options available:
- EMI suppression
- Terminals

Dimensions



ROTATION (VIEWED FROM SHAFT END)
CCW - POSITIVE VOLTAGE TO RED (+), NEGATIVE VOLTAGE TO BLACK (-)
CW - REVERSE POLARITY

NOTE: Consult factory prior to preparing spec control prints. Dimensions are for reference only

Standard Part Numbers and Data

		SHORT STACK MOTOR			LONG STACK MOTOR		
RATIO	TORQUE MULTIPLIER	STANDARD PART NUMBER PREFIX*	MAX CONTINUOUS TORQUE (oz. in.)	"L" MAX (in.)	STANDARD PART NUMBER PREFIX*	MAX CONTINUOUS TORQUE (oz. in.)	"L" MAX (in.)
4	3.0	407A6000	4	3.147	407A6166	6.0	3.457
5	3.8	407A6001	5	3.147	407A6167	7.5	3.457
6	4.5	407A6002	6	3.147	407A6168	9.0	3.457
16	10.0	407A6003	12	3.386	407A6169	20.0	3.696
20	13.0	407A6004	16	3.386	407A6170	26.0	3.696
24	15.0	407A6005	19	3.386	407A6171	30.0	3.696
25	16.0	407A6006	20	3.386	407A6172	32.0	3.696
30	19.0	407A6007	24	3.386	407A6173	38.0	3.696
36	23.0	407A6008	29	3.386	407A6174	46.0	3.696
64	33.0	407A6009	41	3.619	407A6175	66.0	3.929
80	41.0	407A6010	51	3.619	407A6176	82.0	3.929
96	49.0	407A6011	61	3.619	407A6177	98.0	3.929
100	51.0	407A6012	64	3.619	407A6178	105.0	3.929
120	61.0	407A6013	76	3.619	407A6179	120.0	3.929
125	64.0	407A6014	80	3.619	407A6180	125.0	3.929
144	74.0	407A6015	92	3.619	407A6181	150.0	3.929
150	77.0	407A6016	96	3.619	407A6182	155.0	3.929
180	92.0	407A6017	115	3.619	407A6183	185.0	3.929
216	110.0	407A6018	135	3.619	407A6184	220.0	3.929
256	105.0	407A6019	130	3.852	407A6185	210.0	4.162
320	130.0	407A6020	160	3.852	407A6186	260.0	4.162
384	157.0	407A6021	195	3.852	407A6187	315.0	4.162
400	164.0	407A6022	205	3.852	407A6188	330.0	4.162
480	197.0	407A6023	245	3.852	407A6189	395.0	4.162
500	205.0	407A6024	255	3.852	407A6190	410.0	4.162
576	235.0	407A6025	295	3.852	407A6191	470.0	4.162
600	246.0	407A6026	305	3.852	407A6192	490.0	4.162
625	256.0	407A6027	320	3.852	407A6193	510.0	4.162
720	295.0	407A6028	370	3.852	407A6194	590.0	4.162
750	306.0	407A6029	380	3.852	407A6195	610.0	4.162
864	352.0	407A6030	440	3.852	407A6196	705.0	4.162
900	370.0	407A6031	460	3.852	407A6197	740.0	4.162
1,024	334.0	407A6032	415	4.085	407A6198	670.0	4.395
1,080	442.0	407A6033	550	3.852	407A6199	885.0	4.162
1,280	416.0	407A6034	520	4.085	407A6200	830.0	4.395
1,296	530.0	407A6035	660	3.852	407A6201	1,060	4.162
1,536	500.0	407A6036	625	4.085	407A6202	1,000	4.395
1,600	522.0	407A6037	650	4.085	407A6203	1,045	4.395
1,920	625.0	407A6038	780	4.085	407A6204	1,250	4.395
2,000	652.0	407A6039	815	4.085	407A6205	1,250	4.395
2,304	750.0	407A6040	935	4.085	407A6206	1,250	4.395
2,400	780.0	407A6041	975	4.085	407A6207	1,250	4.395
2,500	815.0	407A6042	1,010	4.085	407A6208	1,250	4.395
2,880	940.0	407A6043	1,175	4.085	407A6209	1,250	4.395
3,000	980.0	407A6044	1,200	4.085	407A6210	1,250	4.395
3,125	1,020	407A6045	1,250	4.085	407A6211	1,250	4.395
3,456	1,130	407A6046	1,250	4.085	407A6212	1,250	4.395
3,600	1,170	407A6047	1,250	4.085	407A6213	1,250	4.395
3,750	1,220	407A6048	1,250	4.085	407A6214	1,250	4.395

NOTE: Standard part numbers and data continued on page 20

*When You Order

Each of the basic motor armature windings (see page 21) can be used with any of the gear ratios listed above. To order, state the gear train standard part number prefix, plus a motor armature winding dash number. EXAMPLE: 407A6019-2 is a 256:1 IM-13 short stack gear train with a “-2” armature winding, 12 volts, 5,200 rpm, 1.50 oz. in. torque, etc.

Standard Part Numbers and Data

		SHORT STACK MOTOR			LONG STACK MOTOR		
RATIO	TORQUE MULTIPLIER	STANDARD PART NUMBER PREFIX*	MAX CONTINUOUS TORQUE (oz. in.)	"L" MAX (in.)	STANDARD PART NUMBER PREFIX*	MAX CONTINUOUS TORQUE (oz. in.)	"L" MAX (in.)
4,096	1,070	407A6049	1,250	4.318	407A6215	1,250	4.628
4,320	1,410	407A6050	1,250	4.085	407A6216	1,250	4.395
4,500	1,470	407A6051	1,250	4.085	407A6217	1,250	4.395
5,120	1,340	407A6052	1,250	4.318	407A6218	1,250	4.628
5,184	1,690	407A6053	1,250	4.085	407A6219	1,250	4.395
5,400	1,760	407A6054	1,250	4.085	407A6220	1,250	4.395
6,144	1,610	407A6055	1,250	4.318	407A6221	1,250	4.628
6,400	1,680	407A6056	1,250	4.318	407A6222	1,250	4.628
6,480	2,110	407A6057	1,250	4.085	407A6223	1,250	4.395
7,680	2,010	407A6058	1,250	4.318	407A6224	1,250	4.628
7,776	2,530	407A6059	1,250	4.085	407A6225	1,250	4.395
8,000	2,100	407A6060	1,250	4.318	407A6226	1,250	4.628
9,216	2,390	407A6061	1,250	4.318	407A6227	1,250	4.628
9,600	2,520	407A6062	1,250	4.318	407A6228	1,250	4.628
10,000	2,620	407A6063	1,250	4.318	407A6229	1,250	4.628
11,520	3,010	407A6064	1,250	4.318	407A6230	1,250	4.628
12,000	3,140	407A6065	1,250	4.318	407A6231	1,250	4.628
12,500	3,280	407A6066	1,250	4.318	407A6232	1,250	4.628
13,824	3,620	407A6067	1,250	4.318	407A6233	1,250	4.628
14,400	3,780	407A6068	1,250	4.318	407A6234	1,250	4.628
15,000	3,940	407A6069	1,250	4.318	407A6235	1,250	4.628
15,625	4,100	407A6070	1,250	4.318	407A6236	1,250	4.628
17,280	4,520	407A6071	1,250	4.318	407A6237	1,250	4.628
18,000	4,710	407A6072	1,250	4.318	407A6238	1,250	4.628
18,750	4,910	407A6073	1,250	4.318	407A6239	1,250	4.628
20,736	5,430	407A6074	1,250	4.318	407A6240	1,250	4.628
21,600	5,660	407A6075	1,250	4.318	407A6241	1,250	4.628
22,500	5,900	407A6076	1,250	4.318	407A6242	1,250	4.628
25,920	6,790	407A6077	1,250	4.318	407A6243	1,250	4.628
27,000	7,070	407A6078	1,250	4.318	407A6244	1,250	4.628
31,104	8,150	407A6079	1,250	4.318	407A6245	1,250	4.628
32,400	8,500	407A6080	1,250	4.318	407A6246	1,250	4.628
38,880	10,200	407A6081	1,250	4.318	407A6247	1,250	4.628
46,656	12,200	407A6082	1,250	4.318	407A6248	1,250	4.628

Maximum continuous rated torque values are based upon motor temperature rise considerations. Starting or impact loads greater than 10 times the rated maximum continuous torque (1,500 oz. in. maximum) could result in gear or shaft damage

*When You Order

Each of the basic motor armature windings (see chart, page 21) can be used with any of the gear ratios listed in the preceding charts. To order, state the gear train standard part number prefix, plus a motor armature winding dash number. EXAMPLE: 407A6019-2 is a 256:1 IM-13 short stack gear train with a “-2” armature winding, 12 volts, 5,200 rpm, 1.50 oz. in. torque, etc.

E-2130

Globe Motors™

Basic Motor Data

ARMATURE WINDING DASH NO.*	VOLTAGE (VDC)	SPEED ±10% NO LOAD (rpm)	CURRENT NO LOAD (max amps)	RATED TORQUE (oz. in.)	CURRENT AT RATED TORQUE (max amps)	TORQUE CONSTANT (oz. in./ amps)	RESISTANCE (ohms)
Short Stack — Motors							
-2	12	5,200	.230	1.50	.80	2.90	7.30
-3	24	5,200	.140	1.50	.40	5.60	30.00
Long Stack — Motors							
-2	12	5,200	.220	2.50	1.30	2.90	4.00
-3	24	5,200	.150	2.50	.65	5.85	15.00

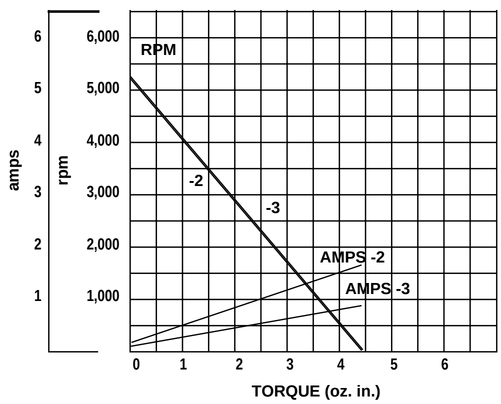
*When You Order

Each of the basic motor armature windings can be used with any of the gear ratios listed in the two preceding charts. To order, state the gear train standard part number prefix, plus a motor armature winding dash number. EXAMPLE: 407A6019-2 is a 256:1 IM-13 short stack gear train with a “-2” armature winding, 12 volts, 5,200 rpm, 1.50 oz. in. torque, etc.

Typical Motor Performance

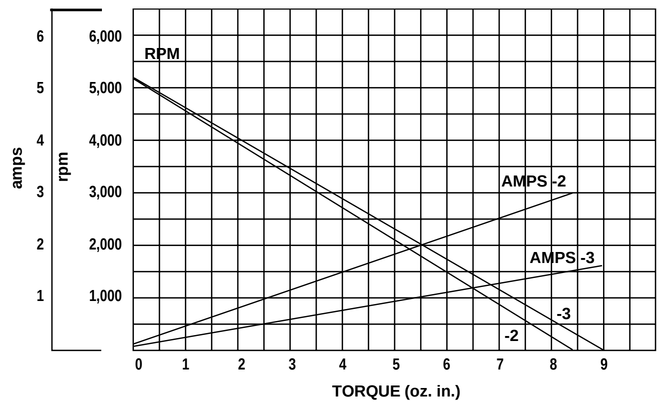
Short Stack Motors

Part Nos.: 407A6000 thru 6082



Long Stack Motors

Part Nos.: 407A6166 thru 6248



September 2003

National Semiconductor

LMC6482
CMOS Dual Rail-To-Rail Input and Output Operational Amplifier

General Description

The LMC6482 provides a common-mode range that extends to both supply rails. This rail-to-rail performance combined with excellent accuracy, due to a high CMRR, makes it unique among rail-to-rail input amplifiers.

It is ideal for systems, such as data acquisition, that require a large input signal range. The LMC6482 is also an excellent upgrade for circuits using limited common-mode range amplifiers such as the TLC272 and TLC277.

Maximum dynamic signal range is assured in low voltage and single supply systems by the LMC6482's rail-to-rail output swing. The LMC6482's rail-to-rail output swing is guaranteed for loads down to 600Ω.

Guaranteed low voltage characteristics and low power dissipation make the LMC6482 especially well-suited for battery-operated systems.

LMC6482 is also available in MSOP package which is almost half the size of a SO-8 device.

See the LMC6484 data sheet for a Quad CMOS operational amplifier with these same features.

Features

(Typical unless otherwise noted)

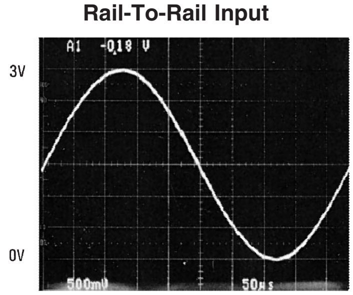
- Rail-to-Rail Input Common-Mode Voltage Range (Guaranteed Over Temperature)
- Rail-to-Rail Output Swing (within 20mV of supply rail, 100kΩ load)
- Guaranteed 3V, 5V and 15V Performance
- Excellent CMRR and PSRR: 82dB
- Ultra Low Input Current: 20fA
- High Voltage Gain (R_L = 500kΩ): 130dB
- Specified for 2kΩ and 600Ω loads
- Available in MSOP Package

Applications

- Data Acquisition Systems
- Transducer Amplifiers
- Hand-held Analytic Instruments
- Medical Instrumentation
- Active Filter, Peak Detector, Sample and Hold, pH Meter, Current Source
- Improved Replacement for TLC272, TLC277

3V Single Supply Buffer Circuit

Rail-To-Rail Input



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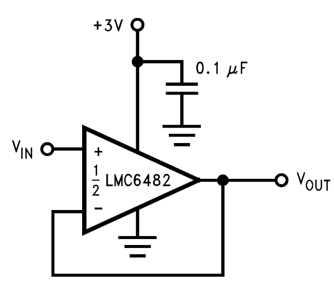

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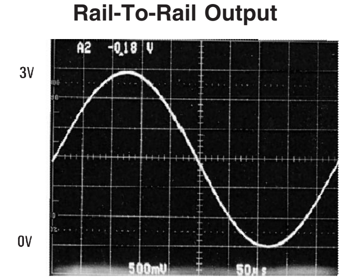
Rail-To-Rail Output



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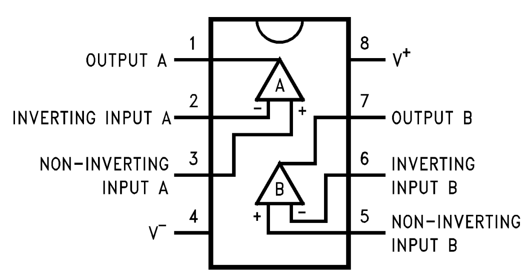
Connection Diagram



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 DS011713

Absolute Maximum Ratings (Note 1)

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

ESD Tolerance (Note 2)	1.5kV
Differential Input Voltage	±Supply Voltage
Voltage at Input/Output Pin	(V^+) +0.3V, (V^-) −0.3V
Supply Voltage ($V^+ - V^-$)	16V
Current at Input Pin (Note 12)	±5mA
Current at Output Pin (Notes 3, 8)	±30mA
Current at Power Supply Pin	40mA
Lead Temperature (Soldering, 10 sec.)	260˚C
Storage Temperature Range	−65˚C to +150˚C
Junction Temperature (Note 4)	150˚C

Operating Ratings (Note 1)

Supply Voltage	3.0V ≤ V+ ≤ 15.5V
Junction Temperature Range	
LMC6482AM	−55˚C ≤ T_J ≤ +125˚C
LMC6482AI, LMC6482I	−40˚C ≤ T_J ≤ +85˚C
Thermal Resistance (θ_{JA})	
N Package, 8-Pin Molded DIP	90˚C/W
M Package, 8-Pin Surface Mount	155˚C/W
MSOP package, 8-Pin Mini SO	194˚C/W

DC Electrical Characteristics

Unless otherwise specified, all limits guaranteed for T_J = 25˚C, V^+ = 5V, V^- = 0V, V_{CM} = V_O = $V^+/2$ and R_L > 1M. **Boldface** limits apply at the temperature extremes.

Symbol	Parameter	Conditions		Typ (Note 5)	LMC6482AI Limit (Note 6)	LMC6482I Limit (Note 6)	LMC6482M Limit (Note 6)	Units
V_{OS}	Input Offset Voltage			0.11	0.750 **1.35**	3.0 **3.7**	3.0 **3.8**	mV max
TCV_{OS}	Input Offset Voltage Average Drift			1.0				μV/˚C
I_B	Input Current	(Note 13)		0.02	**4.0**	**4.0**	**10.0**	pA max
I_{OS}	Input Offset Current	(Note 13)		0.01	**2.0**	**2.0**	**5.0**	pA max
C_{IN}	Common-Mode Input Capacitance			3				pF
R_{IN}	Input Resistance			>10				TeraΩ
CMRR	Common Mode Rejection Ratio	0V ≤ V_{CM} ≤ 15.0V V^+ = 15V		82	70 **67**	65 **62**	65 **60**	dB min
		0V ≤ V_{CM} ≤ 5.0V V^+ = 5V		82	70 **67**	65 **62**	65 **60**	
+PSRR	Positive Power Supply Rejection Ratio	5V ≤ V^+ ≤ 15V, V^- = 0V V_O = 2.5V		82	70 **67**	65 **62**	65 **60**	dB min
−PSRR	Negative Power Supply Rejection Ratio	−5V ≤ V^- ≤ −15V, V^+ = 0V V_O = −2.5V		82	70 **67**	65 **62**	65 **60**	dB min
V_{CM}	Input Common-Mode Voltage Range	V^+ = 5V and 15V For CMRR ≥ 50dB		V^- − 0.3	− 0.25 **0**	− 0.25 **0**	− 0.25 **0**	V max
				V^+ + 0.3V	V^+ + 0.25 **V^+**	V^+ + 0.25 **V^+**	V^+ + 0.25 **V^+**	V min
A_V	Large Signal Voltage Gain	R_L = 2kΩ (Notes 7, 13)	Sourcing	666	140 **84**	120 **72**	120 **60**	V/mV min
			Sinking	75	35 **20**	35 **20**	35 **18**	V/mV min
		R_L = 600Ω (Notes 7, 13)	Sourcing	300	80 **48**	50 **30**	50 **25**	V/mV min
			Sinking	35	20	15	15	V/mV

DC Electrical Characteristics (Continued)

Unless otherwise specified, all limits guaranteed for T_J = 25˚C, V^+ = 5V, V^- = 0V, V_{CM} = V_O = V^+/2 and R_L > 1M. **Boldface** limits apply at the temperature extremes.

Symbol	Parameter	Conditions	Typ (Note 5)	LMC6482AI Limit (Note 6)	LMC6482I Limit (Note 6)	LMC6482M Limit (Note 6)	Units
				13	**10**	**8**	min
V_O	Output Swing	V^+ = 5V R_L = 2kΩ to V^+/2	4.9	4.8 **4.7**	4.8 **4.7**	4.8 **4.7**	V min
			0.1	0.18 **0.24**	0.18 **0.24**	0.18 **0.24**	V max
		V^+ = 5V R_L = 600Ω to V^+/2	4.7	4.5 **4.24**	4.5 **4.24**	4.5 **4.24**	V min
			0.3	0.5 **0.65**	0.5 **0.65**	0.5 **0.65**	V max
		V^+ = 15V R_L = 2kΩ to V^+/2	14.7	14.4 **14.2**	14.4 **14.2**	14.4 **14.2**	V min
			0.16	0.32 **0.45**	0.32 **0.45**	0.32 **0.45**	V max
		V^+ = 15V R_L = 600Ω to V^+/2	14.1	13.4 **13.0**	13.4 **13.0**	13.4 **13.0**	V min
			0.5	1.0 **1.3**	1.0 **1.3**	1.0 **1.3**	V max
I_{SC}	Output Short Circuit Current V^+ = 5V	Sourcing, V_O = 0V	20	16 **12**	16 **12**	16 **10**	mA min
		Sinking, V_O = 5V	15	11 **9.5**	11 **9.5**	11 **8.0**	mA min
I_{SC}	Output Short Circuit Current V^+ = 15V	Sourcing, V_O = 0V	30	28 **22**	28 **22**	28 **20**	mA min
		Sinking, V_O = 12V (Note 8)	30	30 **24**	30 **24**	30 **22**	mA min
I_S	Supply Current	Both Amplifiers V^+ = +5V, V_O = V^+/2	1.0	1.4 **1.8**	1.4 **1.8**	1.4 **1.9**	mA max
		Both Amplifiers V^+ = 15V, V_O = V^+/2	1.3	1.6 **1.9**	1.6 **1.9**	1.6 **2.0**	mA max

AC Electrical Characteristics

Unless otherwise specified, all limits guaranteed for T_J = 25˚C, V^+ = 5V, V^- = 0V, V_{CM} = V_O = V^+/2, and R_L > 1M. **Boldface** limits apply at the temperature extremes.

Symbol	Parameter	Conditions	Typ (Note 5)	LMC6482AI Limit (Note 6)	LMC6482I Limit (Note 6)	LMC6482M Limit (Note 6)	Units
SR	Slew Rate	(Note 9)	1.3	1.0 **0.7**	0.9 **0.63**	0.9 **0.54**	V/µs min
GBW	Gain-Bandwidth Product	V^+ = 15V	1.5				MHz
ϕ_m	Phase Margin		50				Deg
G_m	Gain Margin		15				dB
	Amp-to-Amp Isolation	(Note 10)	150				dB
e_n	Input-Referred Voltage Noise	F = 1kHz V_{cm} = 1V	37				nV/√Hz
i_n	Input-Referred Current Noise	F = 1kHz	0.03				pA/√Hz

AC Electrical Characteristics (Continued)

Unless otherwise specified, all limits guaranteed for T_J = 25˚C, V^+ = 5V, V^- = 0V, V_{CM} = V_O = $V^+/2$, and R_L > 1M. **Boldface** limits apply at the temperature extremes.

Symbol	Parameter	Conditions	Typ (Note 5)	LMC6482AI Limit (Note 6)	LMC6482I Limit (Note 6)	LMC6482M Limit (Note 6)	Units
T.H.D.	Total Harmonic Distortion	F = 10kHz, A_V = −2 R_L = 10kΩ, V_O = 4.1 V_{PP}	0.01				%
		F = 10kHz, A_V = −2 R_L = 10kΩ, V_O = 8.5 V_{PP} V^+ = 10V	0.01				%

DC Electrical Characteristics

Unless otherwise specified, all limits guaranteed for T_J = 25˚C, V^+ = 3V, V^- = 0V, V_{CM} = V_O = $V^+/2$ and R_L > 1M.

Symbol	Parameter	Conditions	Typ (Note 5)	LMC6482AI Limit (Note 6)	LMC6482I Limit (Note 6)	LMC6482M Limit (Note 6)	Units
V_{OS}	Input Offset Voltage		0.9	2.0 **2.7**	3.0 **3.7**	3.0 **3.8**	mV max
TCV_{OS}	Input Offset Voltage Average Drift		2.0				μV/˚C
I_B	Input Bias Current		0.02				pA
I_{OS}	Input Offset Current		0.01				pA
CMRR	Common Mode Rejection Ratio	0V ≤ V_{CM} ≤ 3V	74	64	60	60	dB min
PSRR	Power Supply Rejection Ratio	3V ≤ V^+ ≤ 15V, V^- = 0V	80	68	60	60	dB min
V_{CM}	Input Common-Mode Voltage Range	For CMRR ≥ 50dB	V^- −0.25	0	0	0	V max
			V^+ + 0.25	V^+	V^+	V^+	V min
V_O	Output Swing	R_L = 2kΩ to $V^+/2$	2.8				V
			0.2				V
		R_L = 600Ω to $V^+/2$	2.7	2.5	2.5	2.5	V min
			0.37	0.6	0.6	0.6	V max
I_S	Supply Current	Both Amplifiers	0.825	1.2 **1.5**	1.2 **1.5**	1.2 **1.6**	mA max

AC Electrical Characteristics

Unless otherwise specified, V^+ = 3V, V^- = 0V, V_{CM} = V_O = $V^+/2$, and R_L > 1M.

Symbol	Parameter	Conditions	Typ (Note 5)	LMC6482AI Limit (Note 6)	LMC6482I Limit (Note 6)	LMC6482M Limit (Note 6)	Units
SR	Slew Rate	(Note 11)	0.9				V/μs
GBW	Gain-Bandwidth Product		1.0				MHz
T.H.D.	Total Harmonic Distortion	F = 10kHz, A_V = −2 R_L = 10kΩ, V_O = 2 V_{PP}	0.01				%

Note 1: Absolute Maximum Ratings indicate limts beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is intended to be functional, but specific performance is not guaranteed. For guaranteed specifications and the test conditions, see the Electrical Characteristics.

Note 2: Human body model, 1.5kΩ in series with 100pF. All pins rated per method 3015.6 of MIL-STD-883. This is a Class 1 device rating.

AC Electrical Characteristics (Continued)

Note 3: Applies to both single-supply and split-supply operation. Continuous short circuit operation at elevated ambient temperature can result in exceeding the maximum allowed junction temperature of 150˚C. Output currents in excess of ±30mA over long term may adversely affect reliability.

Note 4: The maximum power dissipation is a function of $T_{J(max)}$, θ_{JA}, and T_A. The maximum allowable power dissipation at any ambient temperature is $P_D = (T_{J(max)} - T_A)/\theta_{JA}$. All numbers apply for packages soldered directly into a PC board.

Note 5: Typical Values represent the most likely parametric norm.

Note 6: All limits are guaranteed by testing or statistical analysis.

Note 7: V^+ = 15V, V_{CM} = 7.5V and R_L connected to 7.5V. For Sourcing tests, 7.5V ≤ V_O ≤ 11.5V. For Sinking tests, 3.5V ≤ V_O ≤ 7.5V.

Note 8: Do not short circuit output to V^+, when V^+ is greater than 13V or reliability will be adversely affected.

Note 9: V^+ = 15V. Connected as Voltage Follower with 10V step input. Number specified is the slower of either the positive or negative slew rates.

Note 10: Input referred, V^+ = 15V and R_L = 100 kΩ connected to 7.5V. Each amp excited in turn with 1 kHz to produce V_O = 12 V_{PP}.

Note 11: Connected as voltage Follower with 2V step input. Number specified is the slower of either the positive or negative slew rates.

Note 12: Limiting input pin current is only necessary for input voltages that exceed absolute maximum input voltage ratings.

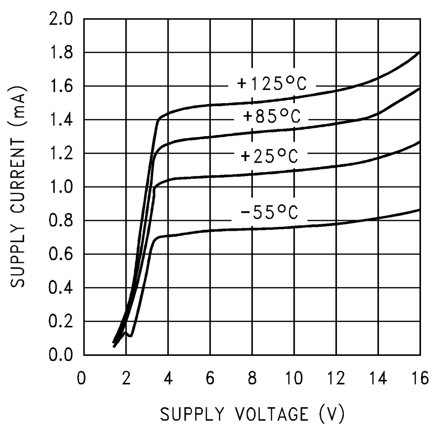
Note 13: Guaranteed limits are dictated by tester limitations and not device performance. Actual performance is reflected in the typical value.

Note 14: For guaranteed Military Temperature parameters see RETS6482X.

Typical Performance Characteristics

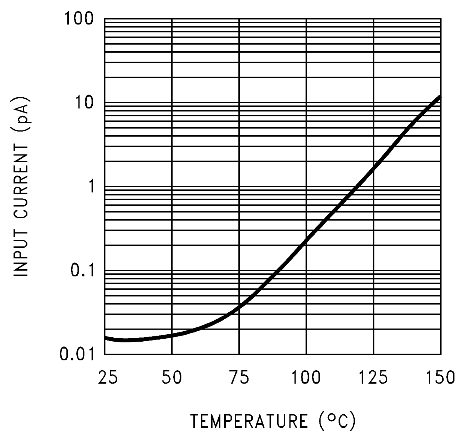
V_S = +15V, Single Supply, T_A = 25˚C unless otherwise specified

Supply Current vs. Supply Voltage



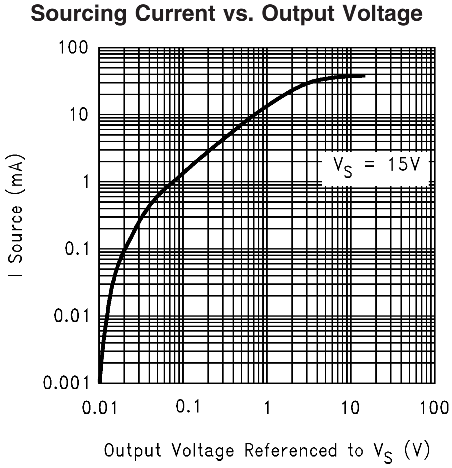
01171340

Input Current vs. Temperature



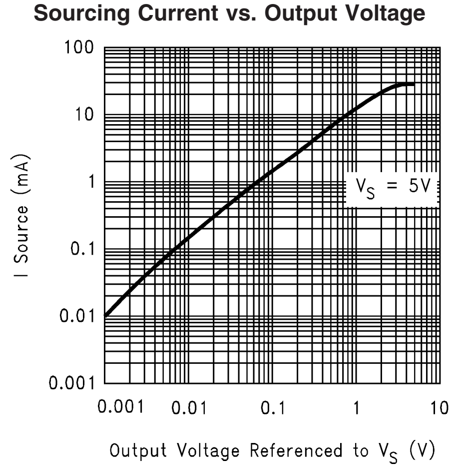
01171341

Sourcing Current vs. Output Voltage



01171342

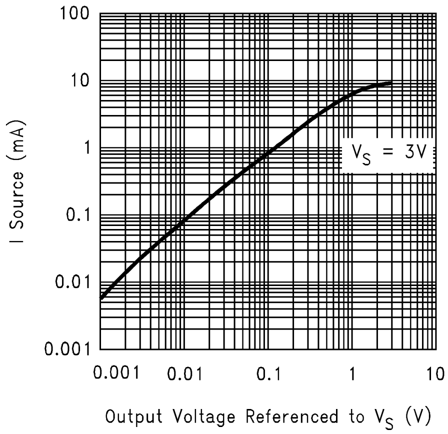
Sourcing Current vs. Output Voltage



01171343

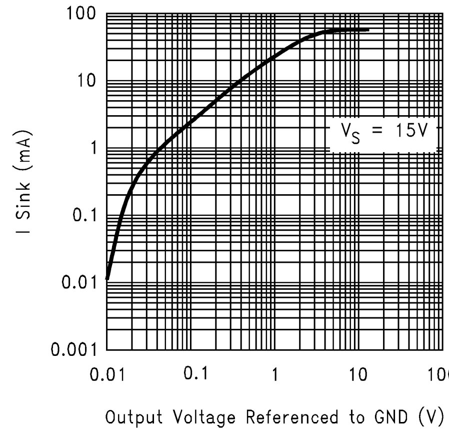
Typical Performance Characteristics V_S = +15V, Single Supply, T_A = 25˚C unless otherwise specified (Continued)

Sourcing Current vs. Output Voltage



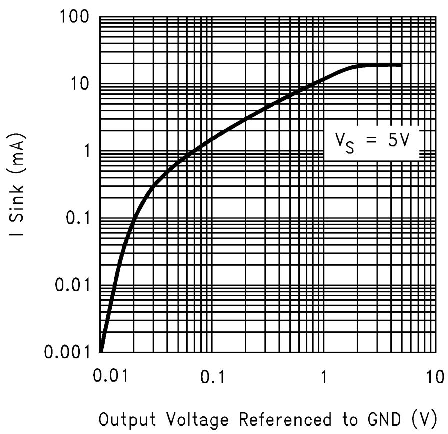
01171344

Sinking Current vs. Output Voltage



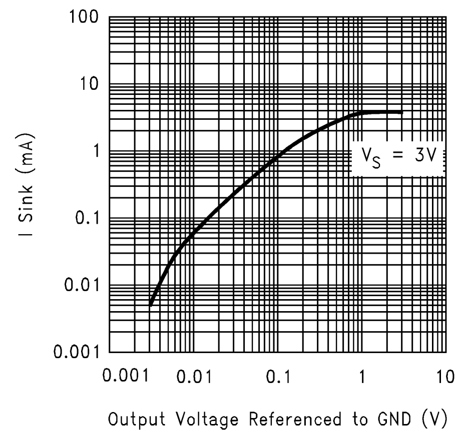
01171345

Sinking Current vs. Output Voltage



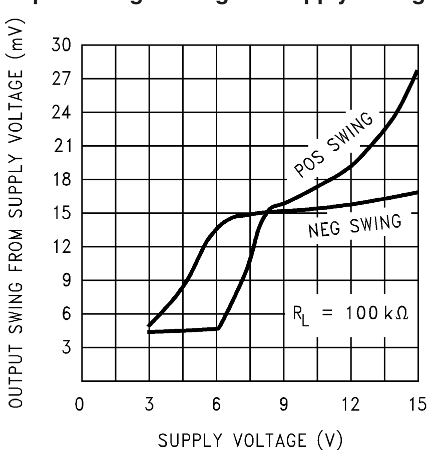
01171346

Sinking Current vs. Output Voltage



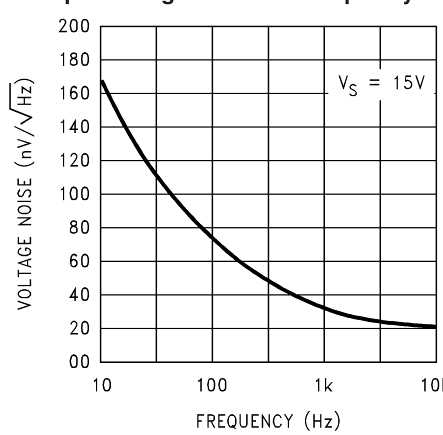
01171347

Output Voltage Swing vs. Supply Voltage



01171348

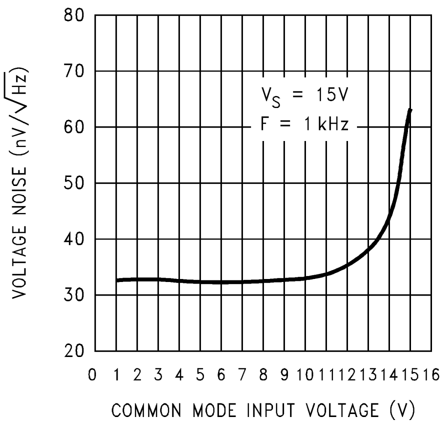
Input Voltage Noise vs. Frequency



01171349

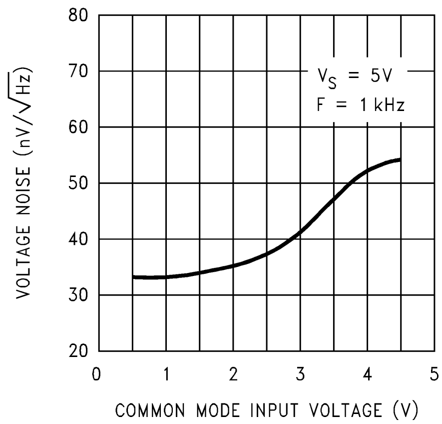
Typical Performance Characteristics V_S = +15V, Single Supply, T_A = 25˚C unless otherwise specified (Continued)

Input Voltage Noise vs. Input Voltage



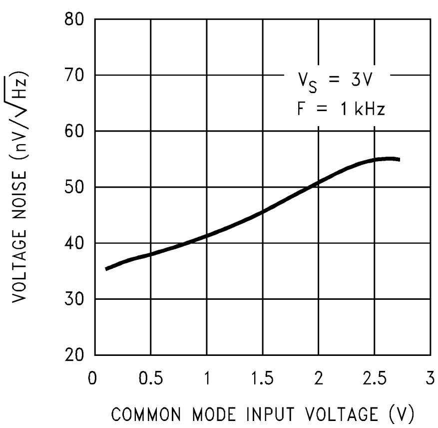
01171350

Input Voltage Noise vs. Input Voltage



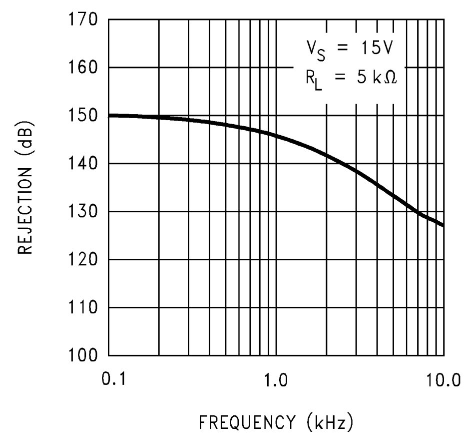
01171351

Input Voltage Noise vs. Input Voltage



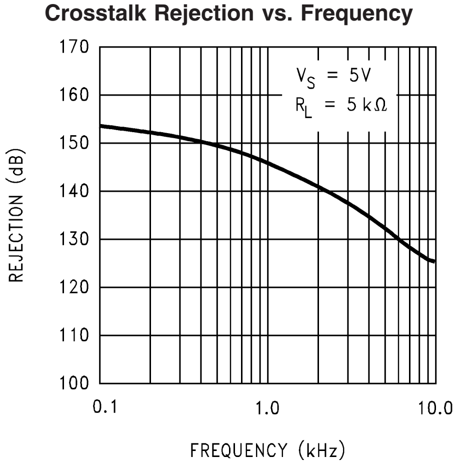
01171352

Crosstalk Rejection vs. Frequency



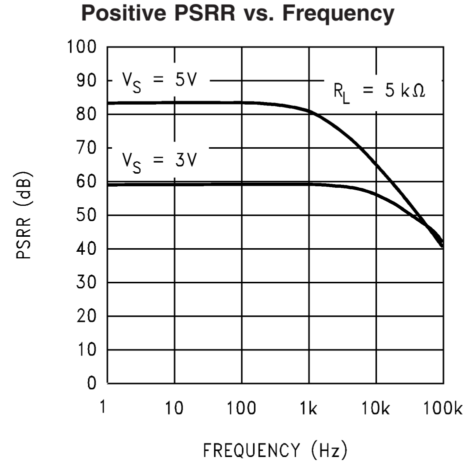
01171353

Crosstalk Rejection vs. Frequency



01171354

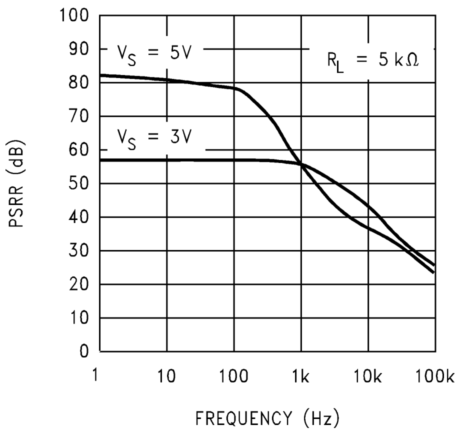
Positive PSRR vs. Frequency



01171355

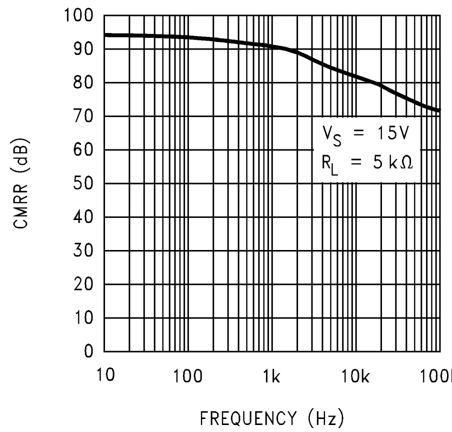
Typical Performance Characteristics V_S = +15V, Single Supply, T_A = 25˚C unless otherwise specified (Continued)

Negative PSRR vs. Frequency



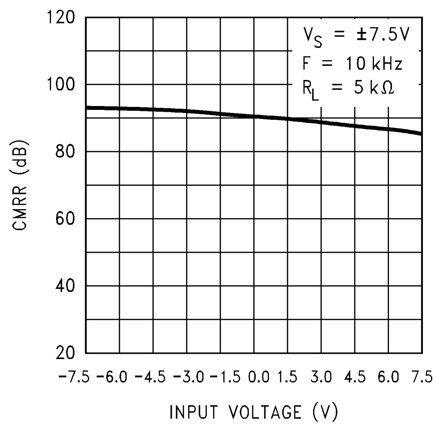
01171356

CMRR vs. Frequency



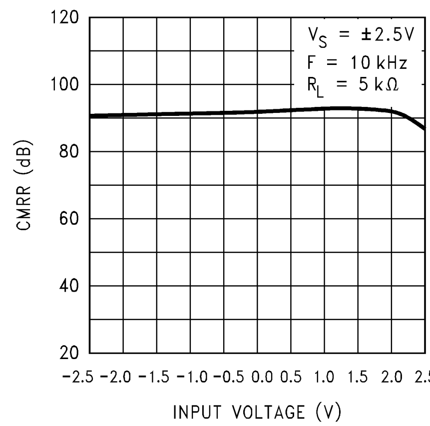
01171357

CMRR vs. Input Voltage



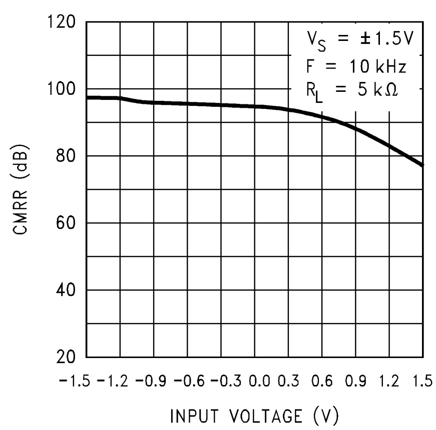
01171358

CMRR vs. Input Voltage



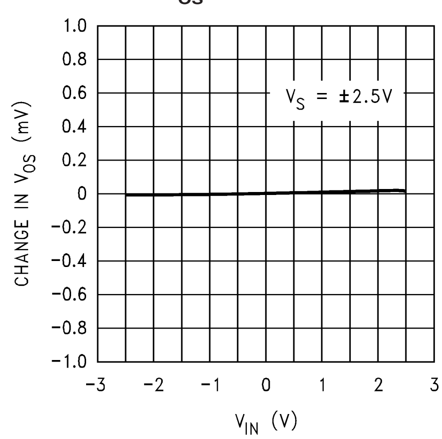
01171359

CMRR vs. Input Voltage



01171360

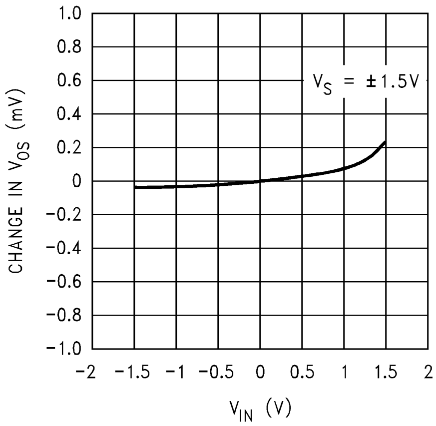
ΔV_{OS} vs. CMR



01171361

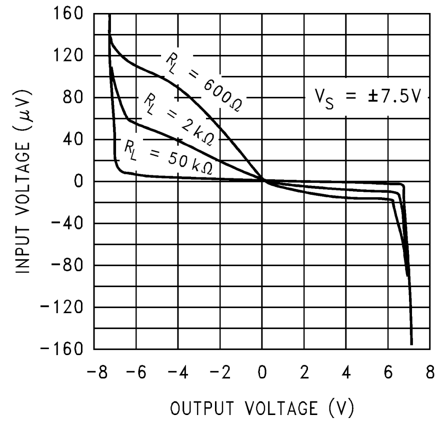
Typical Performance Characteristics V_S = +15V, Single Supply, T_A = 25˚C unless otherwise specified (Continued)

ΔV_{OS} vs. CMR



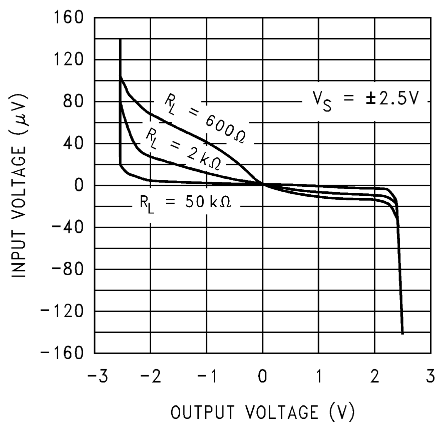
01171362

Input Voltage vs. Output Voltage



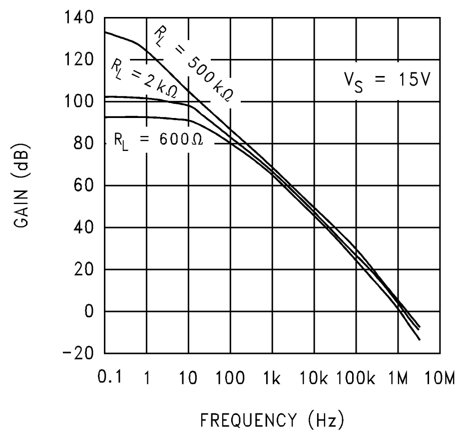
01171363

Input Voltage vs. Output Voltage



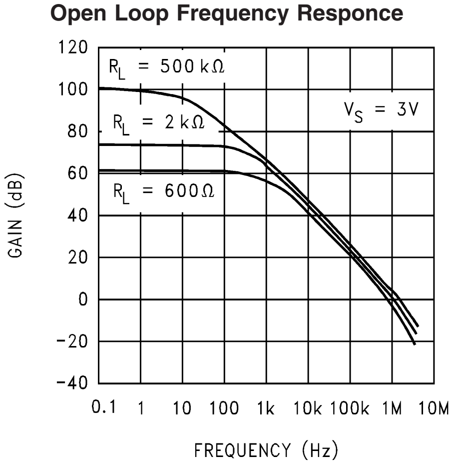
01171364

Open Loop Frequency Response



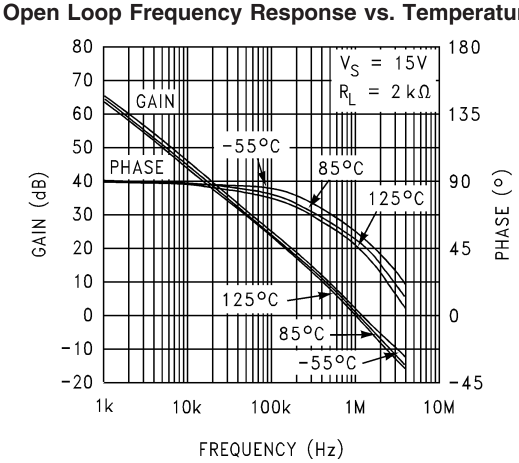
01171365

Open Loop Frequency Responce



01171366

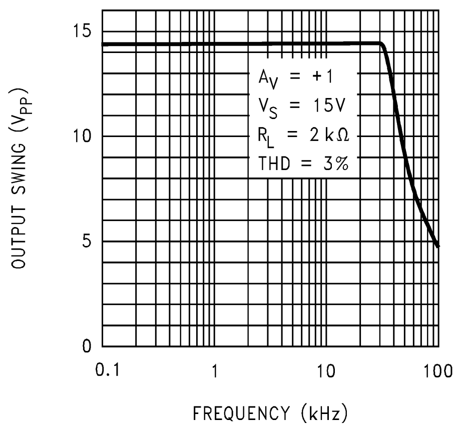
Open Loop Frequency Response vs. Temperature



01171367

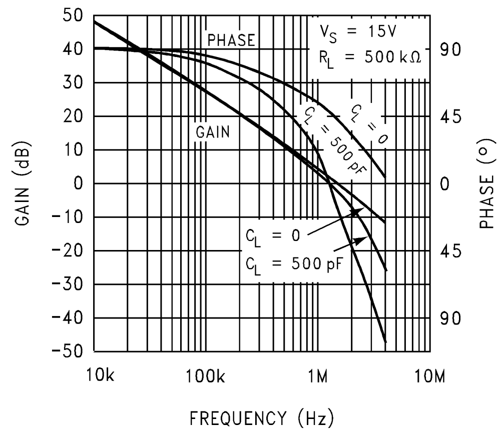
Typical Performance Characteristics V_S = +15V, Single Supply, T_A = 25˚C unless otherwise specified (Continued)

Maximum Output Swing vs. Frequency



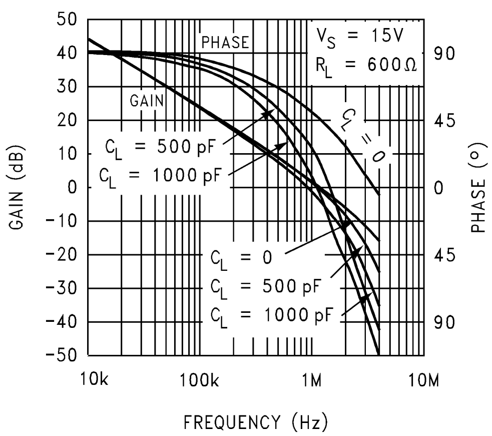
01171368

Gain and Phase vs. Capacitive Load



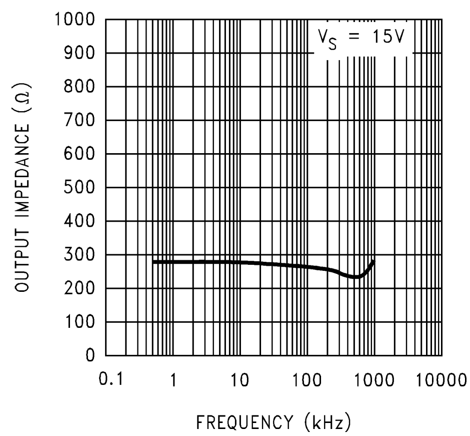
01171369

Gain and Phase vs. Capacitive Load



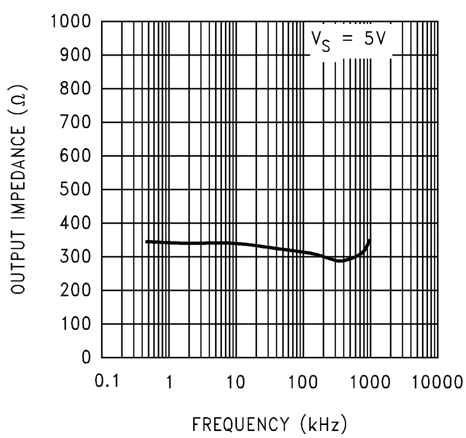
01171370

Open Loop Output Impedance vs. Frequency



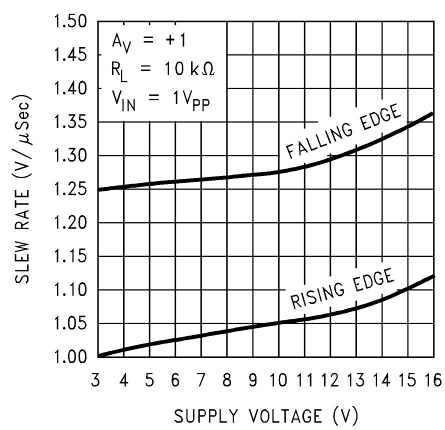
01171371

Open Loop Output Impedance vs. Frequency



01171372

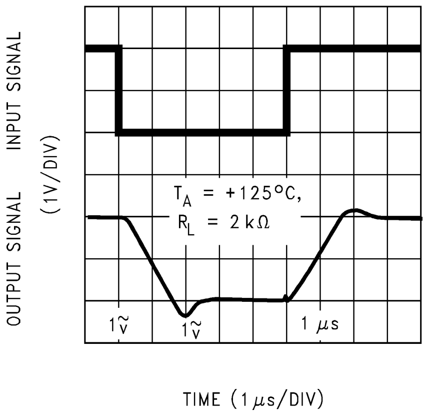
Slew Rate vs. Supply Voltage



01171373

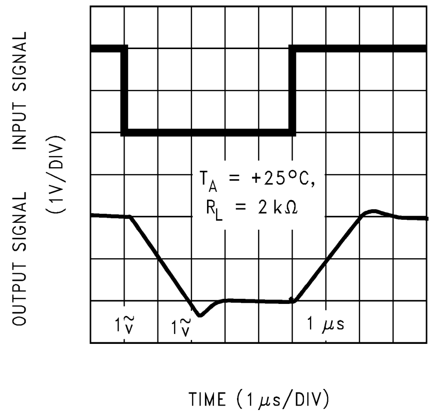
Typical Performance Characteristics V_S = +15V, Single Supply, T_A = 25˚C unless otherwise specified (Continued)

Non-Inverting Large Signal Pulse Response



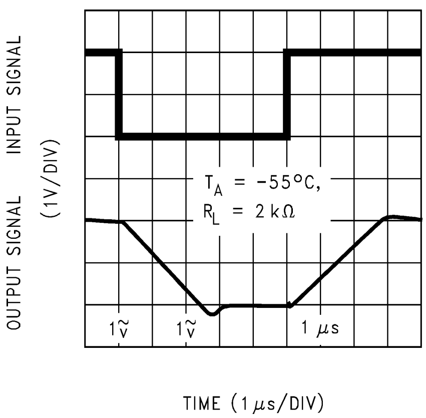
01171374

Non-Inverting Large Signal Pulse Response



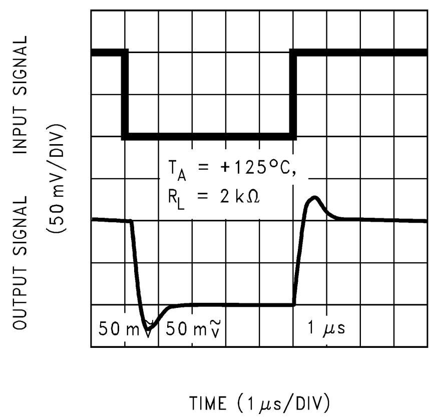
01171375

Non-Inverting Large Signal Pulse Response



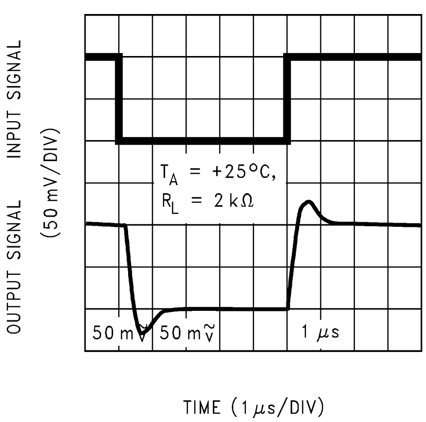
01171376

Non-Inverting Small Signal Pulse Response



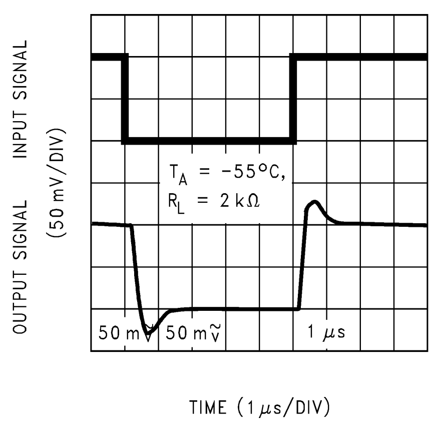
01171377

Non-Inverting Small Signal Pulse Response



01171378

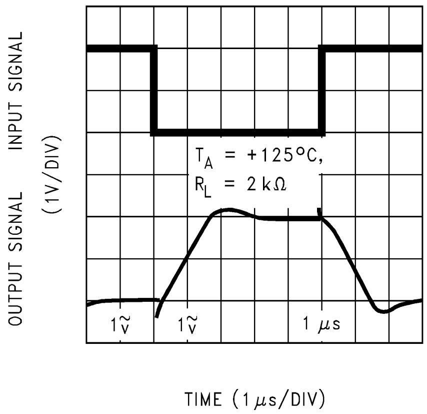
Non-Inverting Small Signal Pulse Response



01171379

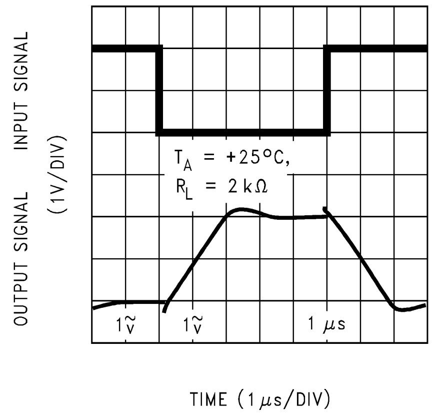
Typical Performance Characteristics V_S = +15V, Single Supply, T_A = 25˚C unless otherwise specified (Continued)

Inverting Large Signal Pulse Response



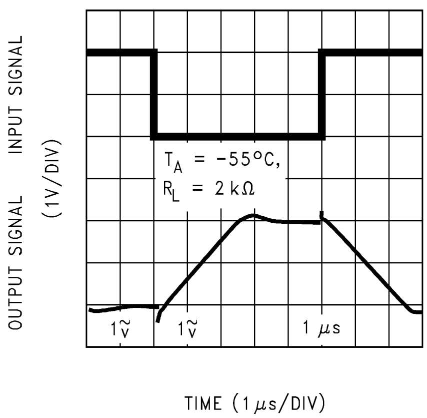
01171380

Inverting Large Signal Pulse Response



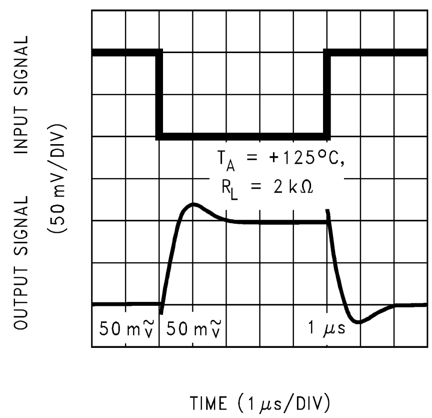
01171381

Inverting Large Signal Pulse Response



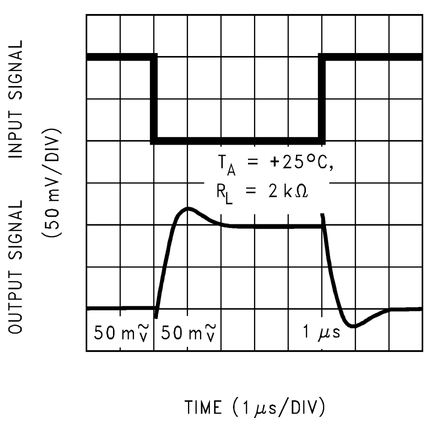
01171382

Inverting Small Signal Pulse Response



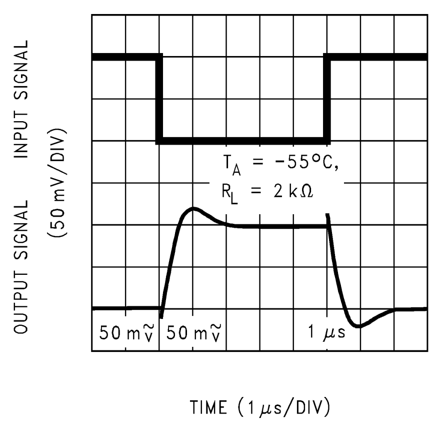
01171383

Inverting Small Signal Pulse Response



01171384

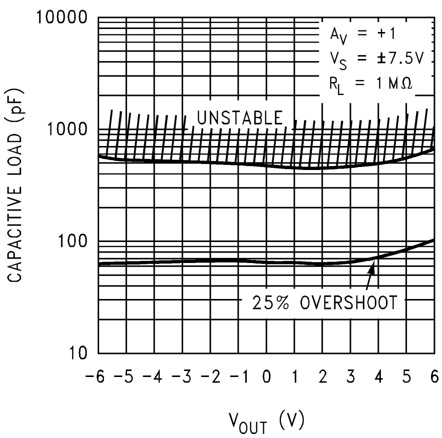
Inverting Small Signal Pulse Response



01171385

Typical Performance Characteristics V_S = +15V, Single Supply, T_A = 25˚C unless otherwise specified (Continued)

Stability vs. Capacitive Load



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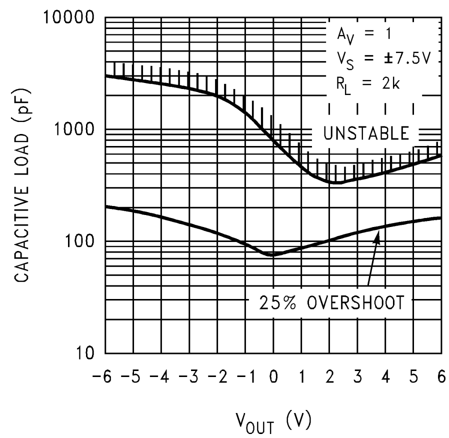
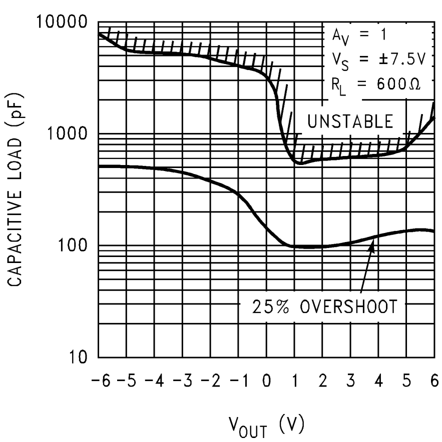
Stability vs. Capacitive Load



01171387

Stability vs. Capacitive Load



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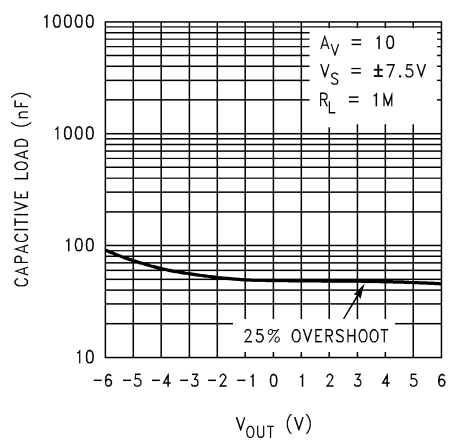
Stability vs. Capacitive Load



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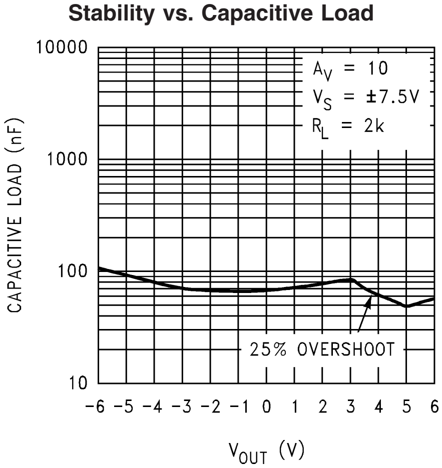
Stability vs. Capacitive Load



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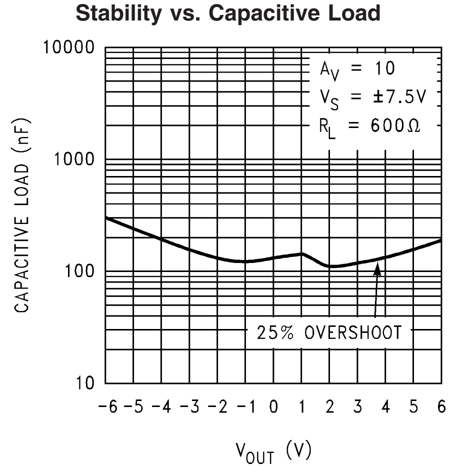
Stability vs. Capacitive Load



01171391

Application Information

1.0 AMPLIFIER TOPOLOGY

The LMC6482 incorporates specially designed wide-compliance range current mirrors and the body effect to extend input common mode range to each supply rail. Complementary paralleled differential input stages, like the type used in other CMOS and bipolar rail-to-rail input amplifiers, were not used because of their inherent accuracy problems due to CMRR, cross-over distortion, and open-loop gain variation.

The LMC6482's input stage design is complemented by an output stage capable of rail-to-rail output swing even when driving a large load. Rail-to-rail output swing is obtained by taking the output directly from the internal integrator instead of an output buffer stage.

2.0 INPUT COMMON-MODE VOLTAGE RANGE

Unlike Bi-FET amplifier designs, the LMC6482 does not exhibit phase inversion when an input voltage exceeds the negative supply voltage. *Figure 1* shows an input voltage exceeding both supplies with no resulting phase inversion on the output.

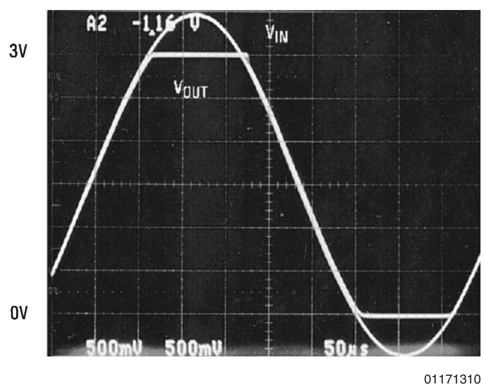


FIGURE 1. An Input Voltage Signal Exceeds the LMC6482 Power Supply Voltages with No Output Phase Inversion

The absolute maximum input voltage is 300mV beyond either supply rail at room temperature. Voltages greatly exceeding this absolute maximum rating, as in *Figure 2*, can cause excessive current to flow in or out of the input pins possibly affecting reliability.

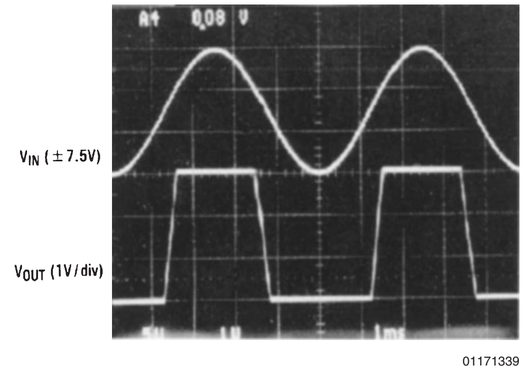


FIGURE 2. A ±7.5V Input Signal Greatly Exceeds the 3V Supply in *Figure 3* Causing No Phase Inversion Due to R_I

Applications that exceed this rating must externally limit the maximum input current to ±5mA with an input resistor (R_I) as shown in *Figure 3*.

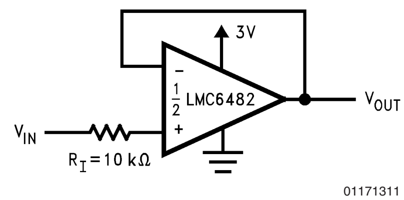


FIGURE 3. R_I Input Current Protection for Voltages Exceeding the Supply Voltages

3.0 RAIL-TO-RAIL OUTPUT

The approximated output resistance of the LMC6482 is 180Ω sourcing and 130Ω sinking at V_S = 3V and 110Ω sourcing and 80Ω sinking at Vs = 5V. Using the calculated output resistance, maximum output voltage swing can be estimated as a function of load.

4.0 CAPACITIVE LOAD TOLERANCE

The LMC6482 can typically directly drive a 100pF load with V_S = 15V at unity gain without oscillating. The unity gain follower is the most sensitive configuration. Direct capacitive loading reduces the phase margin of op-amps. The combination of the op-amp's output impedance and the capacitive load induces phase lag. This results in either an underdamped pulse response or oscillation.

Capacitive load compensation can be accomplished using resistive isolation as shown in *Figure 4*. This simple technique is useful for isolating the capacitive inputs of multiplexers and A/D converters.

Application Information (Continued)

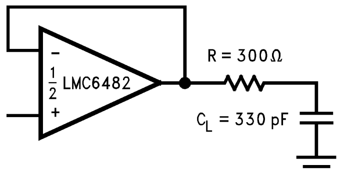


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FIGURE 4. Resistive Isolation of a 330pF Capacitive Load

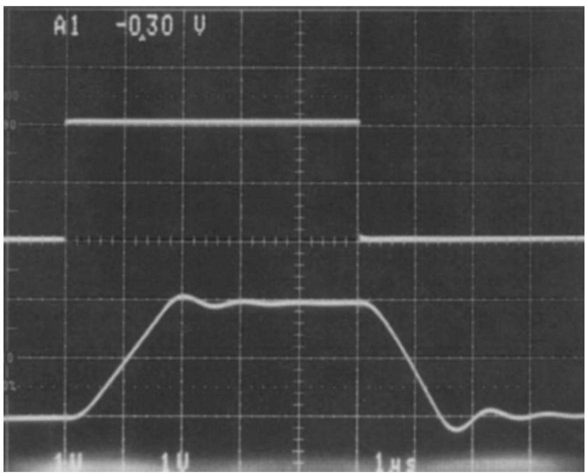

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FIGURE 5. Pulse Response of the LMC6482 Circuit in *Figure 4*

Improved frequency response is achieved by indirectly driving capacitive loads, as shown in *Figure 6*.

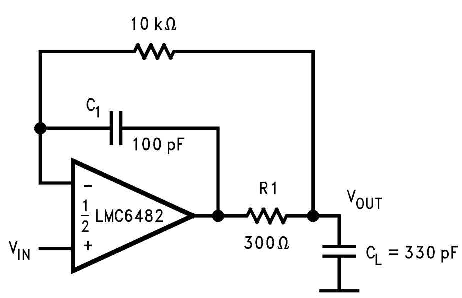

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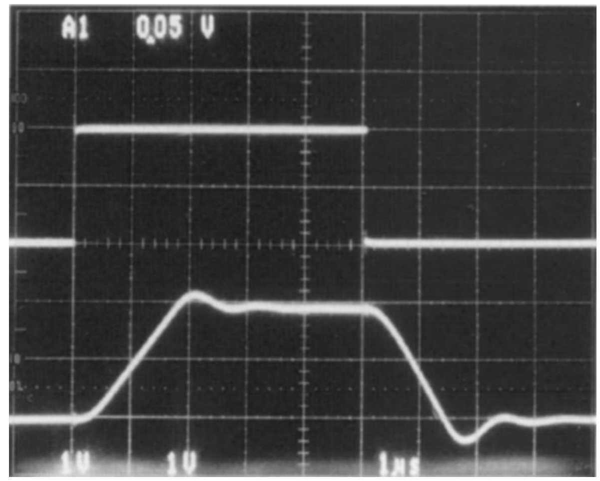
FIGURE 6. LMC6482 Noninverting Amplifier, Compensated to Handle a 330pF Capacitive Load

R1 and C1 serve to counteract the loss of phase margin by feeding forward the high frequency component of the output signal back to the amplifiers inverting input, thereby preserving phase margin in the overall feedback loop. The values of R1 and C1 are experimentally determined for the desired pulse response. The resulting pulse response can be seen in *Figure 7*.

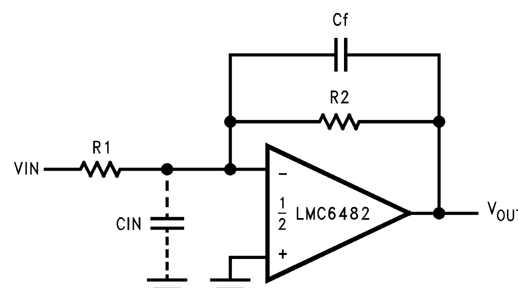


01171316

FIGURE 7. Pulse Response of LMC6482 Circuit in *Figure 6*

5.0 COMPENSATING FOR INPUT CAPACITANCE

It is quite common to use large values of feedback resistance with amplifiers that have ultra-low input current, like the LMC6482. Large feedback resistors can react with small values of input capacitance due to transducers, photodiodes, and circuits board parasitics to reduce phase margins.



01171319

FIGURE 8. Canceling the Effect of Input Capacitance

The effect of input capacitance can be compensated for by adding a feedback capacitor. The feedback capacitor (as in *Figure 8*), C_f, is first estimated by:

$$\frac{1}{2\pi R_1 C_{IN}} \geq \frac{1}{2\pi R_2 C_f}$$

or

$$R_1 C_{IN} \leq R_2 C_f$$

which typically provides significant overcompensation.

Printed circuit board stray capacitance may be larger or smaller than that of a bread-board, so the actual optimum value for C_f may be different. The values of C_f should be checked on the actual circuit. (Refer to the LMC660 quad CMOS amplifier data sheet for a more detailed discussion.)

Application Information (Continued)

6.0 PRINTED-CIRCUIT-BOARD LAYOUT FOR HIGH-IMPEDANCE WORK

It is generally recognized that any circuit which must operate with less than 1000pA of leakage current requires special layout of the PC board. When one wishes to take advantage of the ultra-low input current of the LMC6482, typically less than 20fA, it is essential to have an excellent layout. Fortunately, the techniques of obtaining low leakages are quite simple. First, the user must not ignore the surface leakage of the PC board, even through it may sometimes appear acceptably low, because under conditions of high humidity or dust or contamination, the surface leakage will be appreciable.

To minimize the effect of any surface leakage, lay out a ring of foil completely surrounding the LM6482's inputs and the terminals of capacitors, diodes, conductors, resistors, relay terminals, etc. connected to the op-amp's inputs, as in *Figure 9*. To have a significant effect, guard rings should be placed on both the top and bottom of the PC board. This PC foil must then be connected to a voltage which is at the same voltage as the amplifier inputs, since no leakage current can flow between two points at the same potential. For example, a PC board trace-to-pad resistance of $10^{12}\Omega$, which is normally considered a very large resistance, could leak 5pA if the trace were a 5V bus adjacent to the pad of the input. This would cause a 250 times degradation from the LMC6482's actual performance. However, if a guard ring is held within 5 mV of the inputs, then even a resistance of $10^{11}\Omega$ would cause only 0.05pA of leakage current. See *Figure 10* for typical connections of guard rings for standard op-amp configurations.

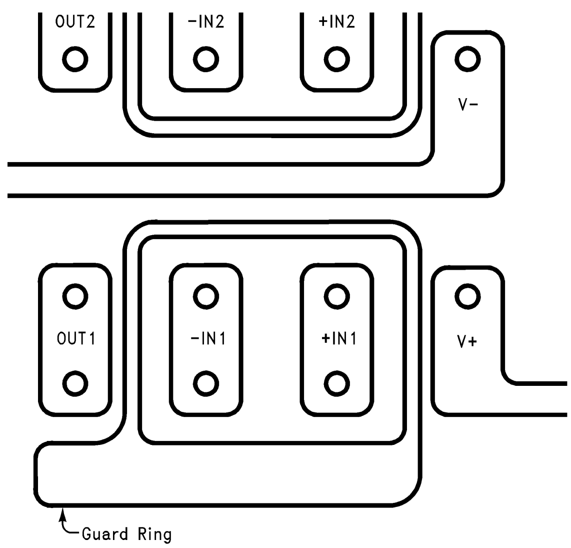
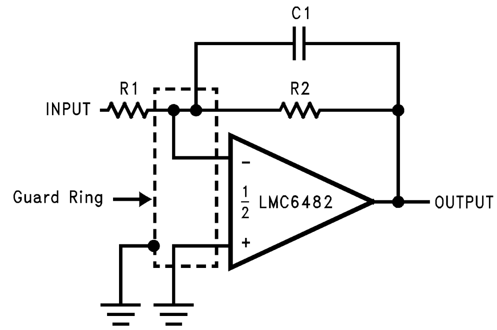
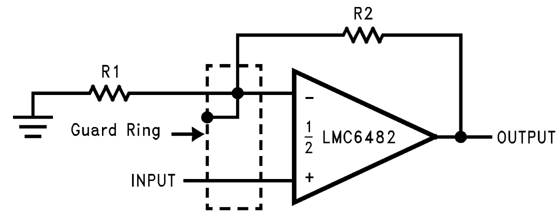


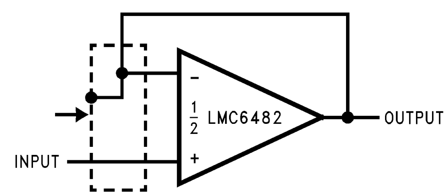
FIGURE 9. Example of Guard Ring in P.C. Board Layout



Inverting Amplifier



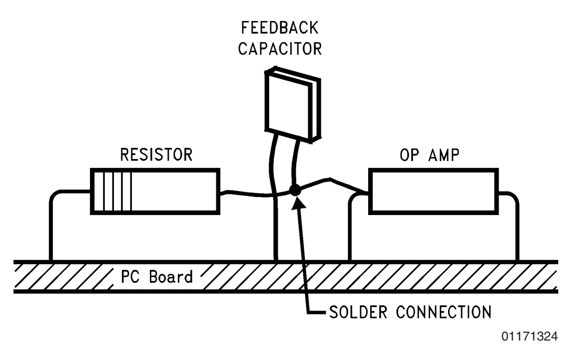
Non-Inverting Amplifier



Follower

FIGURE 10. Typical Connections of Guard Rings

The designer should be aware that when it is inappropriate to lay out a PC board for the sake of just a few circuits, there is another technique which is even better than a guard ring on a PC board: Don't insert the amplifier's input pin into the board at all, but bend it up in the air and use only air as an insulator. Air is an excellent insulator. In this case you may have to forego some of the advantages of PC board construction, but the advantages are sometimes well worth the effort of using point-to-point up-in-the-air wiring. See *Figure 11*.



(Input pins are lifted out of PC board and soldered directly to components. All other pins connected to PC board.)

FIGURE 11. Air Wiring

Application Information (Continued)

7.0 OFFSET VOLTAGE ADJUSTMENT

Offset voltage adjustment circuits are illustrated in *Figure 12 Figure 13*. Large value resistances and potentiometers are used to reduce power consumption while providing typically ±2.5mV of adjustment range, referred to the input, for both configurations with $V_S = \pm 5V$.

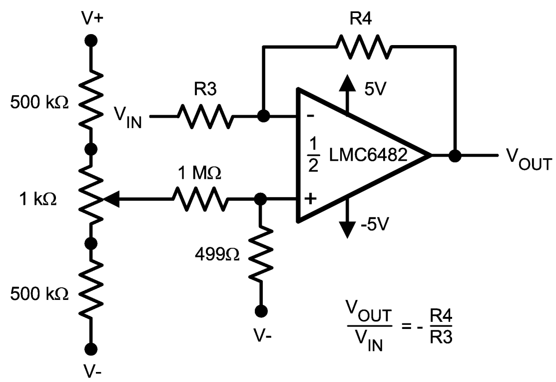


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FIGURE 12. Inverting Configuration Offset Voltage Adjustment

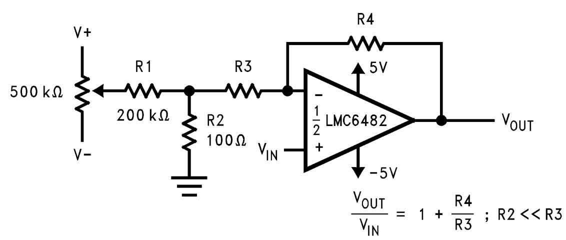

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FIGURE 13. Non-Inverting Configuration Offset Voltage Adjustment

8.0 UPGRADING APPLICATIONS

The LMC6484 quads and LMC6482 duals have industry standard pin outs to retrofit existing applications. System performance can be greatly increased by the LMC6482's features. The key benefit of designing in the LMC6482 is increased linear signal range. Most op-amps have limited input common mode ranges. Signals that exceed this range generate a non-linear output response that persists long after the input signal returns to the common mode range.

Linear signal range is vital in applications such as filters where signal peaking can exceed input common mode ranges resulting in output phase inverison or severe distortion.

9.0 DATA ACQUISITION SYSTEMS

Low power, single supply data acquisition system solutions are provided by buffering the ADC12038 with the LMC6482 (*Figure 14*). Capable of using the full supply range, the LMC6482 does not require input signals to be scaled down to meet limited common mode voltage ranges. The LMC4282 CMRR of 82dB maintains integral linearity of a 12-bit data acquisition system to ±0.325 LSB. Other rail-to-rail input amplifiers with only 50dB of CMRR will degrade the accuracy of the data acquisition system to only 8 bits.

Application Information (Continued)

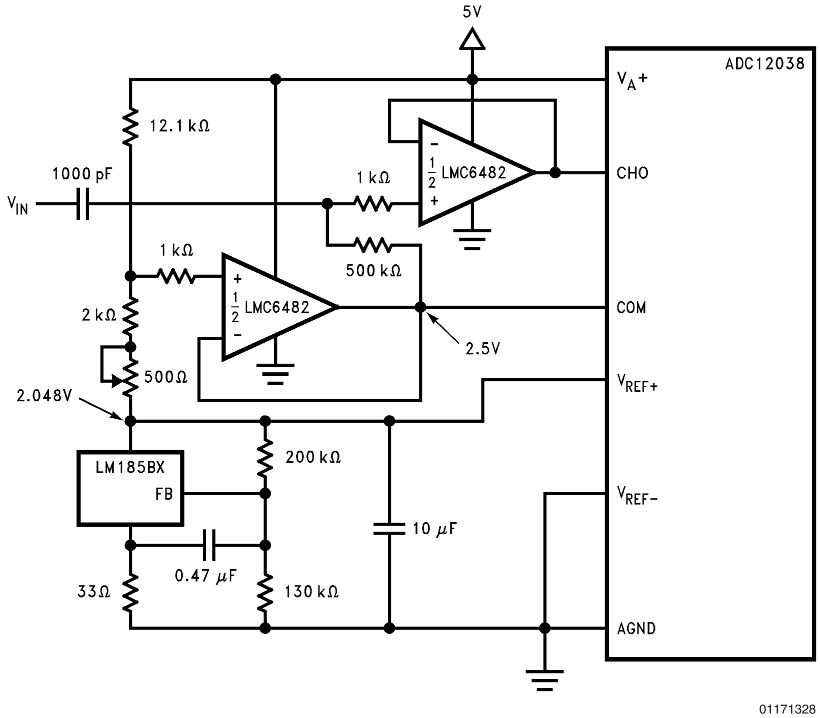


FIGURE 14. Operating from the same Supply Voltage, the LMC6482 buffers the ADC12038 maintaining excellent accuracy

10.0 INSTRUMENTATION CIRCUITS

The LMC6482 has the high input impedance, large common-mode range and high CMRR needed for designing instrumentation circuits. Instrumentation circuits designed with the LMC6482 can reject a larger range of common-mode signals than most in-amps. This makes instrumentation circuits designed with the LMC6482 an excellent choice of noisy or industrial environments. Other applications that benefit from these features include analytic medical instruments, magnetic field detectors, gas detectors, and silicon-based tranducers.

A small valued potentiometer is used in series with R_g to set the differential gain of the 3 op-amp instrumentation circuit in *Figure 15*. This combination is used instead of one large valued potentiometer to increase gain trim accuracy and reduce error due to vibration.

Application Information (Continued)

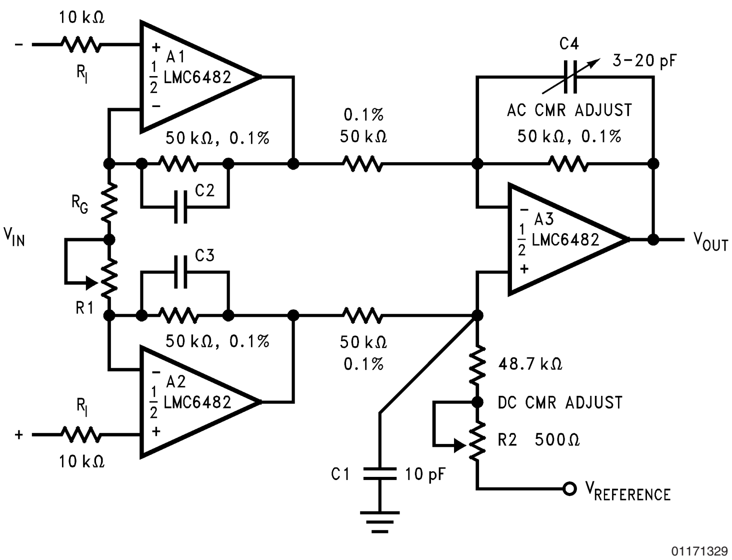


FIGURE 15. Low Power 3 Op-Amp Instrumentation Amplifier

A 2 op-amp instrumentation amplifier designed for a gain of 100 is shown in *Figure 16*. Low sensitivity trimming is made for offset voltage, CMRR and gain. Low cost and low power consumption are the main advantages of this two op-amp circuit.

Higher frequency and larger common-mode range applications are best facilitated by a three op-amp instrumentation amplifier.

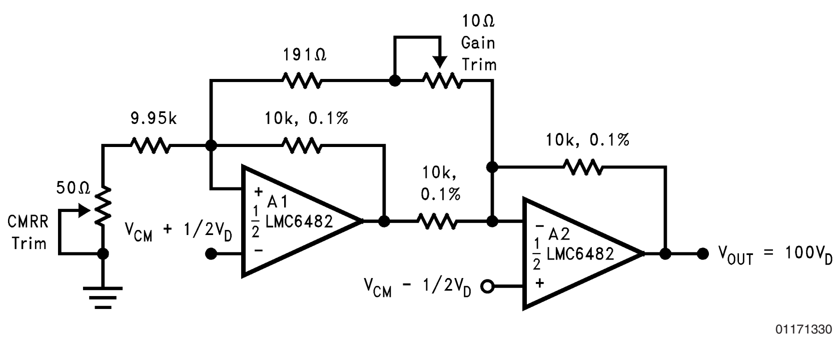


FIGURE 16. Low-Power Two-Op-Amp Instrumentation Amplifier

11.0 SPICE MACROMODEL

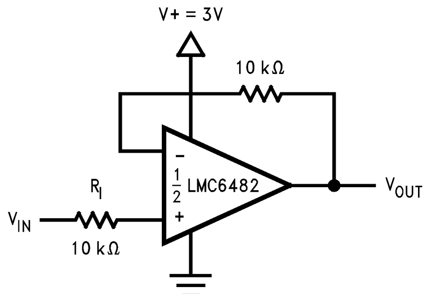
A spice macromodel is available for the LMC6482. This model includes accurate simulation of:

- Input common-mode voltage range
- Frequency and transient response
- GBW dependence on loading conditions
- Quiescent and dynamic supply current
- Output swing dependence on loading conditions

and many more characteristics as listed on the macromodel disk.

Contact your local National Semiconductor sales office to obtain an operational amplifier spice model library disk.

Typical Single-Supply Applications



01171331

FIGURE 17. Half-Wave Rectifier with Input Current Protection (RI)

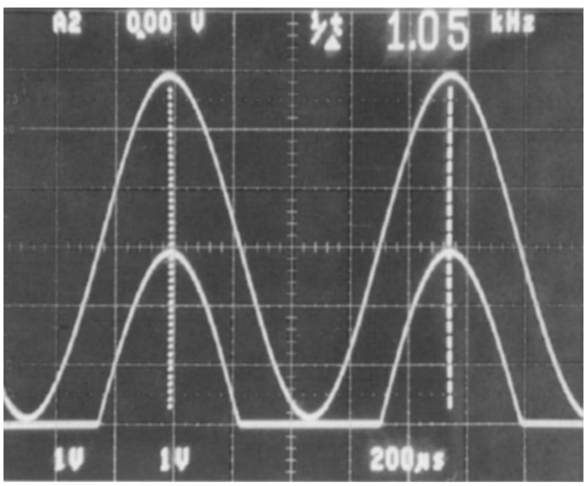


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FIGURE 18. Half-Wave Rectifier Waveform

The circuit in *Figure 17* uses a single supply to half wave rectify a sinusoid centered about ground. R_I limits current into the amplifier caused by the input voltage exceeding the supply voltage. Full wave rectification is provided by the circuit in *Figure 19*.

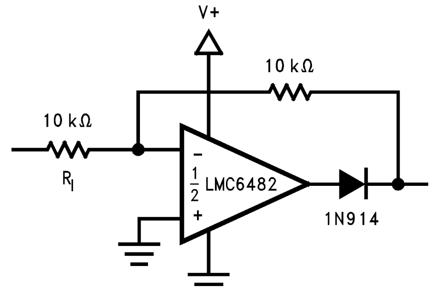

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FIGURE 19. Full Wave Rectifier with Input Current Protection (R_I)

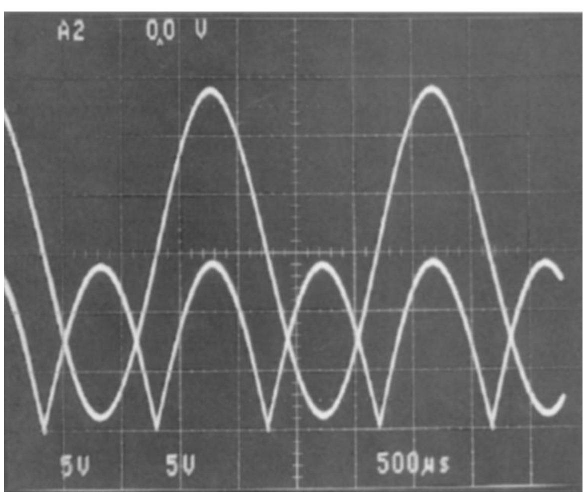

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FIGURE 20. Full Wave Rectifier Waveform

Typical Single-Supply Applications
(Continued)

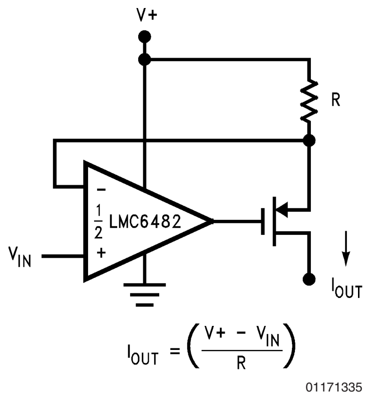


FIGURE 21. Large Compliance Range Current Source

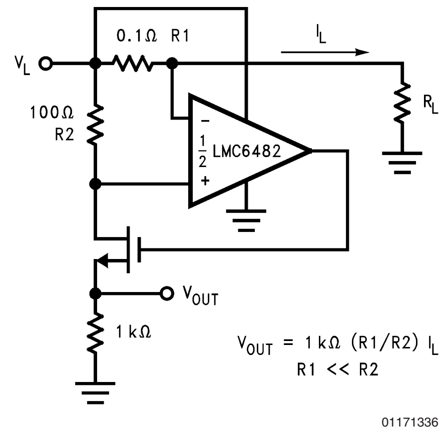


FIGURE 22. Positive Supply Current Sense

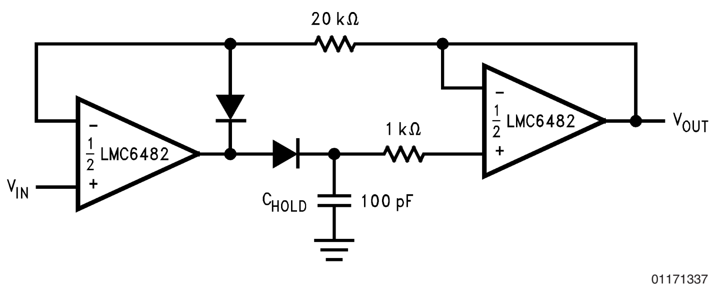


FIGURE 23. Low Voltage Peak Detector with Rail-to-Rail Peak Capture Range

In *Figure 23* dielectric absorption and leakage is minimized by using a polystyrene or polyethylene hold capacitor. The droop rate is primarily determined by the value of C_H and diode leakage current. The ultra-low input current of the LMC6482 has a negligible effect on droop.

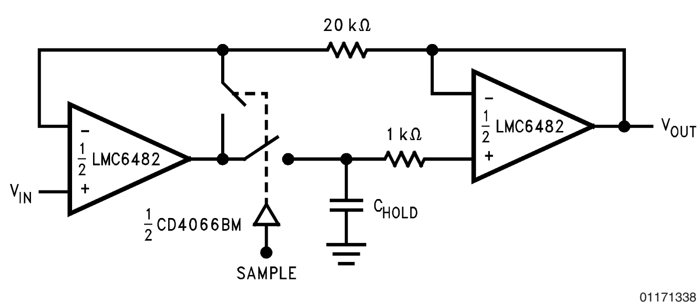
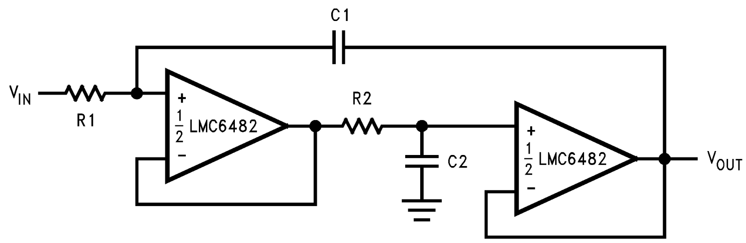


FIGURE 24. Rail-to-Rail Sample and Hold

The LMC6482's high CMRR (82dB) allows excellent accuracy throughout the circuit's rail-to-rail dynamic capture range.

Typical Single-Supply Applications (Continued)



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$$R1 = R2, C1 = C2; f = \frac{1}{2\pi R1\ C1}; DF = \frac{1}{2}\sqrt{\frac{C_2}{C_1}}\sqrt{\frac{R_2}{R_1}}$$

FIGURE 25. Rail-to-Rail Single Supply Low Pass Filter

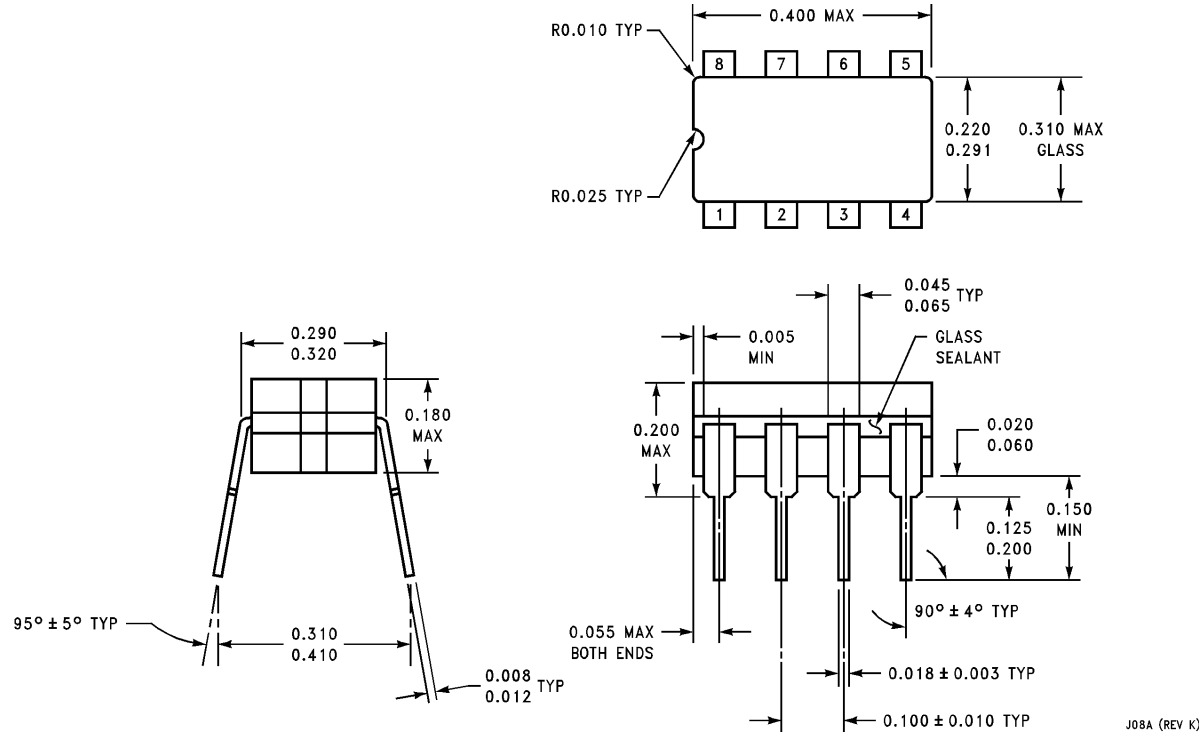
The low pass filter circuit in *Figure 25* can be used as an anti-aliasing filter with the same voltage supply as the A/D converter.

Filter designs can also take advantage of the LMC6482 ultra-low input current. The ultra-low input current yields negligible offset error even when large value resistors are used. This in turn allows the use of smaller valued capacitors which take less board space and cost less.

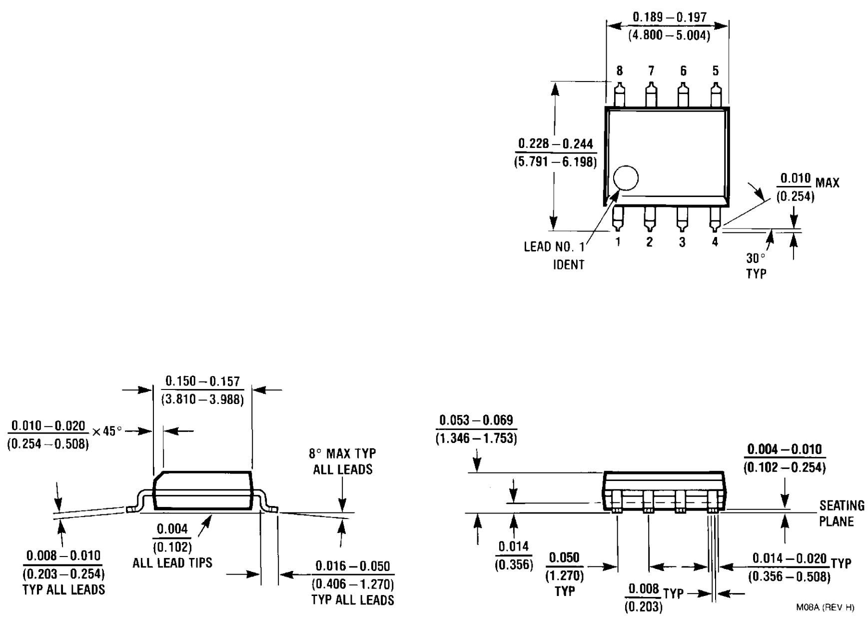
Ordering Information

Package	Temperature Range		NSC Drawing	Transport Media	Package Marking
	Military −55˚C to +125˚C	Industrial −40˚C to +85˚C			
8-Pin Molded DIP		LMC6482AIN, LMC6482IN	N08E	Rail	LMC6482MN, LMC6482AIN, LMC6482IN
8-pin Small Outline		LMC6482AIM, LMC6482AIMX LMC6482IM, LMC6482IMX	M08A	Rail Tape and Reel	LMC6482AIM, LMC6482IM
8-pin Ceramic DIP	LMC6482AMJ/883		J08A	Rail	LMC6482AMJ/883Q5962-9453401MPA
8-pin Mini SO		LMC6482IMM LMC6482IMMX	MUA08A	Rail Tape and Reel	A10

Physical Dimensions inches (millimeters) unless otherwise noted

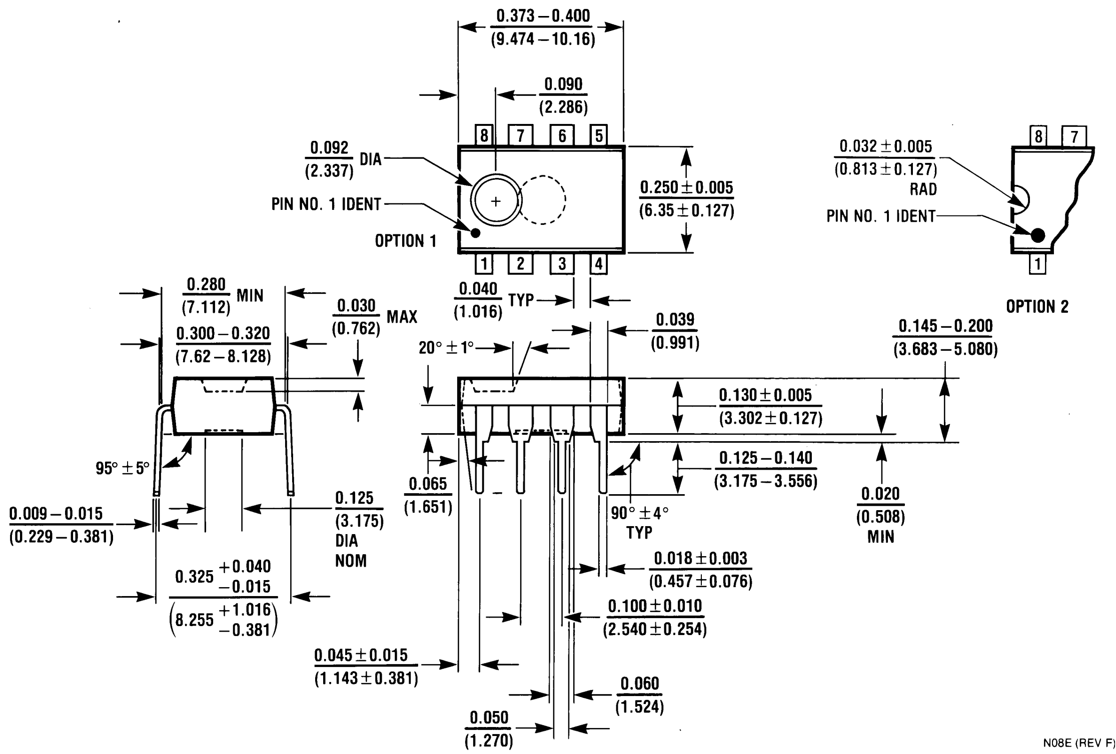


8-Pin Ceramic Dual-In-Line Package
Order Number LMC6482AMJ/883
NS Package Number J08A

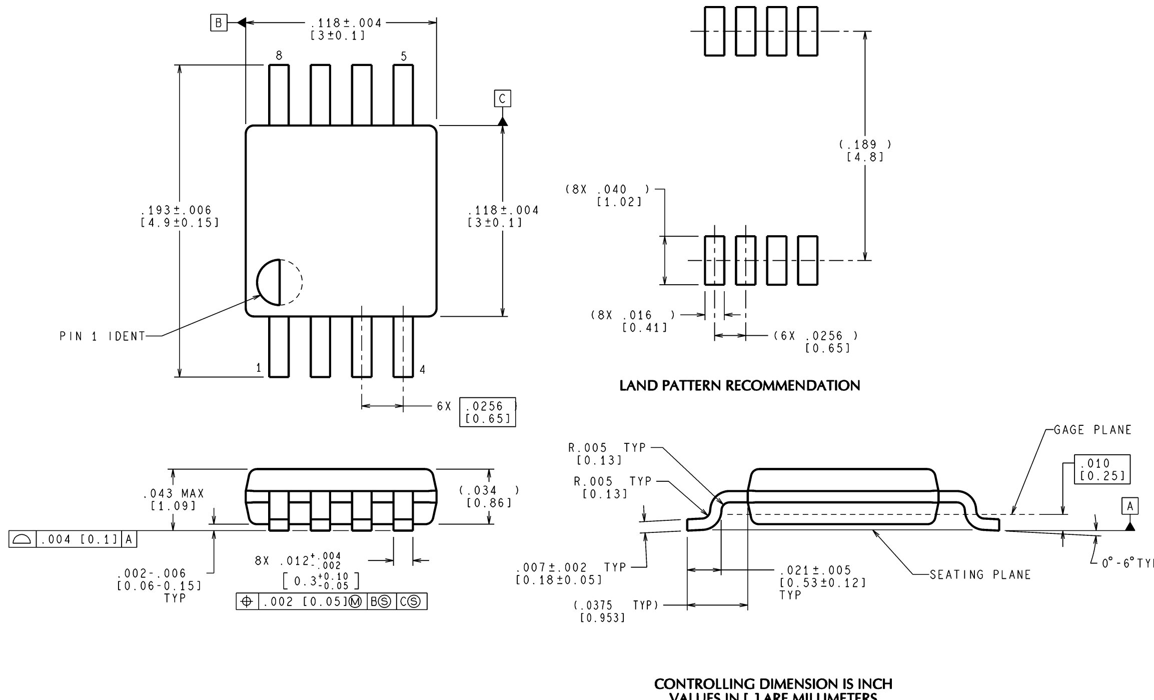


8-Pin Small Outline Package
Order Package Number LMC6482AIM, LMC6482AIMX, LMC6482IM or LMC6482IMX
NS Package Number M08A

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)



8-Pin Molded Dual-In-Line Package
Order Package Number LMC6482AIN, LMC6482IN
NS Package Number N08E



8-Lead Mini Small Outline Molded Package, JEDEC
Order Number LMC6482IMM, or LMC6482IMMX
NS Package Number MUA08A

National Semiconductor

December 1999

LMD18200
3A, 55V H-Bridge

General Description

The LMD18200 is a 3A H-Bridge designed for motion control applications. The device is built using a multi-technology process which combines bipolar and CMOS control circuitry with DMOS power devices on the same monolithic structure. Ideal for driving DC and stepper motors; the LMD18200 accommodates peak output currents up to 6A. An innovative circuit which facilitates low-loss sensing of the output current has been implemented.

Features

- Delivers up to 3A continuous output
- Operates at supply voltages up to 55V
- Low R_{DS}(ON) typically 0.3Ω per switch
- TTL and CMOS compatible inputs
- No “shoot-through” current
- Thermal warning flag output at 145˚C
- Thermal shutdown (outputs off) at 170˚C
- Internal clamp diodes
- Shorted load protection
- Internal charge pump with external bootstrap capability

Applications

- DC and stepper motor drives
- Position and velocity servomechanisms
- Factory automation robots
- Numerically controlled machinery
- Computer printers and plotters

Functional Diagram

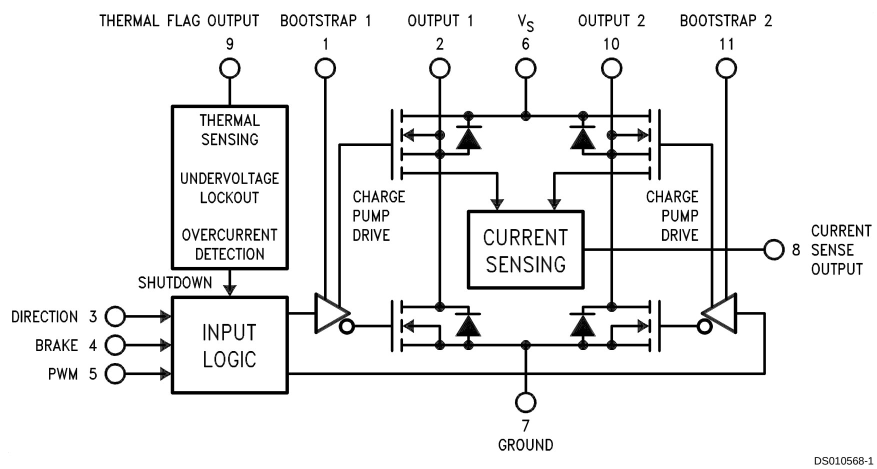
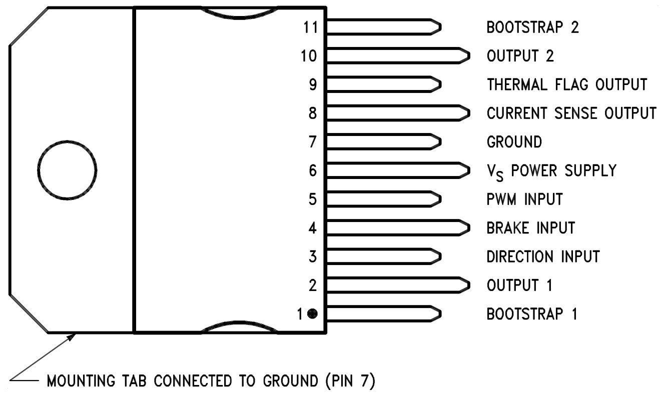
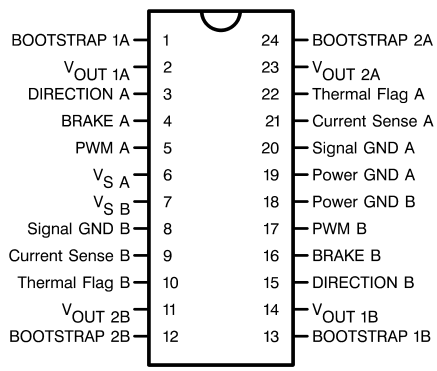


FIGURE 1. Functional Block Diagram of LMD18200

Connection Diagrams and Ordering Information



11-Lead TO-220 Package
Top View
Order Number LMD18200T
See NS Package TA11B



24-Lead Dual-in-Line Package
Top View
Order Number LMD18200-2D-QV
5962-9232501VXA
LMD18200-2D/883
5962-9232501MXA
See NS Package DA24B

Absolute Maximum Ratings (Note 1)

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

Total Supply Voltage (V_S, Pin 6)	60V
Voltage at Pins 3, 4, 5, 8 and 9	12V
Voltage at Bootstrap Pins	
(Pins 1 and 11)	V_{OUT} +16V
Peak Output Current (200 ms)	6A
Continuous Output Current (Note 2)	3A
Power Dissipation (Note 3)	25W
Power Dissipation (T_A = 25˚C, Free Air)	3W
Junction Temperature, $T_{J(max)}$	150˚C
ESD Susceptibility (Note 4)	1500V
Storage Temperature, T_{STG}	−40˚C to +150˚C
Lead Temperature (Soldering, 10 sec.)	300˚C

Operating Ratings (Note 1)

Junction Temperature, T_J	−40˚C to +125˚C
V_S Supply Voltage	+12V to +55V

Electrical Characteristics (Note 5)

The following specifications apply for V_S = 42V, unless otherwise specified. **Boldface** limits apply over the entire operating temperature range, −40˚C ≤ T_J ≤ +125˚C, all other limits are for T_A = T_J = 25˚C.

Symbol	Parameter	Conditions	Typ	Limit	Units
R_{DS}(ON)	Switch ON Resistance	Output Current = 3A (Note 6)	0.33	0.4/**0.6**	Ω (max)
R_{DS}(ON)	Switch ON Resistance	Output Current = 6A (Note 6)	0.33	0.4/**0.6**	Ω (max)
V_{CLAMP}	Clamp Diode Forward Drop	Clamp Current = 3A (Note 6)	1.2	1.5	V (max)
V_{IL}	Logic Low Input Voltage	Pins 3, 4, 5		**−0.1**	V (min)
				0.8	V (max)
I_{IL}	Logic Low Input Current	V_{IN} = −0.1V, Pins = 3, 4, 5		**−10**	µA (max)
V_{IH}	Logic High Input Voltage	Pins 3, 4, 5		**2**	V (min)
				12	V (max)
I_{IH}	Logic High Input Current	V_{IN} = 12V, Pins = 3, 4, 5		**10**	µA (max)
	Current Sense Output	I_{OUT} = 1A (Note 8)	377	325/**300**	µA (min)
				425/**450**	µA (max)
	Current Sense Linearity	1A ≤ I_{OUT} ≤ 3A (Note 7)	±6	±9	%
	Undervoltage Lockout	Outputs turn OFF		9	V (min)
				11	V (max)
T_{JW}	Warning Flag Temperature	Pin 9 ≤ 0.8V, I_L = 2 mA	145		˚C
V_F(ON)	Flag Output Saturation Voltage	T_J = T_{JW}, I_L = 2 mA	0.15		V
I_F(OFF)	Flag Output Leakage	V_F = 12V	0.2	10	µA (max)
T_{JSD}	Shutdown Temperature	Outputs Turn OFF	170		˚C
I_S	Quiescent Supply Current	All Logic Inputs Low	13	25	mA (max)
t_{Don}	Output Turn-On Delay Time	Sourcing Outputs, I_{OUT} = 3A	300		ns
		Sinking Outputs, I_{OUT} = 3A	300		ns
t_{on}	Output Turn-On Switching Time	Bootstrap Capacitor = 10 nF			
		Sourcing Outputs, I_{OUT} = 3A	100		ns
		Sinking Outputs, I_{OUT} = 3A	80		ns
t_{Doff}	Output Turn-Off Delay Times	Sourcing Outputs, I_{OUT} = 3A	200		ns
		Sinking Outputs, I_{OUT} = 3A	200		ns
t_{off}	Output Turn-Off Switching Times	Bootstrap Capacitor = 10 nF			
		Sourcing Outputs, I_{OUT} = 3A	75		ns
		Sinking Outputs, I_{OUT} = 3A	70		ns
t_{pw}	Minimum Input Pulse Width	Pins 3, 4 and 5	1		µs
t_{cpr}	Charge Pump Rise Time	No Bootstrap Capacitor	20		µs

Electrical Characteristics Notes

Note 1: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. DC and AC electrical specifications do not apply when operating the device beyond its rated operating conditions.

Note 2: See Application Information for details regarding current limiting.

Note 3: The maximum power dissipation must be derated at elevated temperatures and is a function of $T_{J(max)}$, θ_{JA}, and T_A. The maximum allowable power dissipation at any temperature is $P_{D(max)} = (T_{J(max)} - T_A)/\theta_{JA}$, or the number given in the Absolute Ratings, whichever is lower. The typical thermal resistance from junction to case (θ_{JC}) is 1.0˚C/W and from junction to ambient (θ_{JA}) is 30˚C/W. For guaranteed operation $T_{J(max)}$ = 125˚C.

Note 4: Human-body model, 100 pF discharged through a 1.5 kΩ resistor. Except Bootstrap pins (pins 1 and 11) which are protected to 1000V of ESD.

Note 5: All limits are 100% production tested at 25˚C. Temperature extreme limits are guaranteed via correlation using accepted SQC (Statistical Quality Control) methods. All limits are used to calculate AOQL, (Average Outgoing Quality Level).

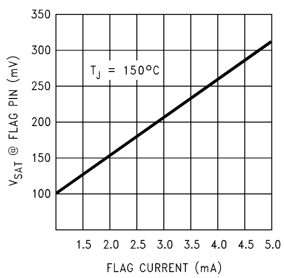
Note 6: Output currents are pulsed (t_W < 2 ms, Duty Cycle < 5%).

Note 7: Regulation is calculated relative to the current sense output value with a 1A load.

Note 8: Selections for tighter tolerance are available. Contact factory.

Typical Performance Characteristics

V_{SAT} vs Flag Current



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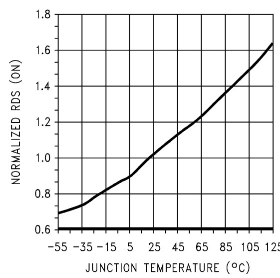
R_{DS}(ON) vs Temperature



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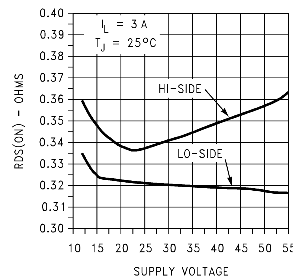
R_{DS}(ON) vs Supply Voltage



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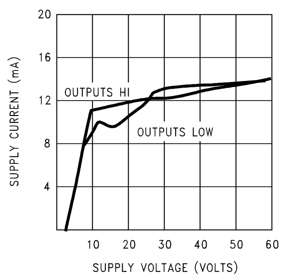
Supply Current vs Supply Voltage



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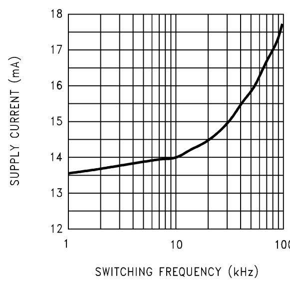
Supply Current vs Frequency (V_S = 42V)



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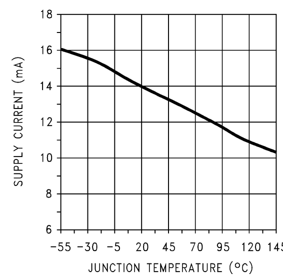
Supply Current vs Temperature (V_S = 42V)



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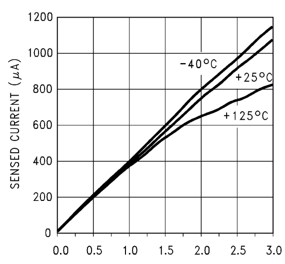
Current Sense Output vs Load Current



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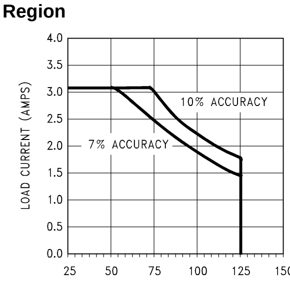
Current Sense Operating Region



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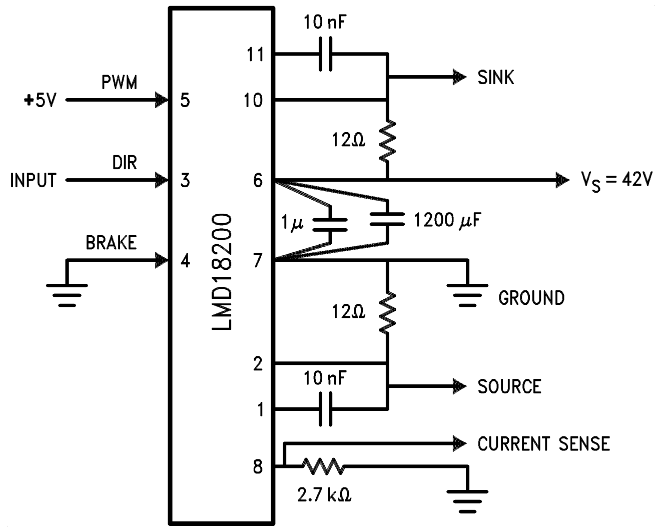
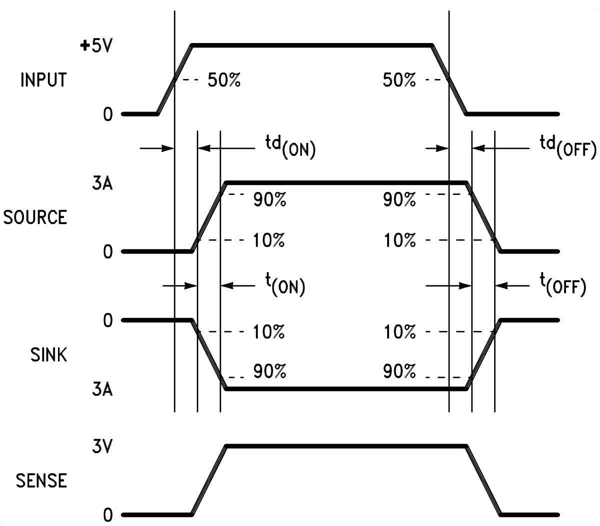
Test Circuit



DS010568-8

Switching Time Definitions



DS010568-9

Pinout Description (See Connection Diagram)

Pin 1, BOOTSTRAP 1 Input: Bootstrap capacitor pin for half H-bridge number 1. The recommended capacitor (10 nF) is connected between pins 1 and 2.

Pin 2, OUTPUT 1: Half H-bridge number 1 output.

Pin 3, DIRECTION Input: See *Table 1*. This input controls the direction of current flow between OUTPUT 1 and OUTPUT 2 (pins 2 and 10) and, therefore, the direction of rotation of a motor load.

Pin 4, BRAKE Input: See *Table 1*. This input is used to brake a motor by effectively shorting its terminals. When braking is desired, this input is taken to a logic high level and it is also necessary to apply logic high to PWM input, pin 5. The drivers that short the motor are determined by the logic level at the DIRECTION input (Pin 3): with Pin 3 logic high, both current sourcing output transistors are ON; with Pin 3 logic low, both current sinking output transistors are ON. All output transistors can be turned OFF by applying a logic high to Pin 4 and a logic low to PWM input Pin 5; in this case only a small bias current (approximately −1.5 mA) exists at each output pin.

Pin 5, PWM Input: See *Table 1*. How this input (and DIRECTION input, Pin 3) is used is determined by the format of the PWM Signal.

Pinout Description

(See Connection Diagram) (Continued)

Pin 6, V_S Power Supply

Pin 7, GROUND Connection: This pin is the ground return, and is internally connected to the mounting tab.

Pin 8, CURRENT SENSE Output: This pin provides the sourcing current sensing output signal, which is typically 377 µA/A.

Pin 9, THERMAL FLAG Output: This pin provides the thermal warning flag output signal. Pin 9 becomes active-low at 145˚C (junction temperature). However the chip will not shut itself down until 170˚C is reached at the junction.

Pin 10, OUTPUT 2: Half H-bridge number 2 output.

Pin 11, BOOTSTRAP 2 Input: Bootstrap capacitor pin for Half H-bridge number 2. The recommended capacitor (10 nF) is connected between pins 10 and 11.

TABLE 1. Logic Truth Table

PWM	Dir	Brake	Active Output Drivers
H	H	L	Source 1, Sink 2
H	L	L	Sink 1, Source 2
L	X	L	Source 1, Source 2
H	H	H	Source 1, Source 2
H	L	H	Sink 1, Sink 2
L	X	H	NONE

Application Information

TYPES OF PWM SIGNALS

The LMD18200 readily interfaces with different forms of PWM signals. Use of the part with two of the more popular forms of PWM is described in the following paragraphs.

Simple, locked anti-phase PWM consists of a single, variable duty-cycle signal in which is encoded both direction and amplitude information (see *Figure 2*). A 50% duty-cycle PWM signal represents zero drive, since the net value of voltage (integrated over one period) delivered to the load is zero. For the LMD18200, the PWM signal drives the direction input (pin 3) and the PWM input (pin 5) is tied to logic high.

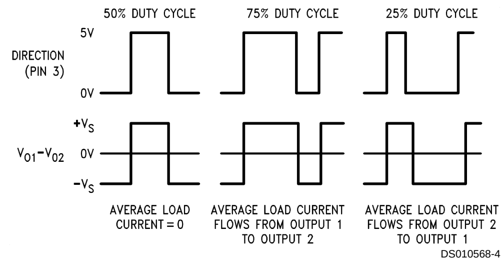


FIGURE 2. Locked Anti-Phase PWM Control

Sign/magnitude PWM consists of separate direction (sign) and amplitude (magnitude) signals (see *Figure 3*). The (absolute) magnitude signal is duty-cycle modulated, and the absence of a pulse signal (a continuous logic low level) represents zero drive. Current delivered to the load is proportional to pulse width. For the LMD18200, the DIRECTION input (pin 3) is driven by the sign signal and the PWM input (pin 5) is driven by the magnitude signal.

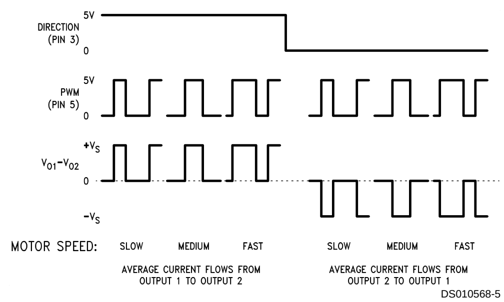


FIGURE 3. Sign/Magnitude PWM Control

SIGNAL TRANSITION REQUIREMENTS

To ensure proper internal logic performance, it is good practice to avoid aligning the falling and rising edges of input signals. A delay of at least 1 µsec should be incorporated between transitions of the Direction, Brake, and/or PWM input signals. A conservative approach is be sure there is at least 500ns delay between the end of the first transition and the beginning of the second transition. See *Figure 4*.

Application Information (Continued)

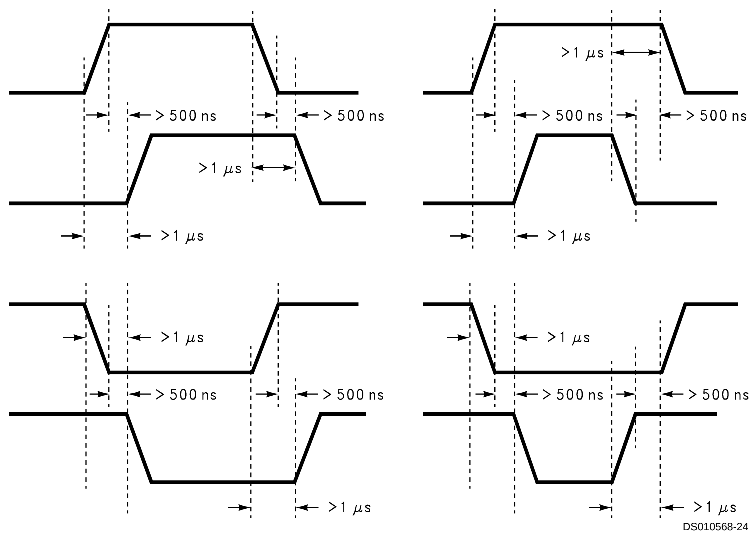


FIGURE 4. Transitions in Brake, Direction, or PWM Must Be Separated By At Least 1 µsec

USING THE CURRENT SENSE OUTPUT

The CURRENT SENSE output (pin 8) has a sensitivity of 377 µA per ampere of output current. For optimal accuracy and linearity of this signal, the value of voltage generating resistor between pin 8 and ground should be chosen to limit the maximum voltage developed at pin 8 to 5V, or less. The maximum voltage compliance is 12V.

It should be noted that the recirculating currents (free wheeling currents) are ignored by the current sense circuitry. Therefore, only the currents in the upper sourcing outputs are sensed.

USING THE THERMAL WARNING FLAG

The THERMAL FLAG output (pin 9) is an open collector transistor. This permits a wired OR connection of thermal warning flag outputs from multiple LMD18200's, and allows the user to set the logic high level of the output signal swing to match system requirements. This output typically drives the interrupt input of a system controller. The interrupt service routine would then be designed to take appropriate steps, such as reducing load currents or initiating an orderly system shutdown. The maximum voltage compliance on the flag pin is 12V.

SUPPLY BYPASSING

During switching transitions the levels of fast current changes experienced may cause troublesome voltage transients across system stray inductance.

It is normally necessary to bypass the supply rail with a high quality capacitor(s) connected as close as possible to the V_S Power Supply (Pin 6) and GROUND (Pin 7). A 1 µF high-frequency ceramic capacitor is recommended. Care should be taken to limit the transients on the supply pin below the Absolute Maximum Rating of the device. When operating the chip at supply voltages above 40V a voltage suppressor (transorb) such as P6KE62A is recommended from supply to ground. Typically the ceramic capacitor can be eliminated in the presence of the voltage suppressor. Note that when driving high load currents a greater amount of supply bypass capacitance (in general at least 100 µF per Amp of load current) is required to absorb the recirculating currents of the inductive loads.

CURRENT LIMITING

Current limiting protection circuitry has been incorporated into the design of the LMD18200. With any power device it is important to consider the effects of the substantial surge currents through the device that may occur as a result of shorted loads. The protection circuitry monitors this increase in current (the threshold is set to approximately 10 Amps) and shuts off the power device as quickly as possible in the event of an overload condition. In a typical motor driving application the most common overload faults are caused by shorted motor windings and locked rotors. Under these conditions the inductance of the motor (as well as any series inductance in the V_{CC} supply line) serves to reduce the magnitude of a current surge to a safe level for the LMD18200. Once the device is shut down, the control circuitry will periodically try to turn the power device back on. This feature allows the immediate return to normal operation in the event that the fault condition has been removed. While the fault remains however, the device will cycle in and out of thermal shutdown. This can create voltage transients on the V_{CC} supply line and therefore proper supply bypassing techniques are required.

The most severe condition for any power device is a direct, hard-wired ("screwdriver") long term short from an output to ground. This condition can generate a surge of current through the power device on the order of 15 Amps and require the die and package to dissipate up to 500 Watts of power for the short time required for the protection circuitry to shut off the power device. This energy can be destructive, particularly at higher operating voltages (>30V) so some precautions are in order. Proper heat sink design is essential and it is normally necessary to heat sink the V_{CC} supply pin (pin 6) with 1 square inch of copper on the PCB.

Application Information (Continued)

INTERNAL CHARGE PUMP AND USE OF BOOTSTRAP CAPACITORS

To turn on the high-side (sourcing) DMOS power devices, the gate of each device must be driven approximately 8V more positive than the supply voltage. To achieve this an internal charge pump is used to provide the gate drive voltage. As shown in *Figure 5*, an internal capacitor is alternately switched to ground and charged to about 14V, then switched to V supply thereby providing a gate drive voltage greater than V supply. This switching action is controlled by a continuously running internal 300 kHz oscillator. The rise time of this drive voltage is typically 20 µs which is suitable for operating frequencies up to 1 kHz.

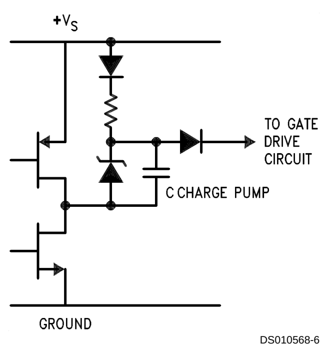


FIGURE 5. Internal Charge Pump Circuitry

For higher switching frequencies, the LMD18200 provides for the use of external bootstrap capacitors. The bootstrap principle is in essence a second charge pump whereby a large value capacitor is used which has enough energy to quickly charge the parasitic gate input capacitance of the power device resulting in much faster rise times. The switching action is accomplished by the power switches themselves *Figure 6*. External 10 nF capacitors, connected from the outputs to the bootstrap pins of each high-side switch provide typically less than 100 ns rise times allowing switching frequencies up to 500 kHz.

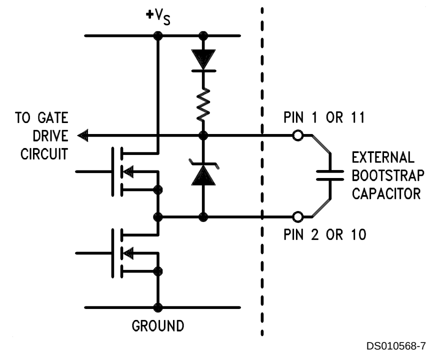


FIGURE 6. Bootstrap Circuitry

INTERNAL PROTECTION DIODES

A major consideration when switching current through inductive loads is protection of the switching power devices from the large voltage transients that occur. Each of the four switches in the LMD18200 have a built-in protection diode to clamp transient voltages exceeding the positive supply or ground to a safe diode voltage drop across the switch.

The reverse recovery characteristics of these diodes, once the transient has subsided, is important. These diodes must come out of conduction quickly and the power switches must be able to conduct the additional reverse recovery current of the diodes. The reverse recovery time of the diodes protecting the sourcing power devices is typically only 70 ns with a reverse recovery current of 1A when tested with a full 6A of forward current through the diode. For the sinking devices the recovery time is typically 100 ns with 4A of reverse current under the same conditions.

Typical Applications

FIXED OFF-TIME CONTROL

This circuit controls the current through the motor by applying an average voltage equal to zero to the motor terminals for a fixed period of time, whenever the current through the motor exceeds the commanded current. This action causes the motor current to vary slightly about an externally controlled average level. The duration of the Off-period is adjusted by the resistor and capacitor combination of the LM555. In this circuit the Sign/Magnitude mode of operation is implemented (see Types of PWM Signals).

Typical Applications (Continued)

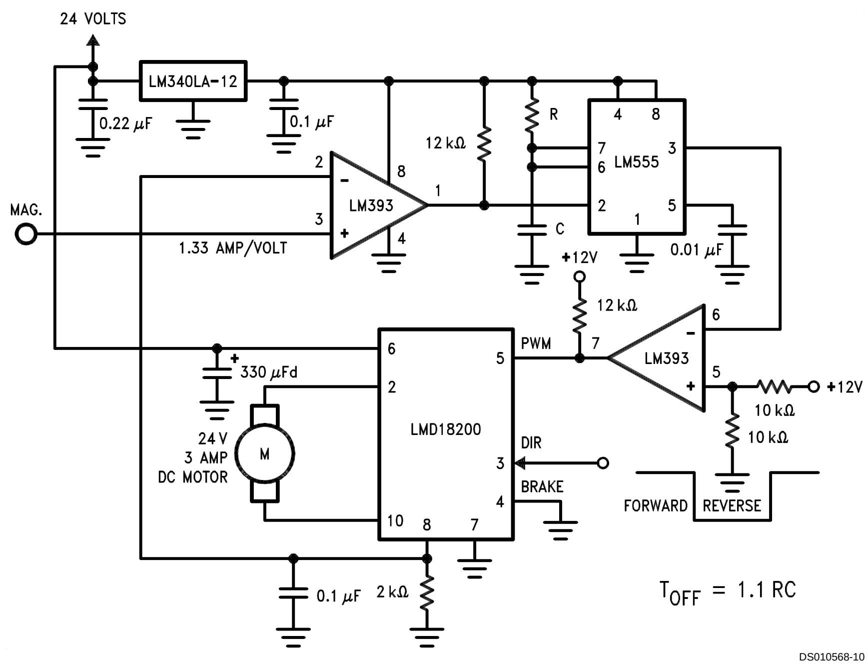


FIGURE 7. Fixed Off-Time Control

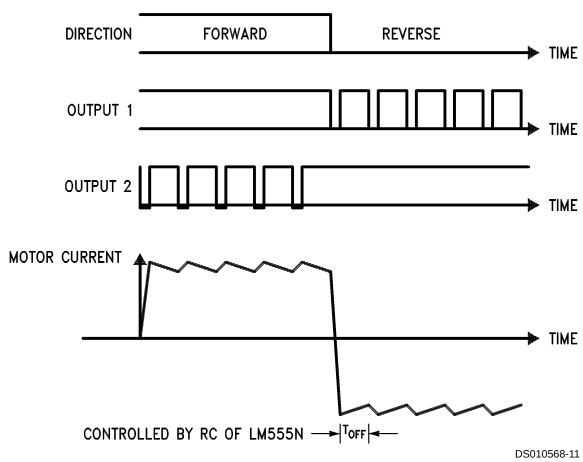


FIGURE 8. Switching Waveforms

TORQUE REGULATION

Locked Anti-Phase Control of a brushed DC motor. Current sense output of the LMD18200 provides load sensing. The LM3525A is a general purpose PWM controller. The relationship of peak motor current to adjustment voltage is shown in *Figure 10*.

Typical Applications (Continued)

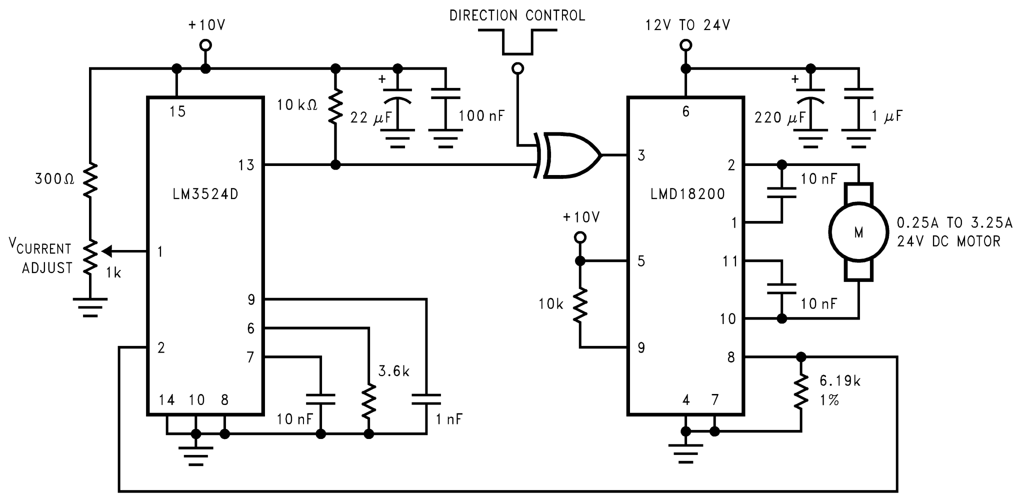


FIGURE 9. Locked Anti-Phase Control Regulates Torque

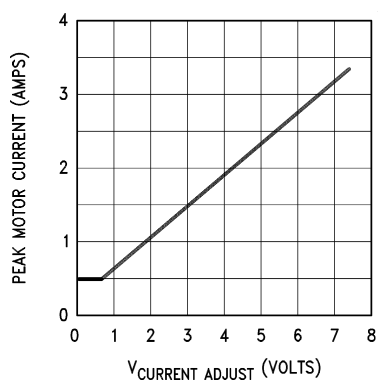


FIGURE 10. Peak Motor Current vs Adjustment Voltage

VELOCITY REGULATION

Utilizes tachometer output from the motor to sense motor speed for a locked anti-phase control loop. The relationship of motor speed to the speed adjustment control voltage is shown in *Figure 12.*

Typical Applications (Continued)

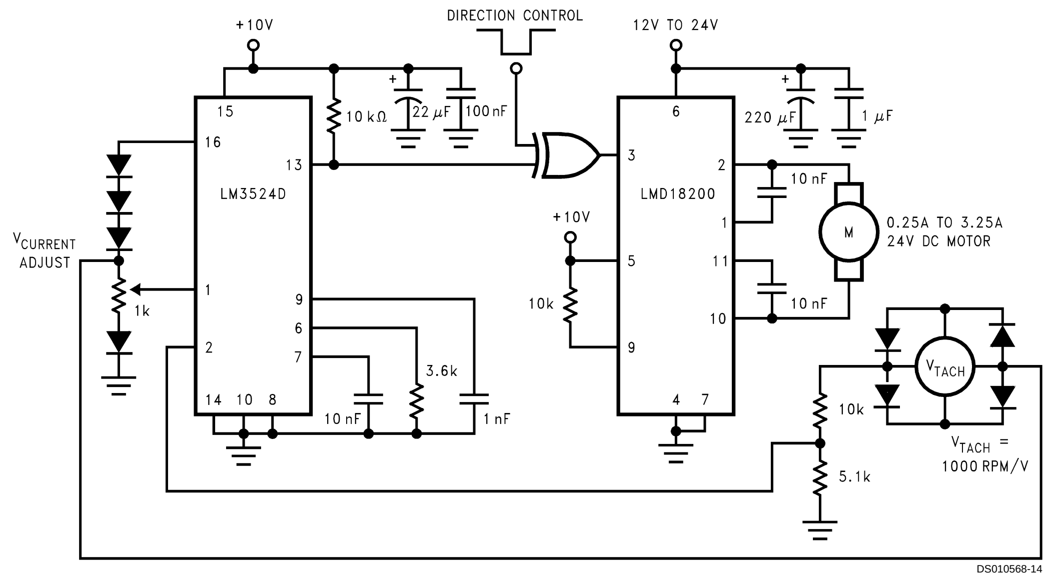


FIGURE 11. Regulate Velocity with Tachometer Feedback

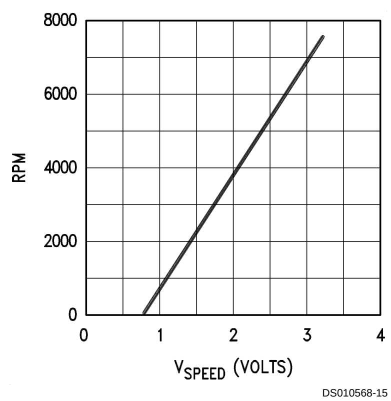
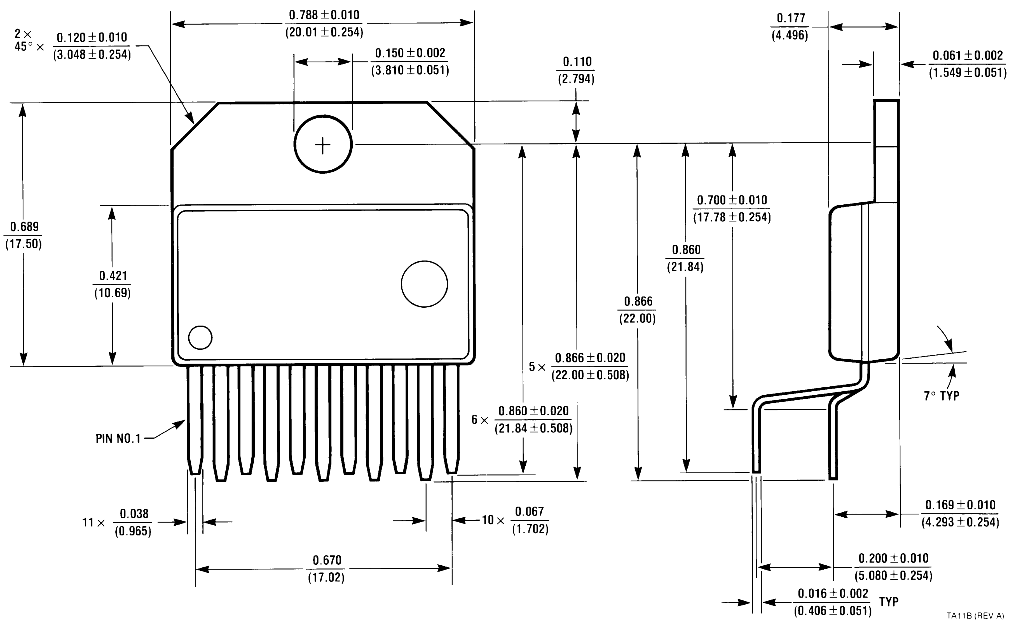
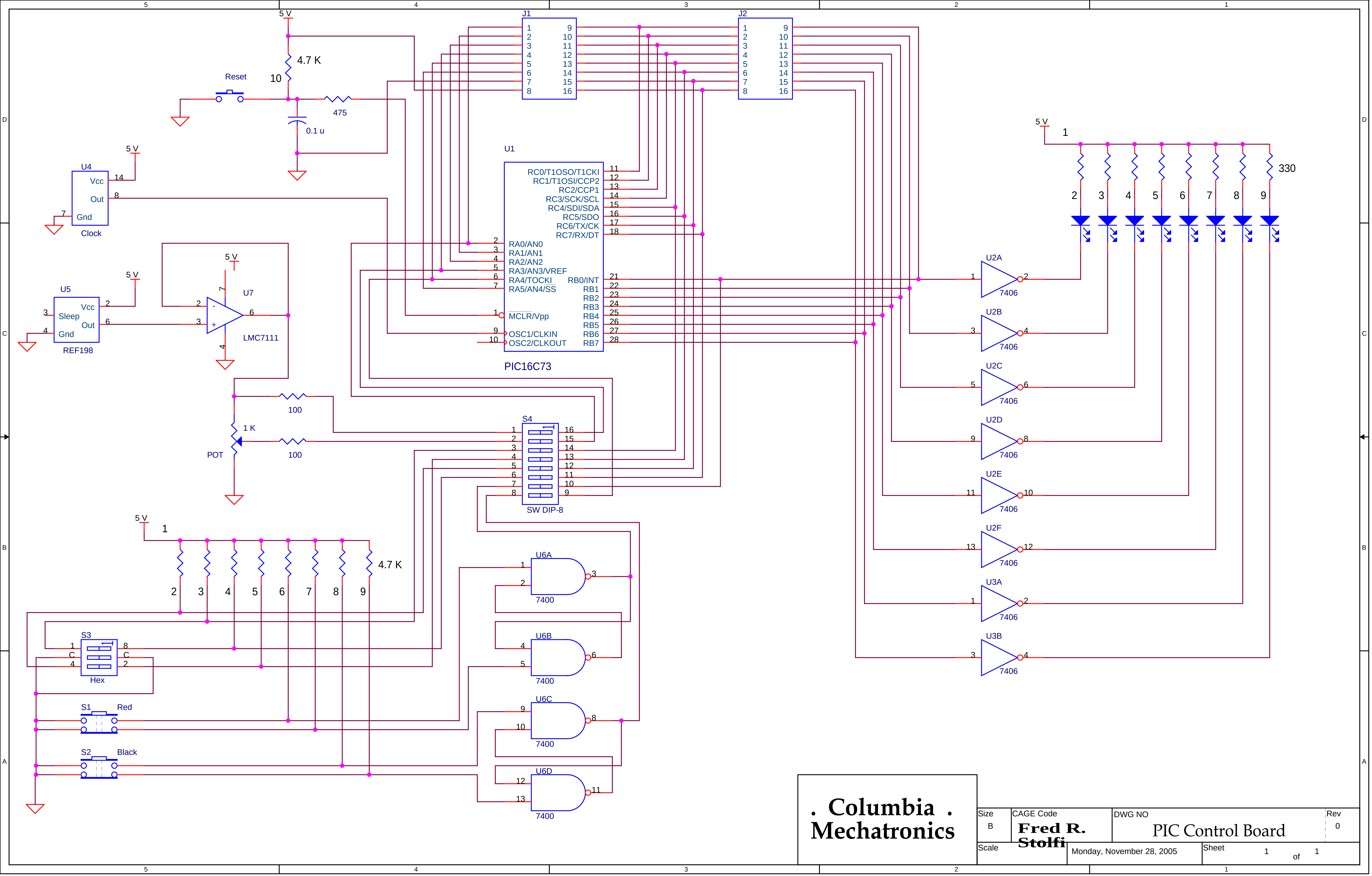


FIGURE 12. Motor Speed vs Control Voltage

Physical Dimensions inches (millimeters) unless otherwise noted



11-Lead TO-220 Power Package (T)
Order Number LMD18200T
NS Package Number TA11B



J1
J2
Reset
4.7 K
10
475
0.1 u
5 V
U4
Vcc
Out
Gnd
Clock
U5
Sleep
REF198
U7
LMC7111
U1
RC0/T1OSO/T1CKI
RC1/T1OSI/CCP2
RC2/CCP1
RC3/SCK/SCL
RC4/SDI/SDA
RC5/SDO
RC6/TX/CK
RC7/RX/DT
RA0/AN0
RA1/AN1
RA2/AN2
RA3/AN3/VREF
RA4/TOCKI
RA5/AN4/SS
RB0/INT
RB1
RB2
RB3
RB4
RB5
RB6
RB7
MCLR/Vpp
OSC1/CLKIN
OSC2/CLKOUT
PIC16C73
100
1 K
POT
S4
SW DIP-8
330
U2A
U2B
U2C
U2D
U2E
U2F
U3A
U3B
7406
U6A
U6B
U6C
U6D
7400
S3
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S1
Red
S2
Black
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Mechatronics
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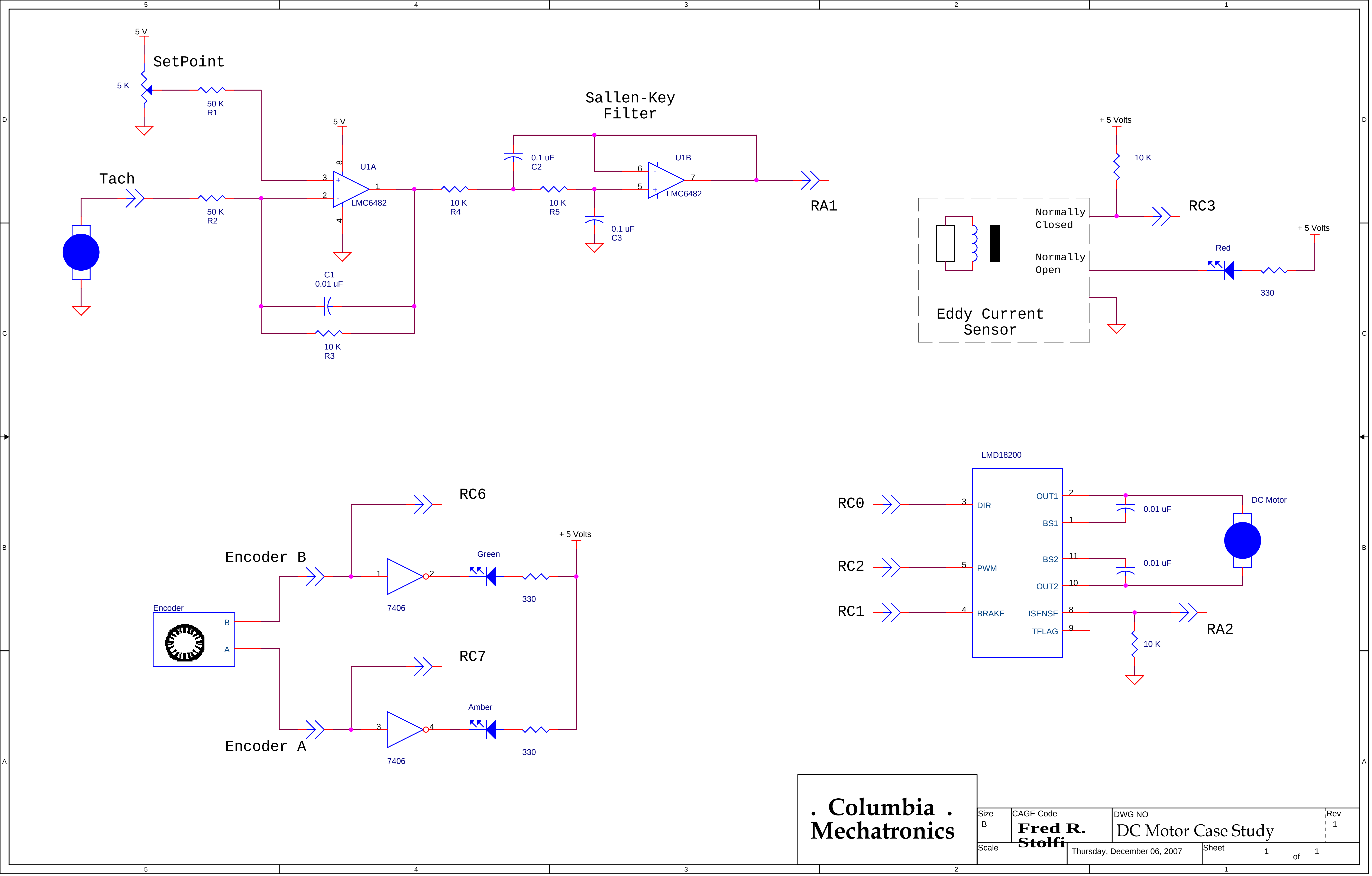
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5 K
50 K R1
Tach
50 K R2
5 V
U1A
LMC6482
C1 0.01 uF
10 K R3
Sallen-Key Filter
0.1 uF C2
10 K R4
10 K R5
0.1 uF C3
U1B
LMC6482
RA1
+ 5 Volts
10 K
RC3
Normally Closed
Normally Open
Eddy Current Sensor
Red
+ 5 Volts
330
RC6
Encoder B
7406
Green
+ 5 Volts
330
Encoder
B
A
RC7
Encoder A
7406
Amber
330
LMD18200
RC0
DIR
RC2
PWM
RC1
BRAKE
OUT1
BS1
BS2
OUT2
ISENSE
TFLAG
0.01 uF
0.01 uF
DC Motor
RA2
10 K
. Columbia . Mechatronics
Size B
CAGE Code
Fred R. Stolfi
DWG NO
DC Motor Case Study
Rev 1
Scale
Thursday, December 06, 2007
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