Inverted Pendulum Control

PHYS 3090: Analog Electronics
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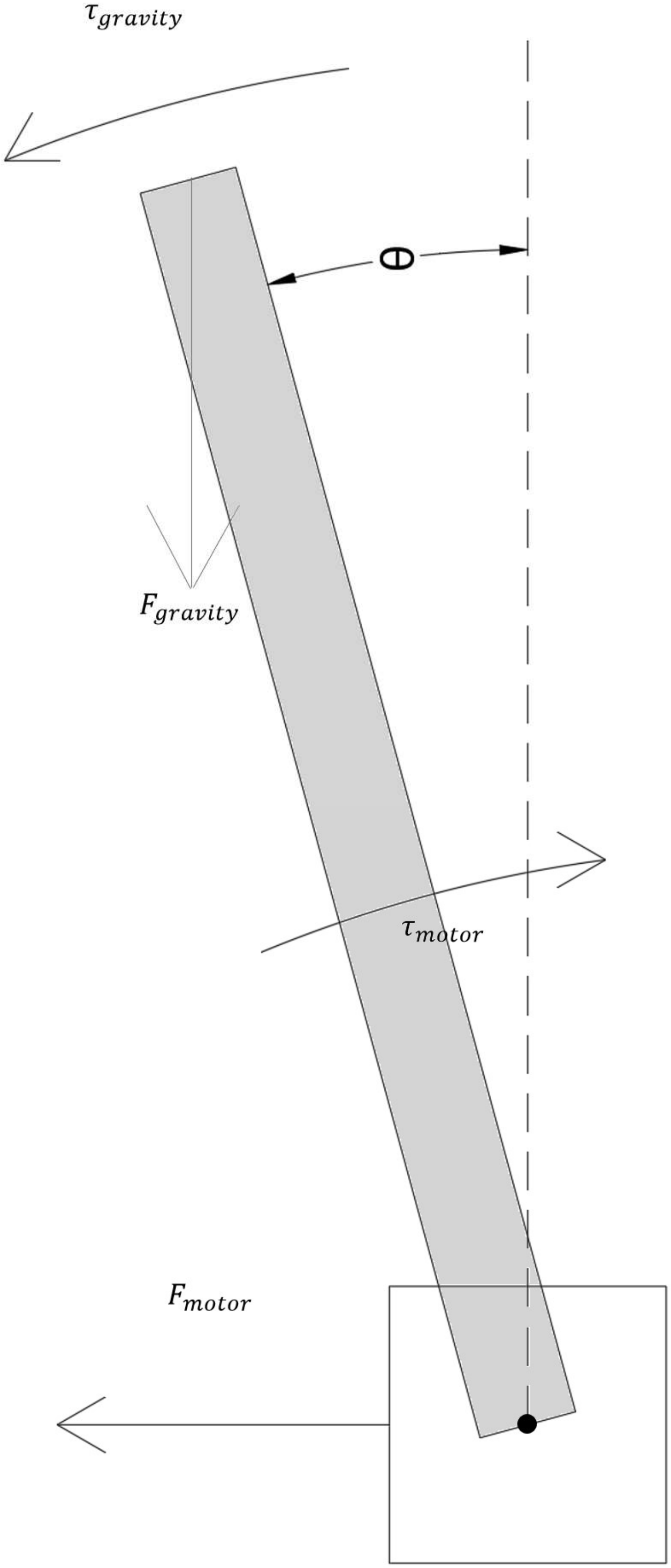
Overview

The purpose of this project was to develop an analog control system for a rotary inverted pendulum. The inverted pendulum (figure 1) is an unstable system that needs active control to remain upright [1]. The inverted pendulum is mounted on a potentiometer used to sense the angle of the pendulum. The potentiometer is then attached to a motor that rotates based on control signals to stabilize the inverted pendulum, this is the rotary aspect of the inverted pendulum. The inverted pendulum will be controlled by rotating the motor to provide an opposite torque to that applied by gravity when the pendulum is displaced from vertical. If the torque applied from the motor is larger than the torque from gravity the pendulum will move towards vertical stabilizing the pendulum. The control signals will need to respond to the angle the pendulum is at relative to vertical to return the pendulum to vertical; as well as the speed of the pendulum to slow it once it reached vertical. Based on these two responses we decided to used PD control for the circuit with the proportional component acting on the angle the pendulum is at, and the derivative component acting on the speed of the pendulum. The circuit has one input and one output; an input voltage from the sensor that is proportional to the angle of the pendulum; and an output control voltage to the motor with enough current to drive the motor. The circuit is designed to operate within 15° of vertical on either side; it is also designed to have the ability to counteract small momentary displacements inside of this window, for example quickly pushing the pendulum with a finger. To operate the system the pendulum will first need to be raised to fully vertical, held there for the control signal to stabilize, and then released. From this point the control will take over stabilizing the pendulum using the motor.

Figure 1: A simplified diagram of the inverted pendulum and the forces acting on it. The inverted pendulum (grey) is mounted on the black pivot point to the rotary arm of the motor (white box). When the inverted pendulum is displaced from vertical (dashed line) to an angle θ the downward force of gravity acts on the pendulum to produce a torque that increases as the pendulum tips more making it an unstable system. This torque can be counteracted by accelerating the motor; when the motor is accelerated a force is applied at the pivot point providing an opposite torque to that of gravity enabling the pendulum to be stabilized if proper control signals are given to the motor.



Operation

The circuit developed over the course of this project is operated with one input from the sensor, and one output to the motor. The output to the sensor provides a constant current; connecting this output to one side of the potentiometer and grounding the centre tap the variable resistance that potentiometer measures based on the angle of the inverted pendulum into a variable voltage. The output to the motor was dependant on the control signals generated throughout the circuit and would be run into one connection of the DC motor with the other side being grounded. In the PCB design additional pads are included to connect the second ports of the sensor and motor to ground however the motor and sensor may be connected to ground in any manner chosen by the user.

The circuit requires 4 power supplies. Positive and negative 15 V 0.5 A constant voltage supplies for power the control circuit and the constant current supply. Positive and negative 24 V 0.5 A constant voltage supplies run the motor. All supplies need a common ground to each other. The power supplies for the motor may need to be revised depending on future changes to the motor and the circuit; if the current motor is continued to be used more power will be required from the motor supplies with slightly increased voltage. If the motor is changed then power requirements of the new motor and possible revisions to the push-pull amplifier based these will need to be considered. Further information on the power requirements is listed in the schematics section.

This circuit has several important safety features. The main safety mechanism built into the circuit is the kill switch. The kill switch is a single pull double throw switch located between the input of the push-pull amplifier and the output of the PD control circuit. This switch allows the input of the push pull to be connected to ground ‘killing’ the output, or to the PD controller enabling control. A diagram of the kill switch, and a more detailed description of it is in the schematics section. The circuit was always run at low voltage, 24 V was the highest voltage used to control the motor, and 15 V used throughout the controller.

The operation of the system needs to be started in a specific manner to ensure the circuit operates as intended. The startup begins by turning on the $\pm$ 15 V supplies to the circuit with the kill switch in the killed position; this ensures that any startup effects on the control signal, especially from the derivative component of control will not destabilize the pendulum. From here the pendulum needs to be raised to vertical and held there while the ± 24 V supplies to the motor are turned on. Then give the system several seconds in this position for the derivative component to fully stabilize and lightly release the pendulum and switch the kill switch to the operate position giving control over to the system. To shutdown the system first switch the kill switch into the killed position and then turn off all power supplies. This ensures that as control is taken away from the circuit the motor is not powered, reducing possibility of damage to the system from the pendulum moving unexpectedly.

As it is currently implemented the circuit has several known limitations. The potentiometer may not be sensitive enough to provide a good measure of the angle of the inverted pendulum, the 15° on either side of vertical control range is small and corresponds to ~200 mV difference between the highest and lowest positions of the pendulum. See week 2 of testing for more information on testing of the sensor circuit. Due to the low sensor voltage a large gain is necessary throughout the circuit which amplifies noise present in the input making the output somewhat noisy especially when the voltage output to the motor neared the supply voltage. The noise also builds throughout the circuit due to the complexity of the circuit. Also due to the complexity of the circuit the control signals will take some time to propagate though the circuit limiting the ability of the circuit to counteract fast changes of the angle of the pendulum; such fast changes were outside the scope of this project due to this limitation of complex analog circuitry. The two-stage push-pull amplifier is complex and adds additional increases to the turn on voltage of the motor which needs ± 1 V input to turn on (week 1 testing). In addition to the turn on voltage of the motor there are 2 silicon transistors to pass through this adds additional ± 1.4 V from the built-in diodes in the transistors [2], [3], [4]. This increases the turn on voltage to 2.5 V hindering the system response at low angles and necessitating high gain throughout the circuit. The motor used to control the pendulum is a heavy motor with high inertia, this makes it slow to accelerate limiting the force that can be applied to the motor. When testing the circuit, the motor currently is current limited. The motor power supplies reach their maximum current of 0.5 A with the motor not moving fast enough to counteract the motion of the pendulum. More information on potential solutions for these problems are listed in the testing section of the project.

Testing

Numerous tests were conducted throughout the development of this control systems, these are listed here in order of the week they were conducted in along with a summary of the progress made that week. These are summaries of the weekly progress reports given throughout this project, specifically focused on the tests conducted on the prototype and changes made due to these tests. The final subsection is the response curves of the final circuit as collected in week 6 of the project but are they were the final tests conducted on the circuit.

Week 1

In week 1 the motor was tested, and a push-pull amplifier to control the motor was constructed and tested. The push-pull amplifier was used to control the motor. It was tested by connecting the output of the push-pull amplifier to one connection of the motor and grounding the other input.

Turn on voltage	$\pm 1.0 \pm 0.1$ V
Turn on current	60 ± 2 mA
Typical operating current	200 ± 5 mA

Table 1: Summary table of the characteristics of the motor, the datasheet for the motor used in this project could not be found so the characteristics that we tested it for are listed in this table. The turn on voltage and current were measured at the lowest voltage input the motor would move at, the plus minus symbol refers to the motor being bipolar and the turn on voltage was either 1 or -1 V. The typical operating current was measured with the voltage increased to the motor; above a voltage of 5 V the current did not change drastically which is where this current was recorded. All measurements were taken with the motor connected directly to a E3612A power supply set to constant voltage operation [5].

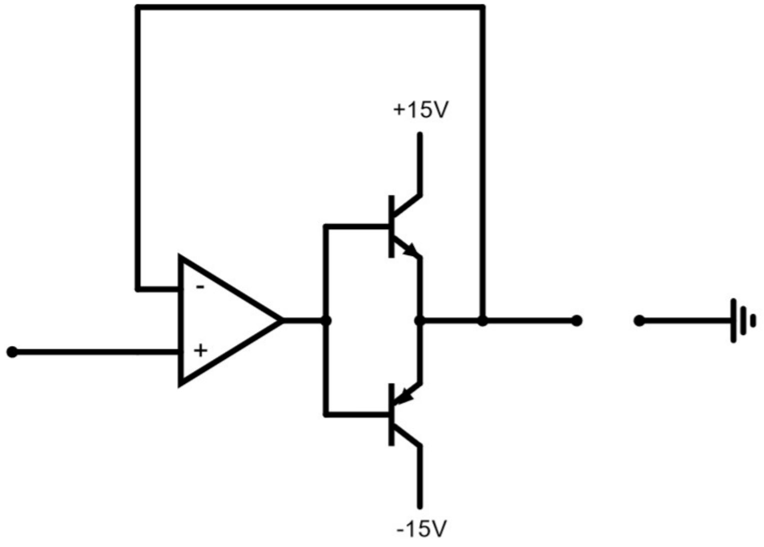


Figure 2: The push-pull amplifier constructed in lad in week 1. The input and output of the operational amplifier have little current. Using the transistors this small current is used to switch much higher supply current that drives the motor. This device has a gain of 1 which means it switches positive and negative current based on an input voltage.

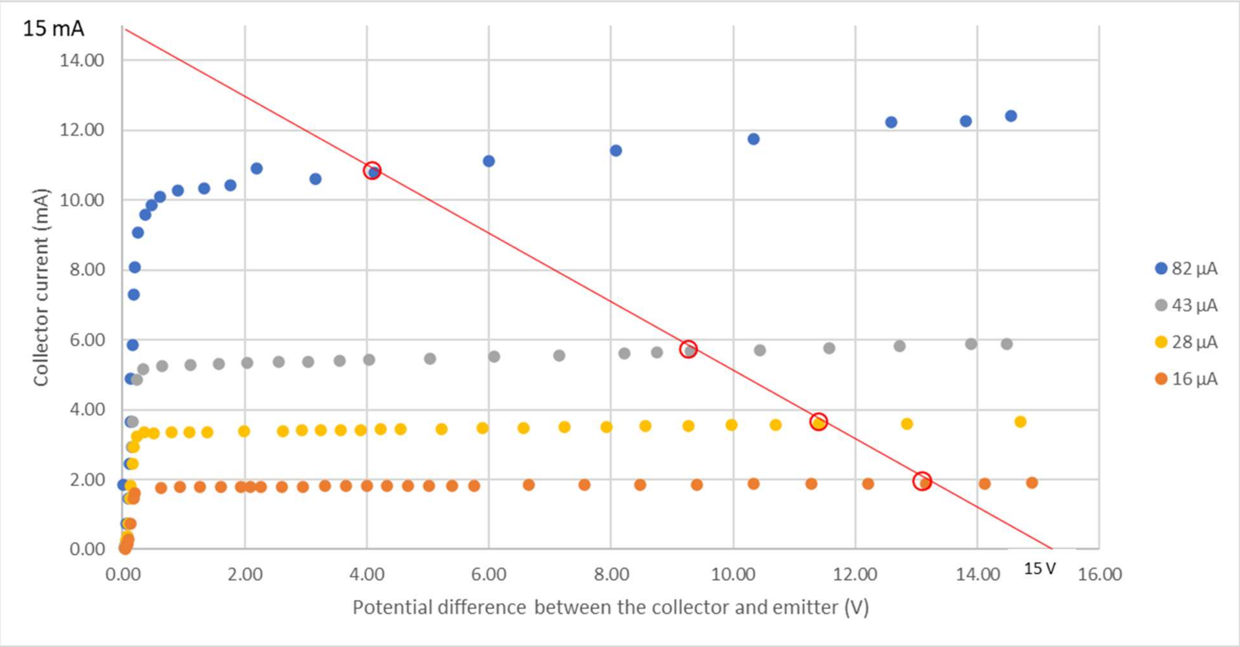


Figure 3: IV characteristic curves for the 2N3904 NPN transistor as taken in lab 2 measurement 4. The collector current and potential difference between the collector and emitter for different values of the base current were recorded as the potential difference was changed. The different base currents were created by changing the value of the resistor between the base and the 5 V power supply. The curves have the expected shape, first current through the device rises rapidly with very small voltage differences, before reaching a current and then the current would stay

near constant as voltage increased. The load line for a 1 $k\Omega$ resistor is drawn on the graph, with the operating point shown on each of the characteristic curves.

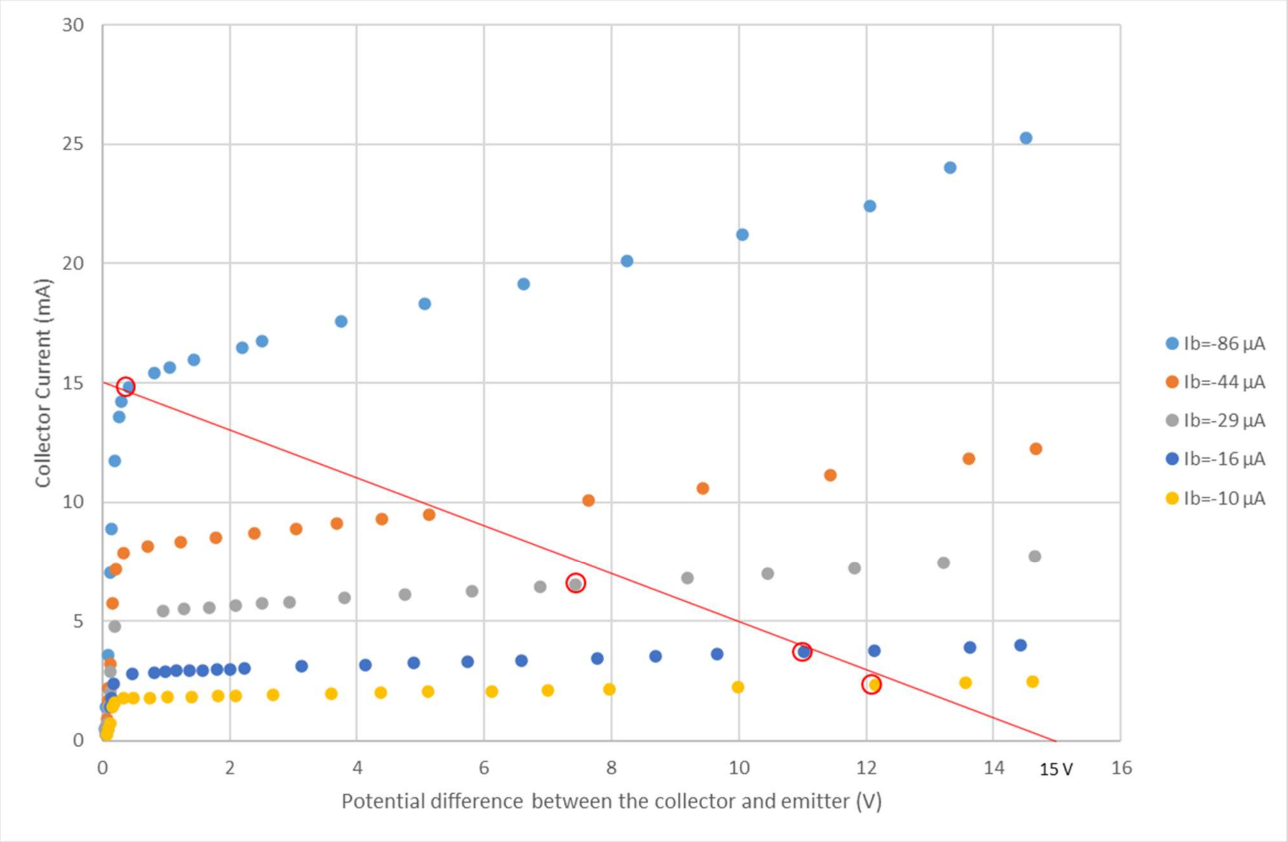


Figure 4: IV characteristic curves for the 2N3906 PNP transistor as measured in lab 2 measurement 7. The collector current and potential difference between the collector and emitter for different values of the base current were recorded as the potential difference was changed. The different base currents were created by changing the value of the resistor between the base and the -5 V power supply. The curves have the expected shape, first current through the device rises rapidly with very small voltage differences, before reaching a current and then the current would stay near constant as voltage increased. The load line for a 1 $k\Omega$ resistor is drawn on the graph, with the operating point shown on each of the characteristic curves.

The curves for the PNPN transistor are more inclined than those for the NPN transistor, and for a given base current more collector current was delivered. Despite these differences the transistors are a matched pair and worked well for the push-pull amplifier.

Week 2

In week 2 a circuit to measure the error of the sensor, and implement proportional control was constructed.

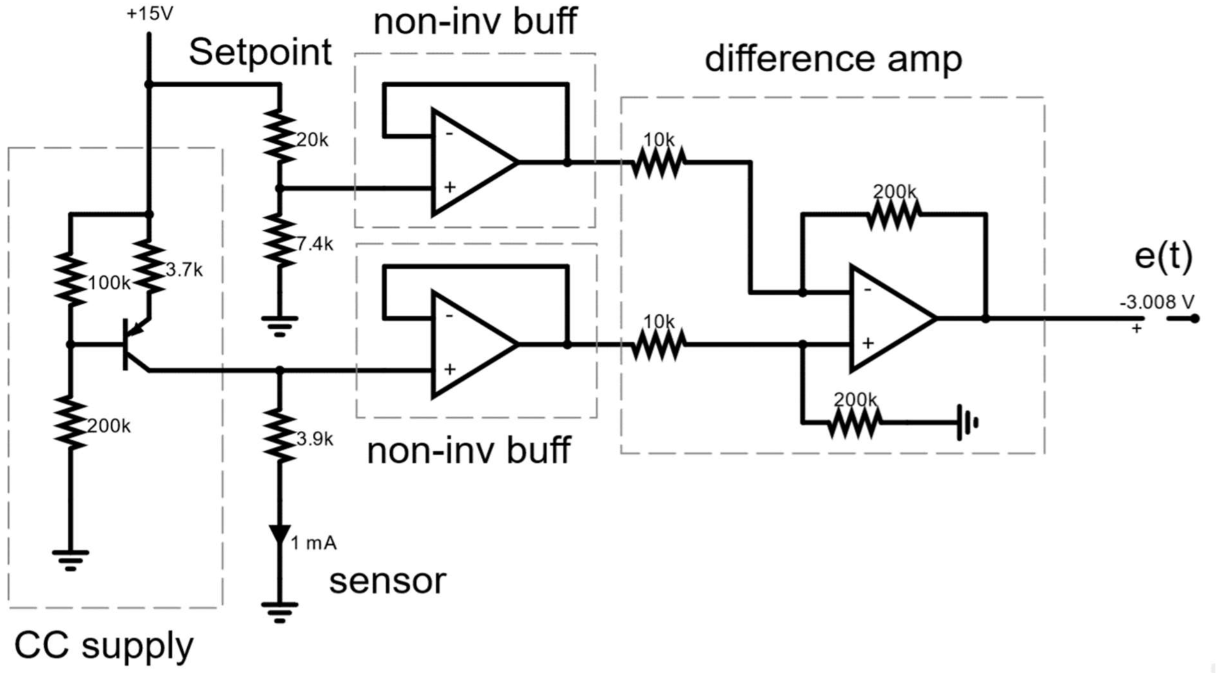


Figure 5: The circuit constructed week 2. This circuit implements proportional control of the inverted pendulum. The circuit consists of a PNP constant current supply using a 2N3906 transistor to make the voltage output of the potentiometer linear with the angle. This output voltage is then fed into a non-inverting buffer to ensure that no current is flowing into the control section of the circuit, and to eliminate any impact of the changing resistance on the circuit. Above that there are 2 resistors making up a voltage divider to change the setpoint of the system, this voltage is also input into a non-inverting buffer for the same reason that the sensor voltage is. The next stage is calculating the error function e(t) which is done with a differential amplifier to take the difference of the sensor and setpoint calculating the error multiplied by some gain which is the proportional coefficient. The final output of this circuit is $u(t) = K_p e(t) = 20e(t)$.

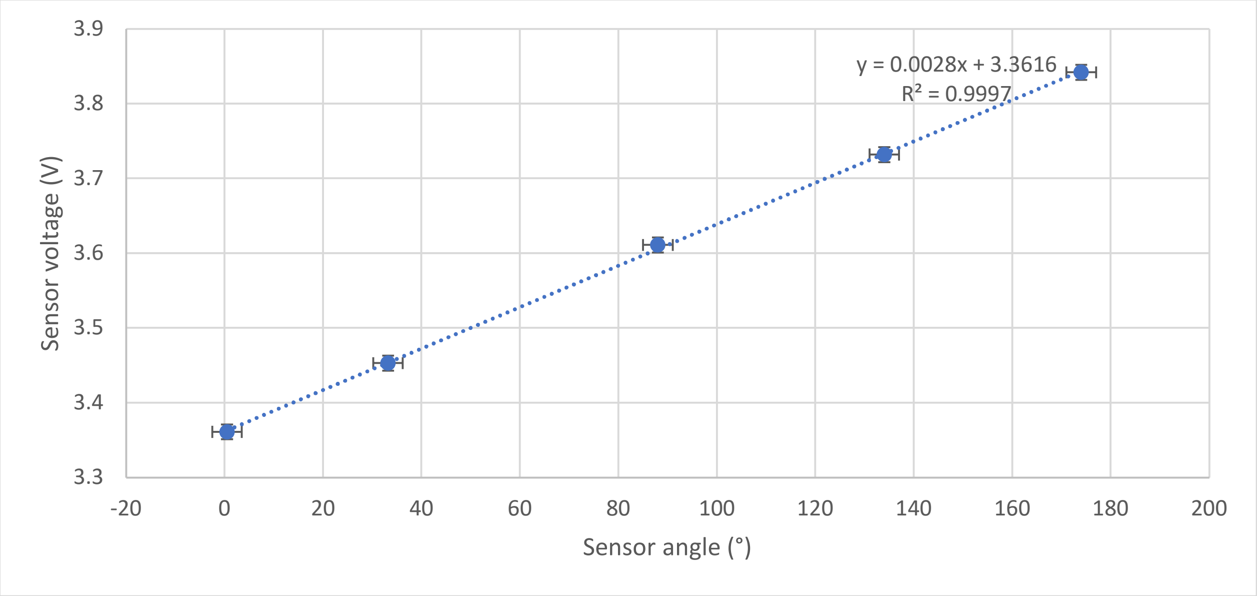


Figure 6: Graph of the sensor voltage against the sensor angle. Using the constant current circuit this graph was created to confirm linearity and determine the setpoint voltage. The sensor was connected to the constant current supply and the sensor was rotated from 0° to 180° taking measurements of the output voltage. From that data this graph was created. The sensor voltage increases linearly with the angle according to the equation $V_s = 3.3616(\theta) + 0.0027$. The R^2 of 0.9997 is very close to 1 indicating that this is a linear relationship. The error in the voltage is ± 0.01 V, and the error in the angle is ±3°, error bars were generated from these values, and the graph is linear within this margin of error.

Week 3

First thermal testing of the sensor circuit was conducted to ensure heating from current flow did not impact the voltage drop across the sensor. This test was conducted using a voltage probe attached to a LabQuest 2 data recorder, the ends of the voltage probe were connected across the sensor, and it was set to record voltage for 30 minutes at intervals of 1 sample per second while the pendulum was lying on the table. For the first several seconds the circuit was turned off, to obtain a baseline, and it was then turned on and data collection continued.

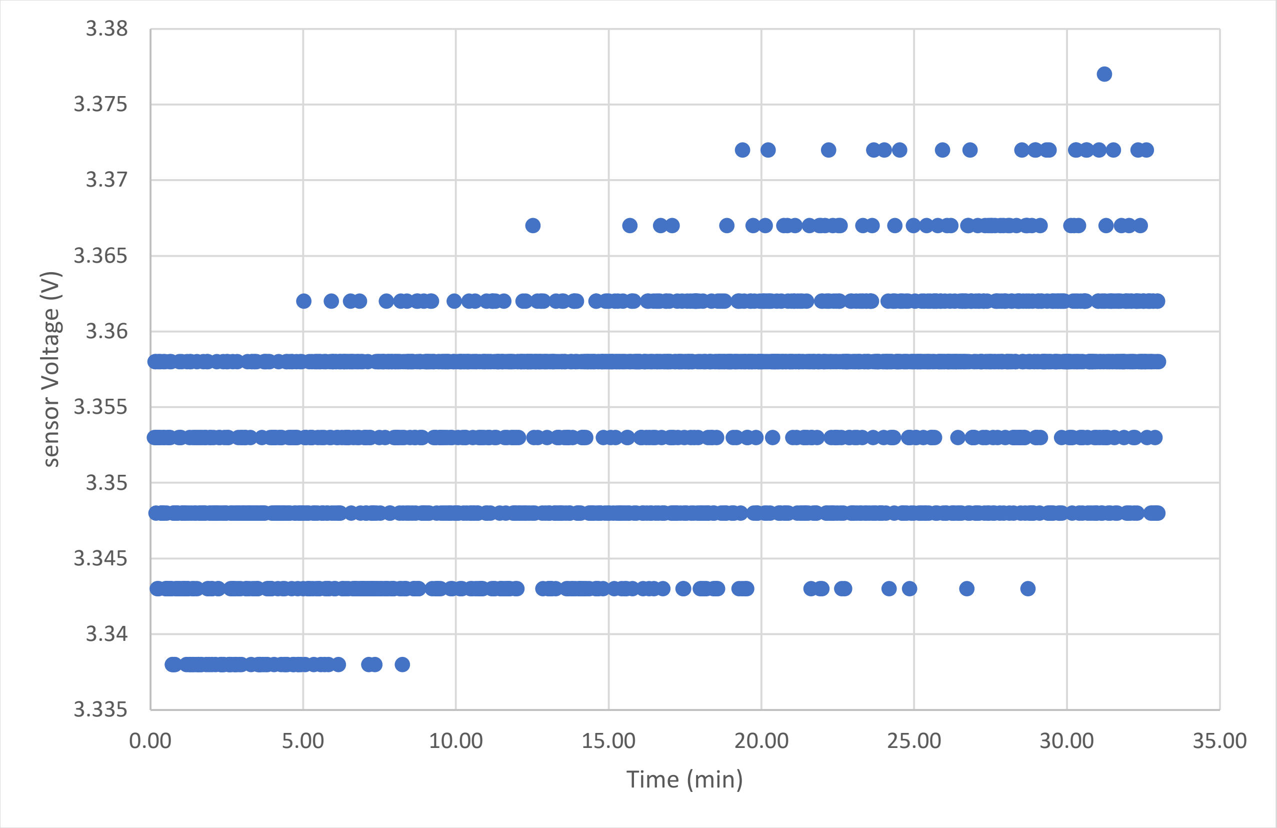


Figure 7: Graph of the voltage across the sensor against the time, when the baseline was collected the voltage across the sensor fluctuated around zero. When it was turned on the voltage drop across the sensor jumped up to ~3.5 V, and then it fluctuated around that value for the rest of the test with a weak increasing trend. From table 1 the equation from a linear regression applied to this section of the graph is $V = 0.00034t + 3.34849$ with an R^2 of 0.217. Therefore, the impact of temperature in negligible on the voltage across the sensor, and any thermal effect is not detectable above fluctuations in the measurement.

Based on the results of this test it we decided it will be unnecessary to make any changes to the sensor circuit to eliminate thermal effects. We also decided, even though this test does not show thermal effects as the circuit warms up, to turn the circuit on and wait several seconds before the pendulum control is turned on. This is to ensure no thermal, or other turn on effects impact the operation of the circuit.

Secondly in week 3 the full PD control circuit was constructed. In addition to the proportional component construction last week a derivative control component was constructed.

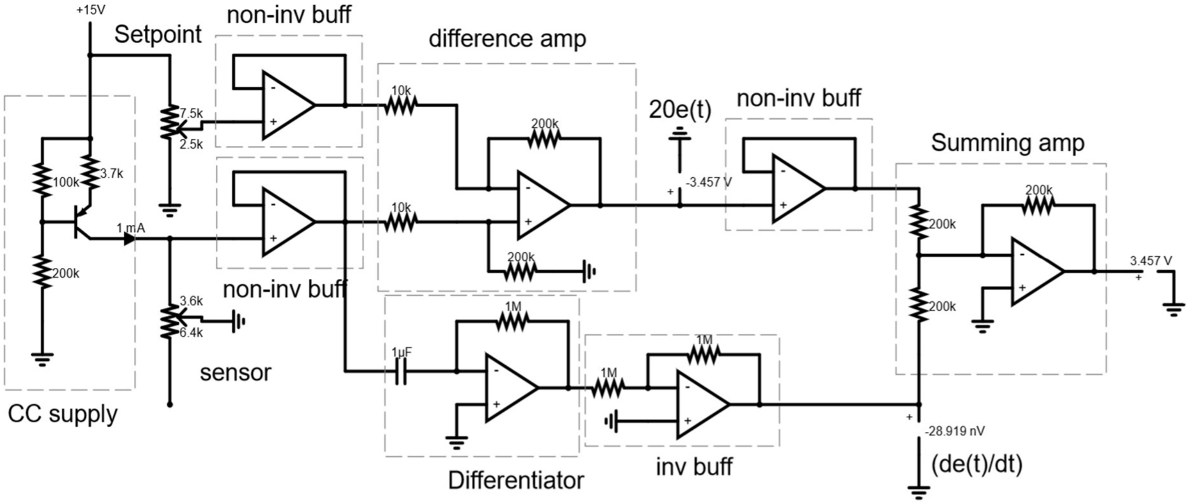


Figure 8: The full control circuit used to calculate the equation $u(t) = 20e(t) + 0.1\frac{de(t)}{dt}$ the additions from last week are the derivative control circuit, a non-inverting buffer on the output of the difference amplifier, and the summing amplifier to add the derivative and proportional components together. The derivative control circuit consists of a differentiator with the and an inverting buffer, the output is marked as (de(t)/dt). The inverting buffer eliminates the negative on the gain of the output of the differentiator and enables additional gain to be added to the derivative circuit without worrying about the response time of a capacitor. The summing amplifier calculates the control signal u(t) and outputs it into the push pull amplifier used to control the motor.

The circuit developed this week is a full PD control circuit. It calculates the equation $u(t) = 40e(t) + 0.2\frac{de(t)}{dt}$. This PD control equation can be used to control the inverted pendulum. The proportional and derivative control elements of the circuit are constructed separately, and the results are summed using a summing amplifier. The output of the PD control circuit was attached to the input of the motor to control it. The current circuit was tested both with and without the pendulum on the motor and we learned that it did control the motor, with the motor spinning to counteract the motion of the pendulum. The motor, however, did not spin fast enough to stabilize the pendulum and it needed more power to control the circuit.

Week 4

The full circuit was assembled from the PD control circuit completed in week 3 and the push-pull amplifier constructed in week 1. The goal was to test the control circuitry and make improvements to enable it to better control the inverted pendulum. Firstly, the circuit was tuned, with the inverted pendulum held vertically the setpoint was adjusted until the summing amplifier at the end of the PD circuit read 0 V. The main part of the control circuitry to be tested was the proportional component, we wanted to ensure the proportional component had ahigh enough gain to counteract the motion of the pendulum under gravity before introducing the derivative component.

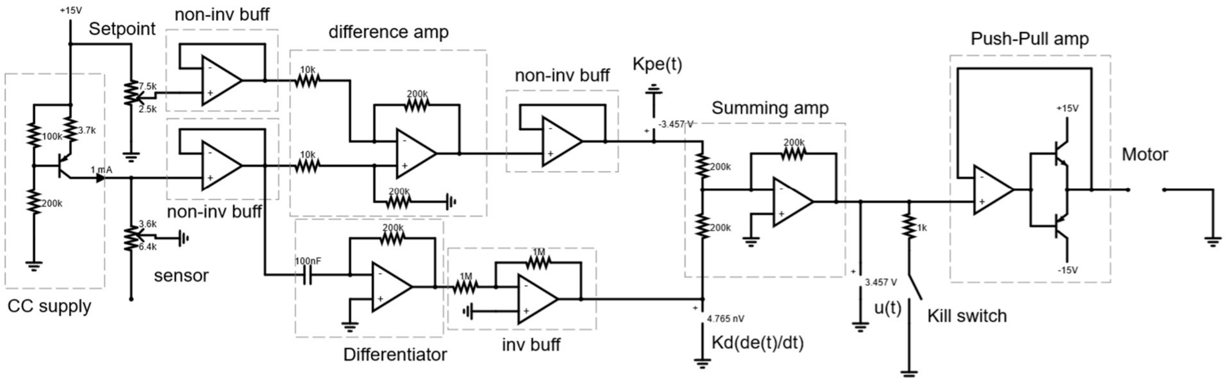


Figure 9: The circuit from week 4 of the project, the constant current supply takes the sensor voltage and inputs it into the control circuit. The differentiator implements derivative control, the difference amplifier implements proportional control, and the summing amplifier adds them together to create the control signal. This is then input into the push-pull amplifier which switches enough current to control the motor.

With the gain of the proportional component increased the control equation for the circuit becomes $u(t) = 42.6e$. With this gain the circuit was tested with the pendulum both connected and disconnected. In all tests the output current of the circuit was not high enough to turn the motor to counteract the falling of the pendulum. If the current was increased the transistors would fail so we determined that the push-pull amplifier needed to be revised to switch more current or replaced with a device that could act similarly to the push-pull amplifier but switch higher current.

Week 5

Week 5 was concerned with replacing the push-pull amplifier with a LA 6500 power amplifier. The power amplifier works like a regular operational amplifier, but it can output much more power; this one specifically can output large currents of up to 1.0 A [6]. We believed this current would be enough to turn the motor fast enough to counteract the motion of the pendulum.

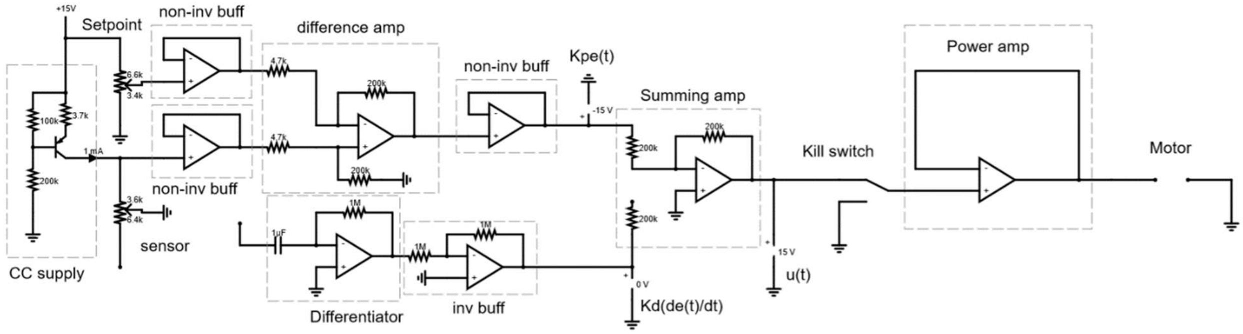


Figure 10: The week 5 control circuit constructed this week. The changes from the previous week's version are the kill switch being changed to a single pole double throw switch, and the replacement of the push-pull amplifier with a power amplifier. Large parts of the testing of the circuit were conducted with only the power amplifier and the motor, however. For simplicity the power amplifier was connected to the ±15 V supplies of the trainer board not the full ±18 V it can handle which may limits the output current of the power amplifier and may need to be revised.

To create the response curve of the power amplifier the input was connected to a DC power supply and the output was connected to the motor to apply a real-world load. This setup had the power amplifier set up as a non-inverting buffer with the motor connected to the output. Additionally, to check the stability of the output an oscilloscope was connected to the output of the power amplifier. Measurements were planned to be taken starting at 0 V input and increasing voltage until the positive saturation point was found and then decreasing until the negative saturation point was found. The values are listed as typically ±13 V with a minimum of ±12 V. Figure 11 is the curve of the amplifier and figures 12-14 are the oscilloscope captures showing the stability of the output.

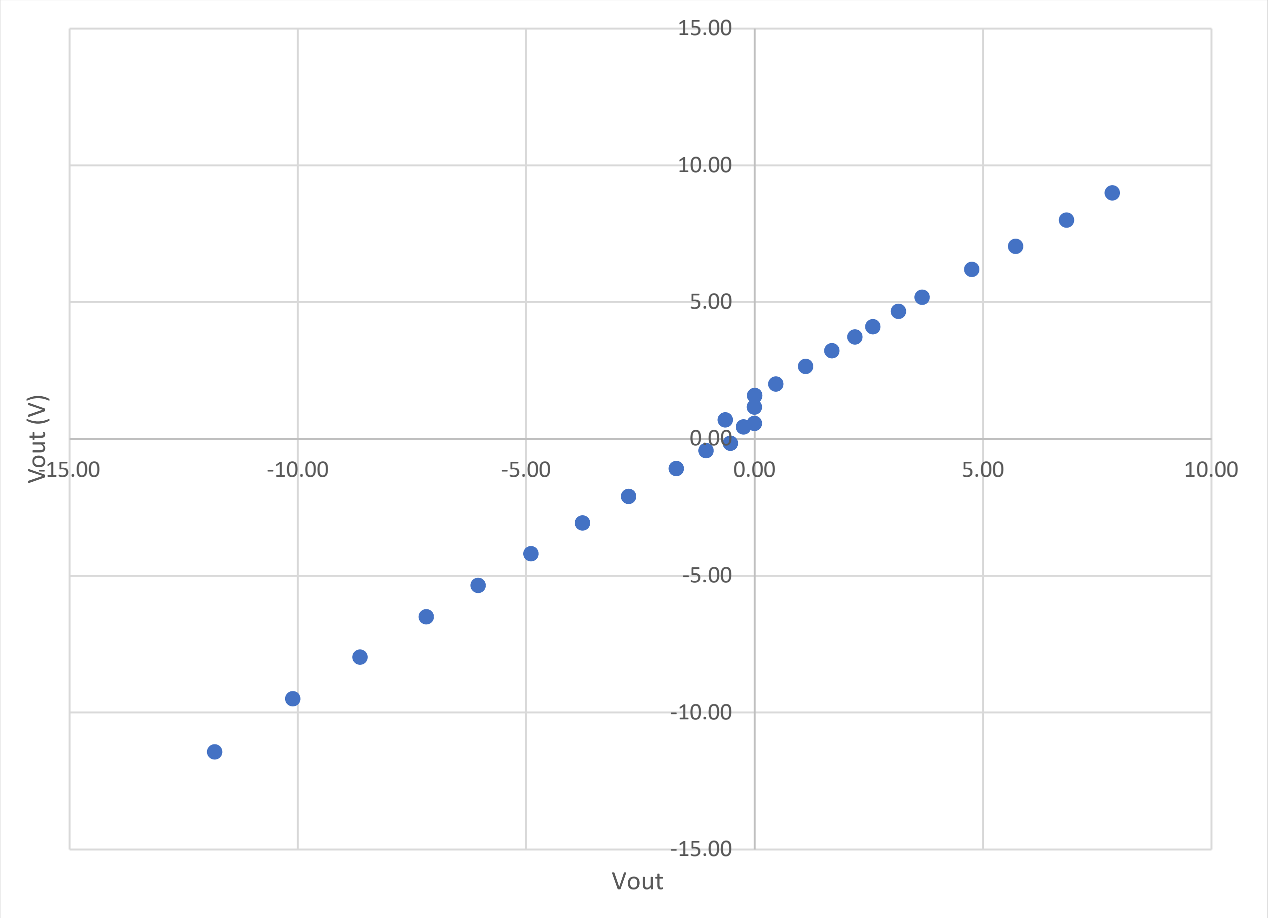


Figure 11: The curve produced from plotting the input voltage against the output voltage for the LA 6500 power amplifier. Measurements stopped being taken when the spikes in the output rendered it unstable, more information on the instability of the output is shown below in figures 12-14. The graph appears linear, and the positive section had an offset of +1.5 V with a gain of 1. The negative section at first appeared to have an offset of +0.7 V and a gain of 1, however when additional points were taken these offsets varied anywhere from +1.5 V to +0.6 V with no observable pattern in what caused changes in the offset.

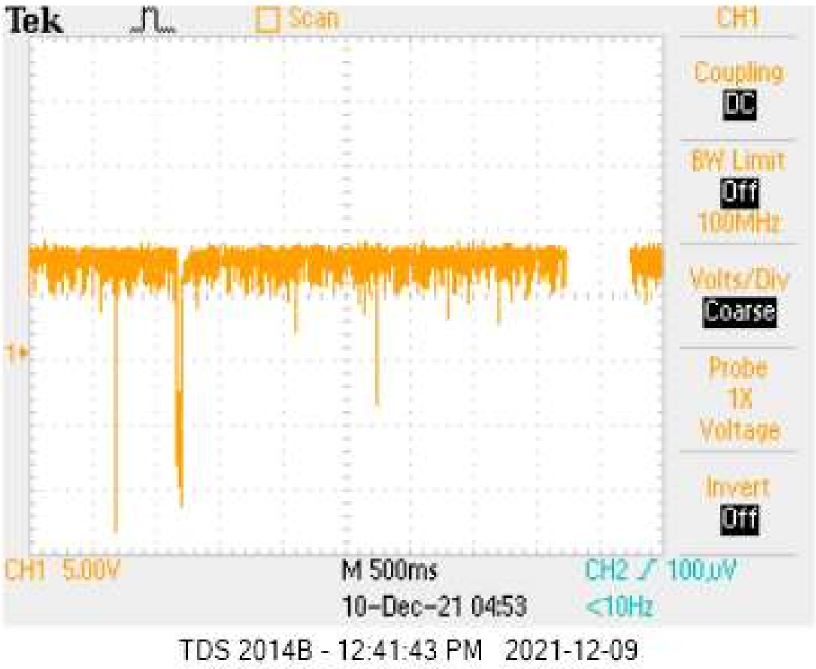


Figure 12: An image of the oscilloscope showing some of the oscillations that were causing problems with the motor, this graph was taken at an input voltage of 7 V. The sustained drop in voltage in the third time division from the left corresponded to a noticeable drop in the rotation speed of the motor that made a noise.

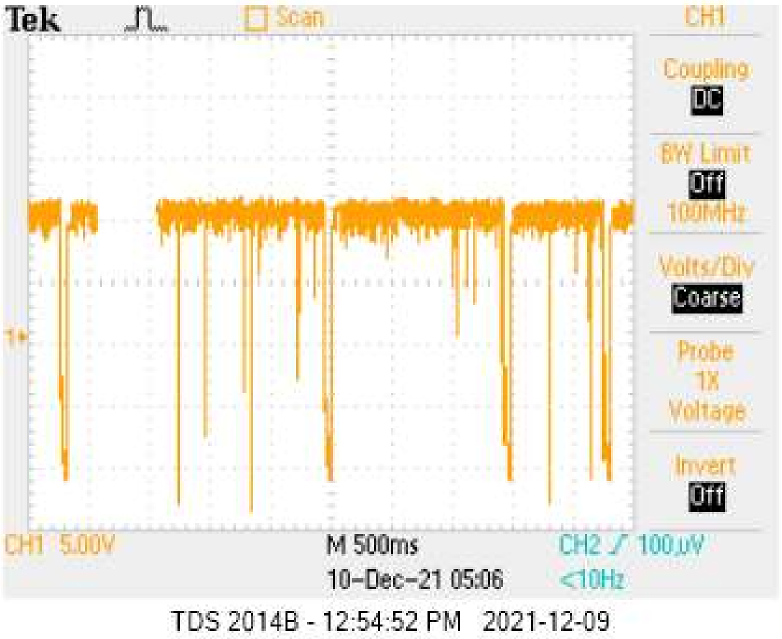


Figure 13: As the input voltage was further increased to 9 V more spikes showed up in output to the motor, with some of the spikes lasting longer in duration than previously observed. During these longer spikes the motor stopped for long enough to be noticeable with human eyes and made a louder sound than heard previously. Due to this behavior the output did not stabilize at this input voltage and the highest point on the graph below (figure 7) was taken at 7.83 V input.

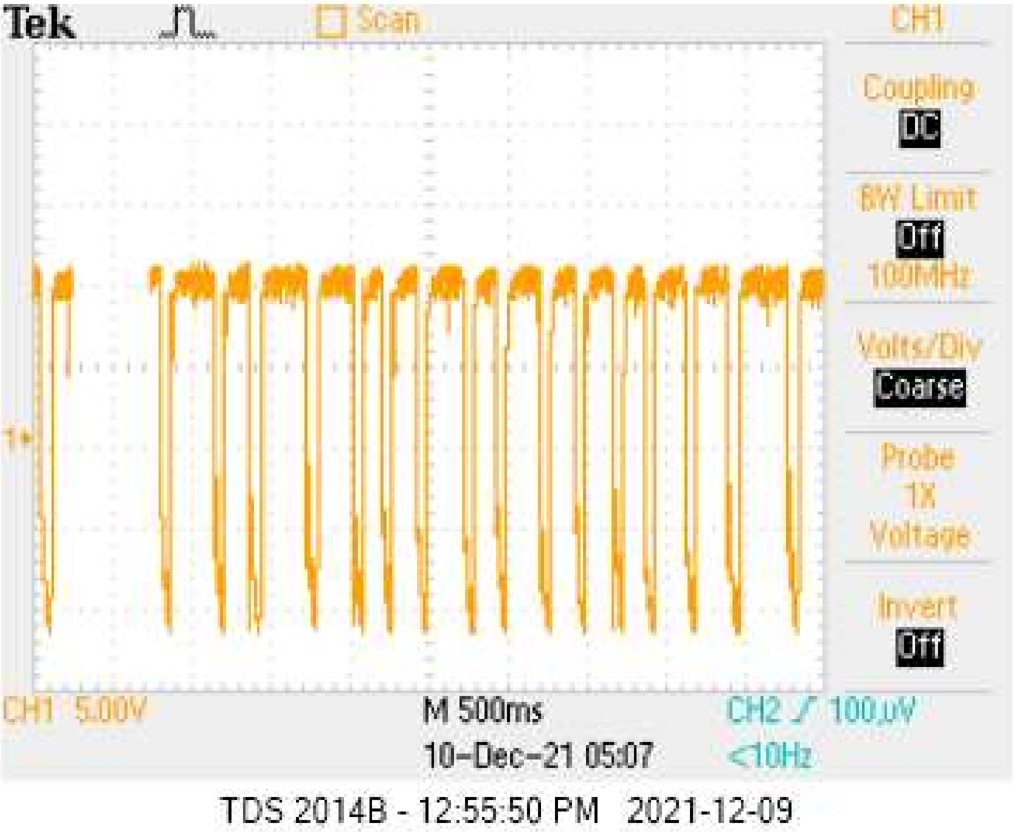


Figure 14: When the input to the power amplifier was increased to 10 V the spikes became more drastic and seemed almost periodic. The spikes shown in this capture are longer in duration than the previous ones, more numerous, and more consistent in the voltage they dropped down to, which was around -11 V. Due to this behavior we moved on to testing the output of the device with a negative input voltage to complete the curve and test if this behavior persisted with a negative input voltage.

The push-pull amplifier was replaced with a power amplifier which was intended to have the same behavior but deliver higher current to the motor. Basic tuning of the setpoint was done with the output of the power amplifier. The power amplifier was tested, and we observed a linear relationship between the input and output voltages. However, when the input was positive and over 5 V large downward spikes in output voltage were present. Also, the power amplifier had a varying offset that could no be eliminated or explained making it unsuitable for use in this control circuit. For next week either a new working power amplifier or some modification to the push-pull amplifier needs to be introduced to power the motor.

Week 6

In week 6 the push-pull amplifier was revised to a 2-stage push-pull amplifier and final testing of the circuit was conducted, including the collection of response curves. Due to the issues with the power amplifier including the changing offset and the output instability the motor control circuit had to be revised. We decided to use a 2-stage push-pull amplifier (figure 15) to control the motor.

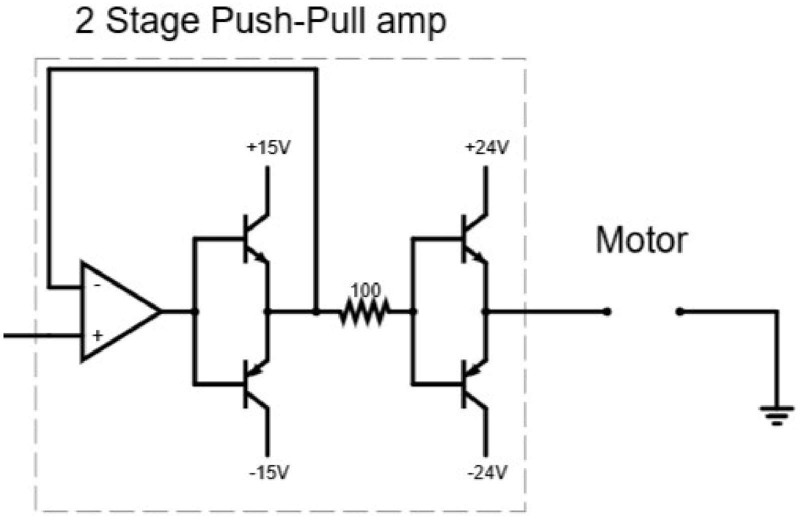


Figure 15: The two-stage push-pull amplifier. The first stage was the standard push-pull amplifier constructed in week 1 of this project with the 2N3904 and 2N3906 transistors. However, from that instead of connecting directly to the motor the output of this feeds into a second stage which has two high-power transistors, the 2N3055 and MJ2955 which can switch higher current and voltage and are connected to ± 24 V 0.5 A power supplies to supply the motor with more current and voltage.

The first test conducted on the 2-stage push-pull amplifier was to determine if the feedback should come from stage 1 or stage 2. Using a function generator to input a wavform to the push-pull amplifier and the output across the motor was recorded. This was done with the feedback from both stages.

For all waveforms shown in this section the input is shown in yellow, and the output is shown in blue.

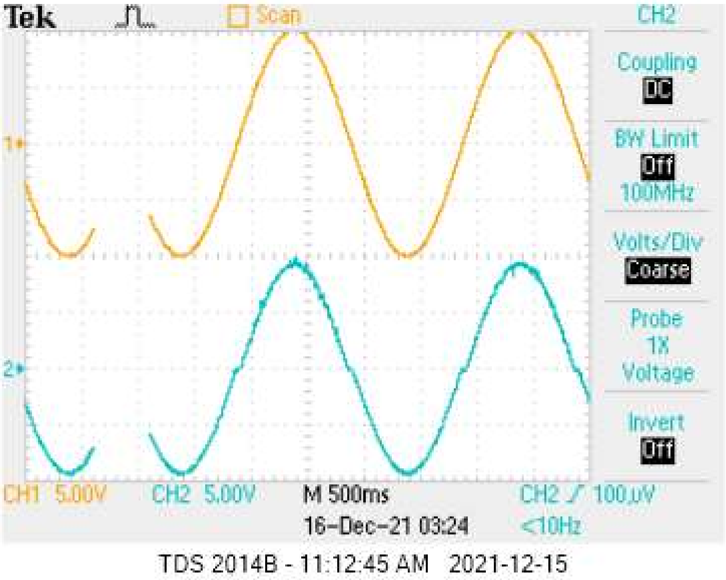


Figure 16: The output waveform of the push pull with the feedback line connected to stage 1. The input is a sine wave with an amplitude of 10 V and a frequency of 0.5 Hz The output is also a sine wave with a slight flattening in the middle due to the voltage drop across the constituent transistors. The output has low noise and closely matches the input.

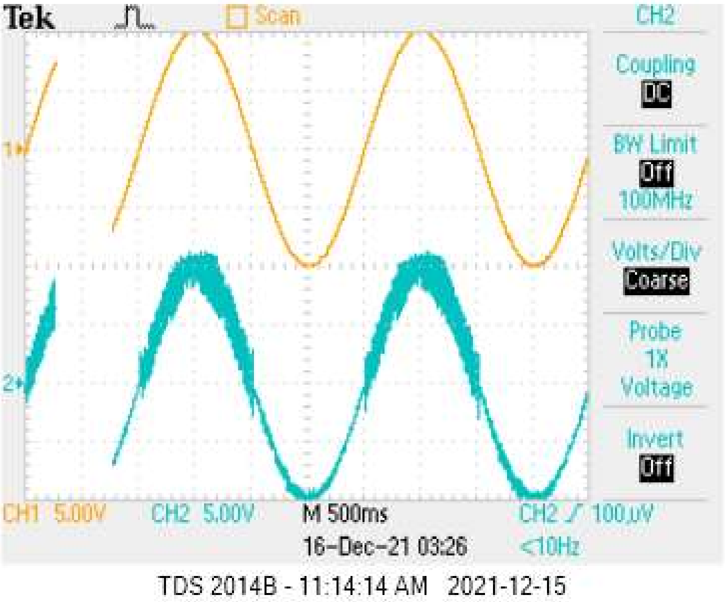


Figure 17: The output waveform of the push pull with the feedback line connected to the second stage. The input is still a sine wave with the same characteristics as used previously. The output is much noisier than the input.

Based on these results we decided to go with a feedback line connected to the first stage of the amplifier since it greatly reduced noise in the output. Following this the final circuit was constructed by connecting the two-stage push-pull amplifier to the complete circuit and the response curves were taken. First the pendulum was disconnected from the motor so responses to specific inputs could be collected, (figures 18-21), then the pendulum was mounted on the motor and the final response curves were collected (figures 22 & 23).

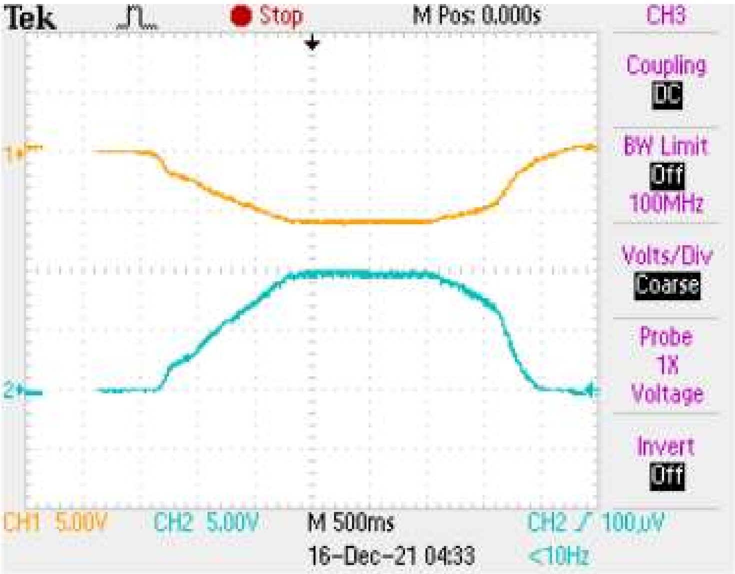


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Figure 18: The proportional control response of the circuit to the pendulum being displaced from vertical and held there, the output voltage to the motor increases as the angle is increased and decreases when the pendulum is returned to vertical with the shape of these curves matching each other closely. The derivative control was disconnected when this waveform was taken so the output is only based on proportional control.

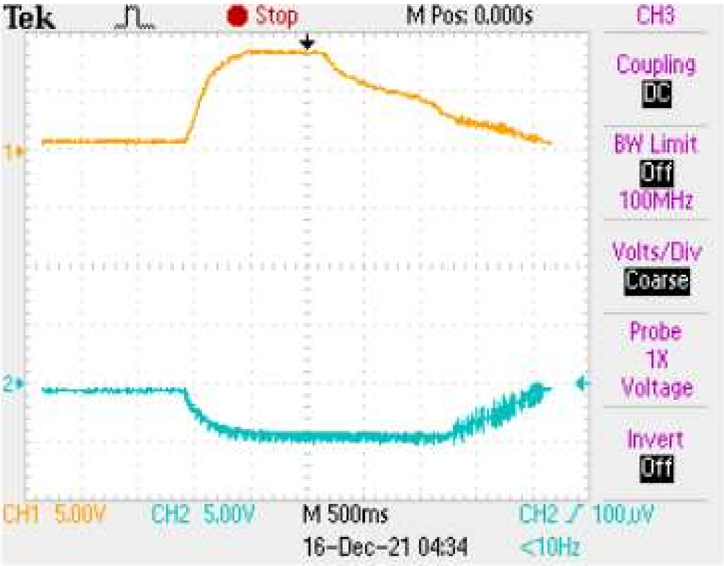

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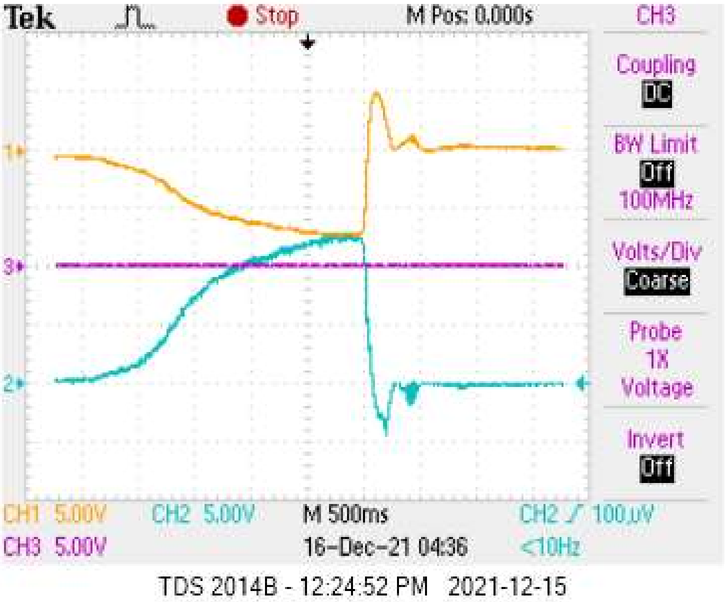
Figure 19: The PD response of the circuit. When the input was increased the derivative component manifests in the initial increase in voltage making the output increase faster than the input. When the angle is then decreased the derivative component maintains the output signal for some time before also falling off as the pendulum nears vertical.



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CH3
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CH1 5.00V CH2 5.00V M 500ms CH2 ∕ 100µV
CH3 5.00V 16-Dec-21 04:36 <10Hz
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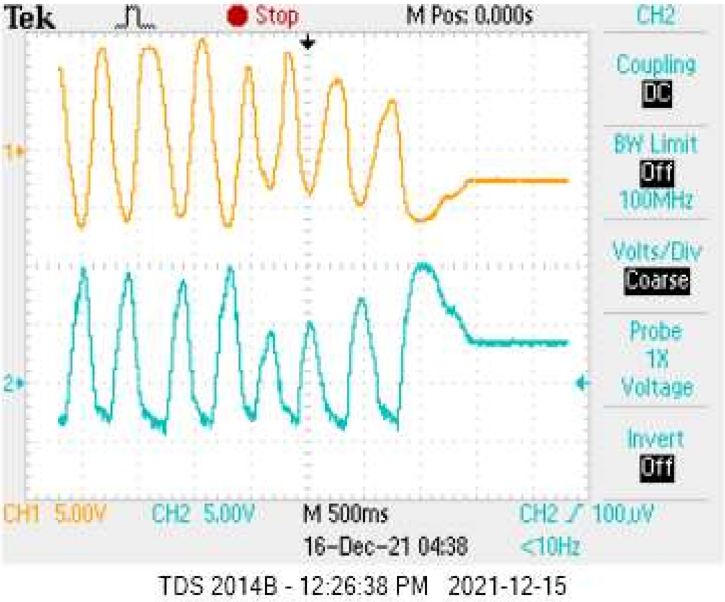
Figure 20: The response of the system to a rapid change in the position of the pendulum. When the angle is changed rapidly the derivative component becomes large and has a noticeable impact on the output of the circuit causing the value of the control signal on the peaks to be higher than it would have been with only proportional control.



M Pos: 0.000s
CH2
Coupling DC
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CH1 5.00V CH2 5.00V M 500ms CH2 ∕ 100µV
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Figure 21: The response of the circuit to an oscillating input. The derivative component makes the peaks of the output waveform sharper than those of the input waveform.

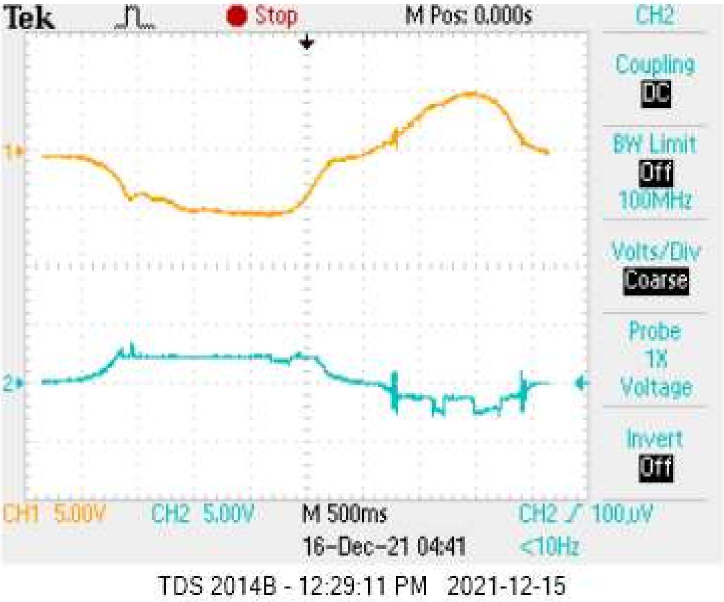

Figure 22: With the motor fully in control of the circuit the control voltage is lower than the input voltage since the circuit was reaching the current limit of the power supplies used to power the motor.

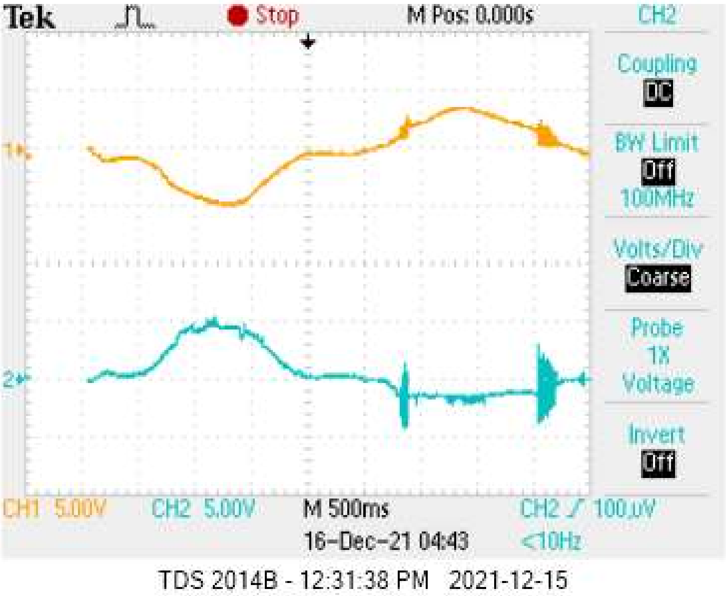

Figure 23: The current limited behavior of the circuit persists when it is tested with slightly different input conditions. This indicates an ongoing problem with either the push-pull amplifier not providing enough current to run the motor, or with the motor itself, it would need be replaced with one that drew less current to resolve this issue.

User testing

The user can conduct a few simple tests with the inverted pendulum and sensor assembly disconnected from the motor to ensure the system is working. The first set of tests can be conducted using only 2 voltmeters and some simple math to test the control signals as they propagate through the circuit. First the power, inputs and outputs must be connected to the PCB. Then the circuit then must be turned on using the kill switch with the pendulum dismounted from the motor. All tests in this series will be conducted by tilting the pendulum and observing the effect on the motor and test voltages from throughout the circuit (see the schematics section). Test voltages will be recorded using voltmeters with the common input connected to ground and the voltage input connected to the appropriate test point in the circuit. Information on replacement parts is in table 2 of the schematics section which is a parts list of all components mounted on the PCB.

The sensor and setpoint voltages should be equal, connect one voltmeter to TP2 (the sensor voltage) and the other to TP1 (the setpoint). Compare these values, they should agree; if they do not adjust the screw on the setpoint potentiometer (until the two voltmeters read the same. This has calibrated the setpoint to the sensor voltage. Further calibration of the setpoint needs to be conducted throughout the circuit. The setpoint needs to be adjusted to that the output of the complete circuit is 0. To do this connect a voltmeter to the output of the push-pull amplifier with the motor allowed to run adjust the setpoint until with the pendulum held vertically the output reads 0 V. This counteracts the drift throughout the circuit and any offsets introduced by the operational amplifiers or unbalanced resistors.

To check the polarity of the motor inputs. Hold the pendulum vertical with the sensor pointing towards you and tilt it slightly in one direction. The motor should turn to counteract the motion of the pendulum; the rotation should be in the same direction you tilted the motor, if it is in the opposite direction reverse the polarity of inputs to the motor and repeat this test.

Additional testing can be conducted using a 2 channel or higher oscilloscope to ensure the control responses of the circuit are working as intended. Continuing to keep the pendulum disconnected from the motor connect one probe to the output of the difference amplifier, this is to measure the error function e(t), connect the other probe to the output to the motor to measure the control signal u(t). Set the oscilloscope to take a large time interval of several seconds and with both voltages set to record a range of ± 15 V. First slowly tilt the pendulum over, while keeping the speed of rotation as constant as possible from vertical to one edge of the control window over 1-2 seconds. Following this freeze the oscilloscope. The input and output waveforms should be very similar however the output should have a slight offset introduced by the derivative that manifests as a small spike at the start of the increase in the angle of the pendulum. If this behavior is observed then the control circuit has both components of control present and should work as intended.

Schematics

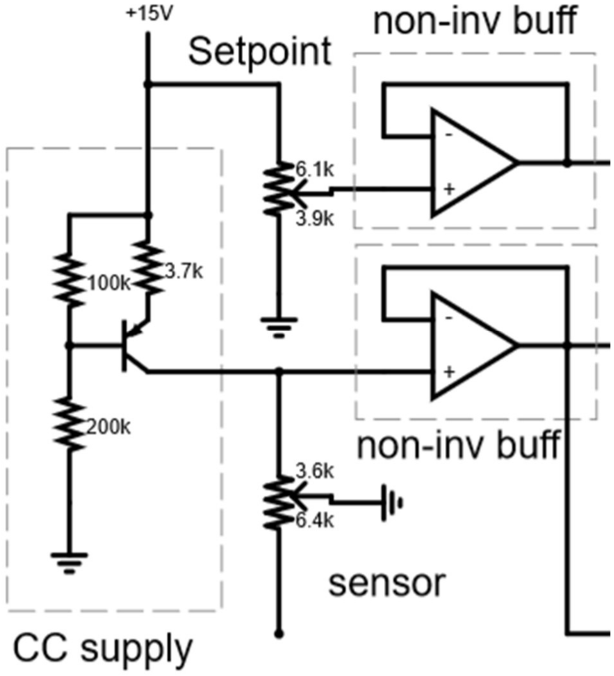

Figure 24: The sensor and setpoint component of the circuit. The transistor used for the PNP constant current supply is a 2N3906. The voltage divider on the left side biases the transistor, in combination with the small resistor connected to the emitter this makes the current constant. The constant current supply is connected to one end of the sensor potentiometer with the centre tap grounded. This converts the variable resistance that the potentiometer measures the angle as into a variable voltage that the analog control can work with. Since the sensor potentiometer is linear the voltage will also be linear with the angle of the potentiometer. The setpoint is set using a potentiometer as a voltage divider; the centre tap sets the setpoint volta, one side is connected to ground and the other to 15 V. The potentiometer allows the setpoint to be quickly and easily tuned to correct changes in the conditions the circuit is operating in. To isolate the impact of the resistors from the control circuit the sensor and setpoint voltages they are input into a non-inverting buffers.

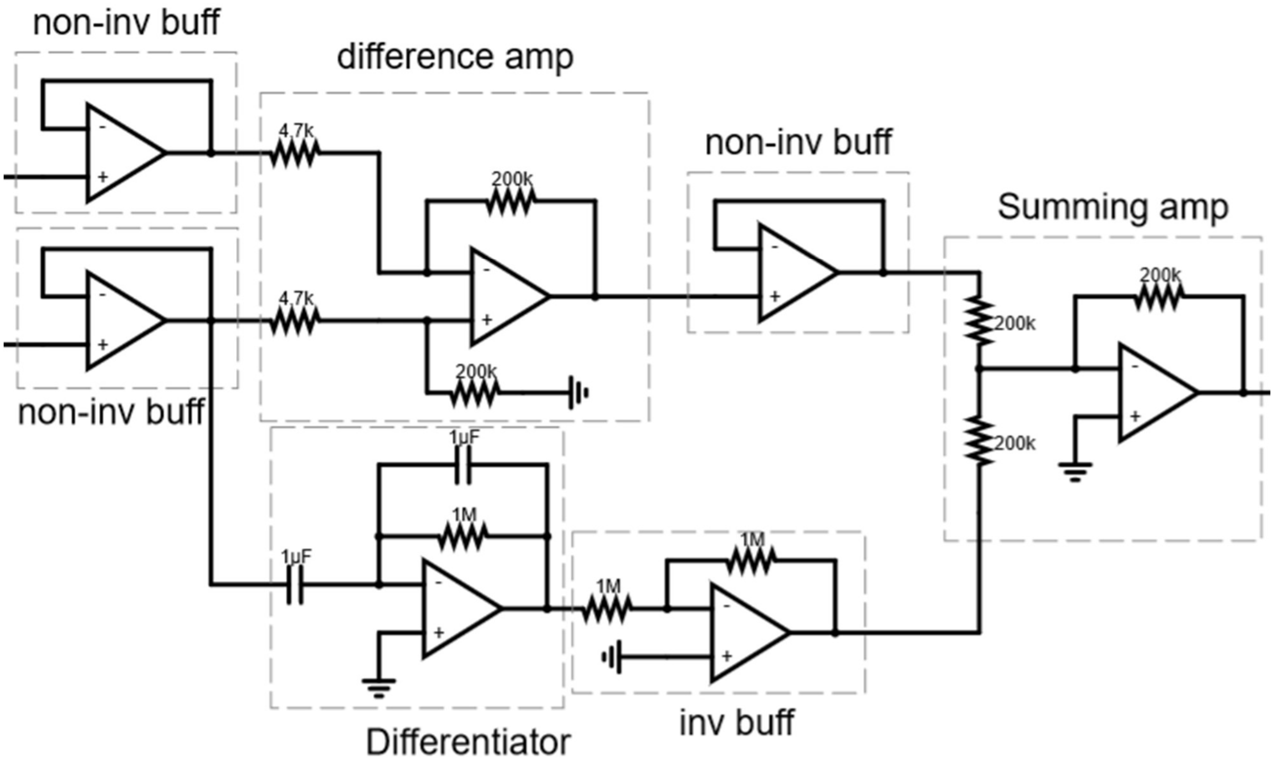

Figure 25: The PD control circuit. Input is taken from the sensor and setpoint and based on these values the control signal is generated. The proportional component of the circuit is implemented using a difference amplifier which takes the difference between the sensor and the setpoint calculating the error. This error is then multiplied by the gain of the difference amplifier to create the proportional component of the control signal which is $42.6e(t)$. The proportional component is then input into a non-inverting buffer to isolate the previous components of the circuit from the output. The derivate component is created using only the sensor voltage; since the setpoint voltage is constant the derivative of the error is equivalent to the derivative of the sensor voltage. The derivative component is calculated using an inverting differentiator with a capacitor filter in parallel with the feedback resistor to act as a filter on the noise introduced by the differentiator. The output of the inverting differentiator is then input into an inverting buffer to make the circuit calculate the derivative with no inversion; the inverting buffer also can be used in further testing to increase the derivative gain without increasing the capacitor value and limiting the response time of the circuit. The output of the derivative component is $0.1\frac{d(e(t))}{dt}$. Finally using a summing amplifier the proportional and derivative components are summed and multiplied by the gain of 2

to calculate the final control PD control signal for the circuit. Thus, the PD control signal calculated is $u(t) = 85.2e(t) + 0.2\frac{d(e(t))}{dt}$.

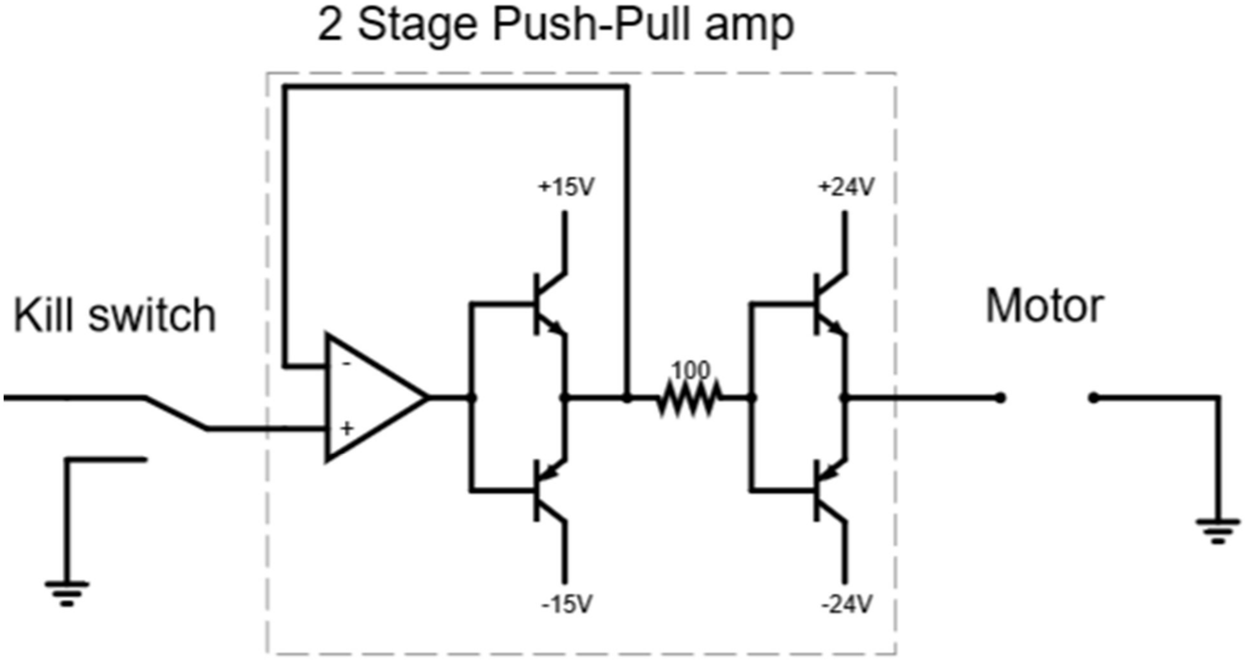

Figure 26: The kill switch is a single pull double throw switch located between the input of the push-pull amplifier and the output of the PD control circuit. The common (pole) port of the switch is connected to the push pull amplifier, one of the throw ports is connected to the output of the PD control, and the other throw port is connected to ground. The setup enables the input of the push-pull amplifier to be connected to ground locking the input and output to 0 V disabling control of the motor and putting the circuit into a killed state. The other option connects the input of the push-pull amplifier to the output of the PD control enabling the circuit to control the motor. The circuit was operated with the off switches for all power supplies within easy reach to shut off power if there was an issue with the kill switch. The two-stage push-pull amplifier achieves greater current amplification than a standard push-pull amplifier by adding a second stage of power transistors to switch high current. The first stage is a standard push-pull amplifier using 2N3904 and 2N3906 transistors. The output of these transistors is used to provide enough current to the 2N3055 and MJ2955 power transistors to switch 24 V 0.5 A power supplies to power the motor with higher voltage and current than what otherwise would have been possible.

Additionally, the circuit needs power to run the motor, supply the sensor with current, and generate the control signals; this is provided by ± 15 V 0.5 A and ± 24 V 0.5 A supplies which need to be connected to a common ground. The ± 15 V supplies provide power to all operational amplifiers as well as the constant current supply and the first stage of transistors in the push-pull amplifier. The supplies used in testing this were the supplies built into the PB-503 circuit trainer [7]. The supplies connected to the power transistors variable DC power supplies set to ± 24 V supplies to run the motor with high current. These are two Agilent E3612A power supplies and wer operated in constant voltage mode for this circuit [5]The current motor needs a large amount of current to run even with these supply voltages so higher current supplies may be necessary to fully control the motor (as discussed in the future work component of the conclusion).

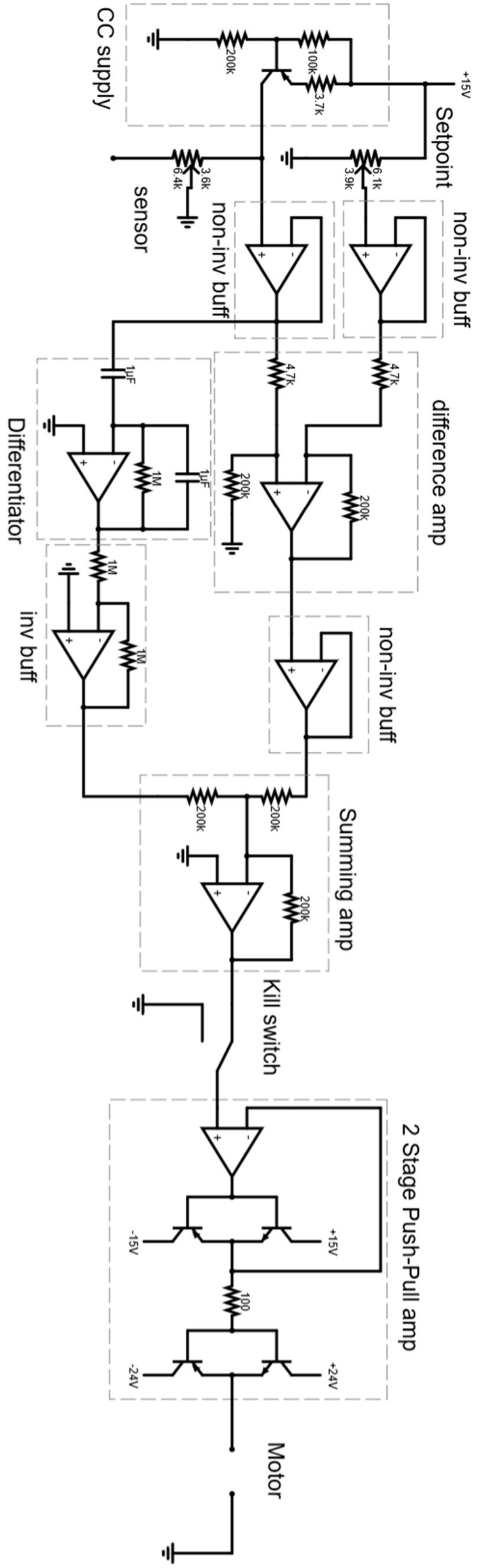

Figure 27: The final circuit diagram of the complete circuit constructed during this project. It is the combination of the three components shown above. The input is taken from the sensor which is then used to calculate the PD control equation

$$u(t) = 85.2e(t) + 0.2\frac{d\big(e(t)\big)}{dt}$$

This control signal is the used to control the motor and counteract the motion of the inverted pendulum. For clarity the power signals to the operational amplifiers are not shown in this diagram.

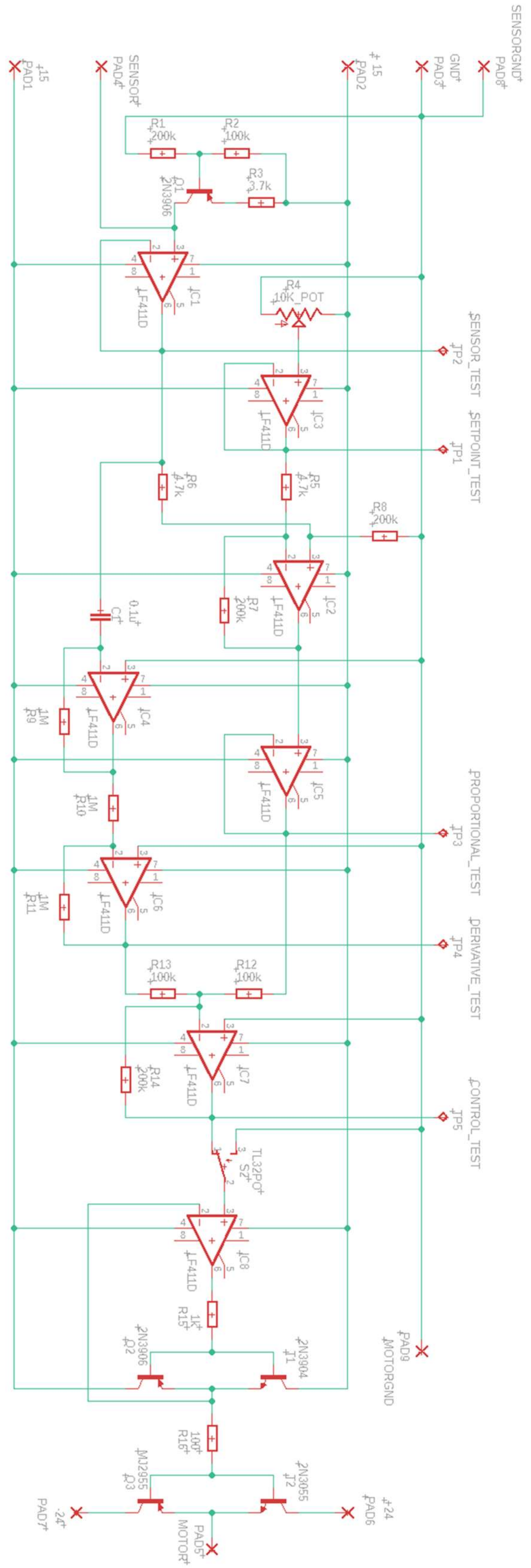

Figure 28: The final circuit as implemented in EAGLE. In contrast to figure 27 all power and ground connections are shown. This is the circuit as it would be implemented on a PCB, the motor and sensor would be connected externally using pads, all other components would be mounted to the PCB. The supply voltages are also taken in from pads, including a common ground that all power supplies should be connected to. Test points were also added to the circuit to test various control voltages throughout the circuit to ensure it is operating as it should be.

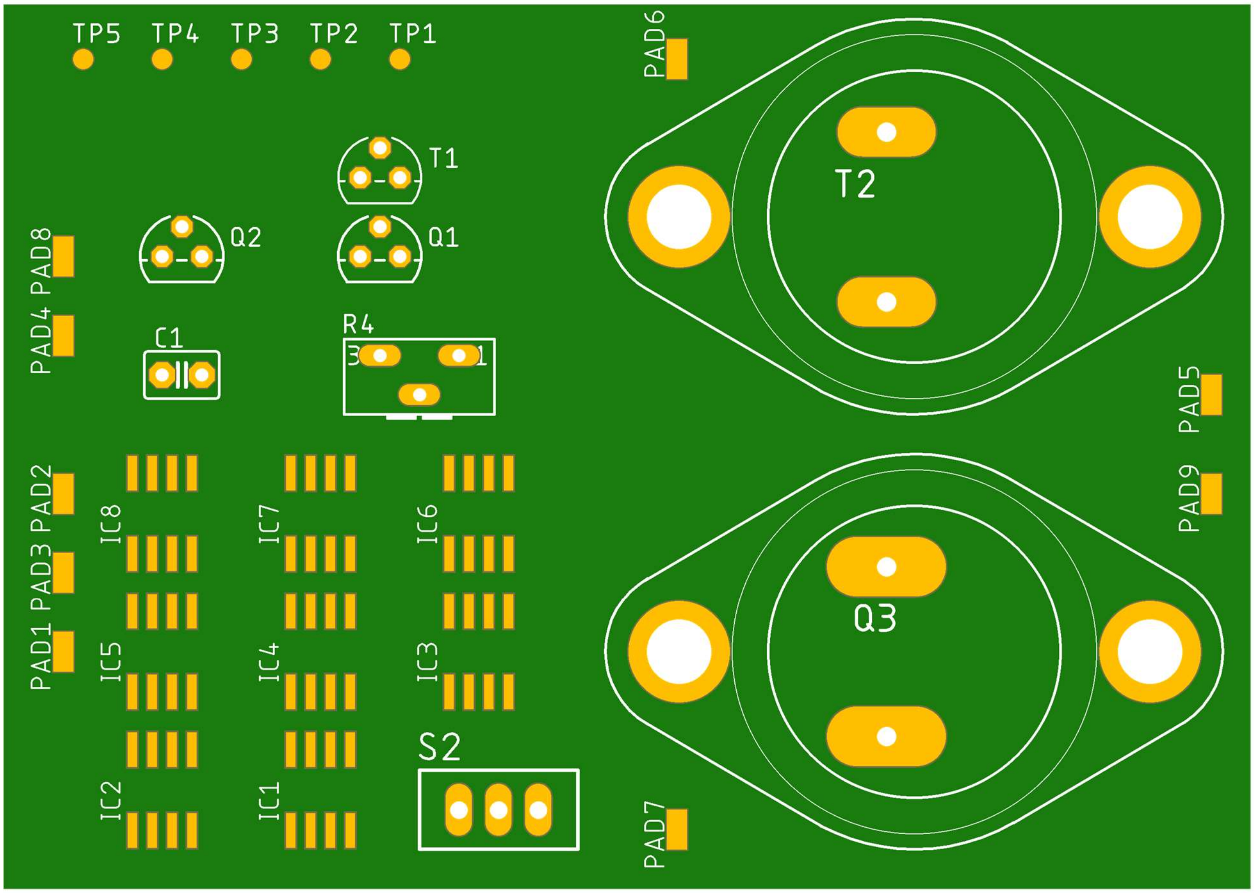

Figure 29: The top side of the PCB design completed in EAGLE, the connections and labels are as shown in tables 3 and 2. of the circuit diagram in EAGLE. The pads are as shown in the table above and are arranged in groups to enable easy identification and connection of th supplies to the circuit. The test points TP1 – TP5 enable the user to test the control singnals throughout the circuit and ensure the system is working properly. Note that EAGLE had an error with the resistors and did not create a board design including them; so the final board would be larger and include the 14 resistors including the large 10 W resistor between the first and second stages of the push-pull amplifier. This board however follows the design philosophy we will use for the final board, the two large transistors and their power supplies will be connected on one end of the boad for easier installation of a heatsink and to limit the distance the high current has to travel. The operational amplifiers will be positioned together with the resistors and capacitors in between them as nesseacry. The small transistors and the potentiometer will be positioned together with the potentiometer positioned near the edge for easy adjustment of the setpoint. The inputs for the

power and ground for the circuit, the sensor connections, and the motor outputs are positioned together for clarity. The test points ar postioned in a row on one side of the circuit with the increasing number corresponding to being further along in the circuit.

Table 2: Parts list of the final circuit. Values and part numbers are only listed if nessecary, the passive resistors and capacitors, and the potentiometer only need to fit the drilled form factor in the circuit and the specific model is umimportant, only the value is. For the operatinonal amplifiers and the transistors the part is important and as such islisted instead of a value.

Part name	Part Number	Amount	Value
Capacitor		2	0.1 μF
Resistor		3	100 k Ω
Resistor		4	200 k Ω
Resistor		3	1 M Ω
Resistor		1	3.7 k Ω
Resistor		2	4.7 k Ω
Resistor		1	100 Ω
Potentiometer		1	10 k Ω
Operational Amplifier	LF411	8	
NPN transistor	2N3904	1	
PNP Transistor	2N3906	2	
NPN transistor	2N3055	1	
PNP Transistor	MJ2955	1	

Table 3: Mapping of inputs and outputs. The circuit contains a 9 input and output pads, this table list what they are either connected.

Pad	Description	Connection
PAD1	Voltage input	-15 V
PAD2	Voltage input	+15 V
PAD3	Ground input	GND
PAD4	Sensor input	Side of sensor
PAD5	Motor output	Input wire of motor
PAD6	Motor voltage input	+24 V
PAD7	Motor voltage input	-24 V
PAD8	Sensor ground	Centre tap of sensor
PAD9	Motor ground	Ground wire of motor

Table 4: Test pad connections; the circuit contains 5 test pads this table lists the signal they test. To test a voltage it must be measured off the correct test pad relative to the common ground.

Test Point	Description
TP1	Setpoint
TP2	Sensor voltage
TP3	Proportional control $42.6e(t)$
TP4	Derivate control $0.1\frac{d(e(t))}{dt}$
TP5	PD control $u(t) = 85.2(t) + 0.2\frac{d(e(t))}{dt}$

Conclusion

An analog control system was developed for a rotary inverted pendulum. The control circuit has 3 major sections, the constant current supply for the sensor, PD control, and the motor controller. A PNP constant current supply is used to create a linearly varying voltage based on the angle of the sensor potentiometer which measure changes in angle as a change in resistance. Using this sensor voltage the PD control circuit implements the equation below:

$$u(t) = 85.2(t) + 0.2\frac{d\big(e(t)\big)}{dt}$$

The proportional component of this equation acts on the error from vertical of the inverted pendulum and acts to reduce this error. The derivative component acts on the rate of change of the inverted pendulum, it decreases the speed of the pendulum to damp any oscillations present from the proportional control overshooting and stabilize the pendulum once it is returned to vertical. This was implemented using operational amplifiers to calculate the above equation. Finally, the motor was controlled with a two-stage push-pull amplifier. The motor needs high current to operate and the operational amplifiers that calculate the PD control equation output is a voltage with no current. The two-stage push-pull amplifier takes input from a voltage signal and using the two stages of transistors switches high current to run the motor. The circuit was implemented as a prototype on breadboards connected to a circuit trainer; this circuit took input from the sensor and output the resulting control signal to the motor. A kill switch was implemented to disable the output of the circuit when switched into the ‘killed’ position. The circuit was turned, and the design improved iteratively over the course of this project especially in the last half of the project time.

A large and complex analog control circuit to implement PD control of a complex system was developed, and a prototype was constructed. The constant current section of the circuit converted the variable resistance of the potentiometer into a variable voltage. The setpoint is user adjustable using the potentiometer, it can be tuned with a screwdriver to tune the circuit. Both the proportional and derivative components of the control circuit respond as designed to motion of the pendulum; they are added together to create the final control signal. The gain of all components was adjustable by changing the resistors attached to operational amplifiers allowing the circuit to be easily improved upon. The circuit responds correctly to pendulum motion, but it currently does not move the motor fast enough to counteract the motion of the motor. This is caused by a combination of issues with the sensor, push-pull amplifier, and the motor. The potentiometer may not be sensitive enough for precise control of the system.

The high inertia of the motor means it accelerates slowly and uses large current to operate necessitating the complex circuitry of the two-stage push-pull amplifier to operate. The turn on voltage due to the high inertia of the motor and the two-stage push-pull amplifier means output must be above 2.5 V to turn on the motor. This is a significant fraction of the control range of the circuit. When operated the circuit is current limited due to a combination of these factors. Additional issues that may be present but do not currently impact the operation of the circuit are: the large gain present throughout the circuit amplifies noise in the sensor signal and the complexity of the circuit introduces additional noise; due to the complexity of the circuit control signals will take time to propagate though the circuit slowing the response.

The circuit took input from a sensor calculated a control signal, and PD control was able to be implemented from this input, the output was then based on the control signal. Even though the motor output was current limited the control signal was as expected and the only changes that need to be made to the overall construction are in the push-pull amplifier and to the motor other than tuning of the gain of individual components to achieve basic control of the inverted pendulum. Over the course of this project, we worked as a group to solve a complex control problem. Work was divided based on individual strengths, we worked collaboratively to achieve more than we could have individually. This project extended our practical knowledge of analog circuitry including circuit design, testing, iterative design, and reporting.

To improve the circuit enough for it to take full control of the inverted pendulum there are several things w could test. First would be using high current power supplies to the input of the power switching transistors, if the circuit can be provided with 1.5 A max current supplies to the push-pull amplifier we will be able to rule out current limitations from the circuit. High current supplies should be useable with the current circuit as it stands; however, heatsinks may need to be added to the power transistors and the motor to dissipate the additional heat caused by this current. With higher current supplies connected to the circuit a longer pendulum will fall slower than a shorted one so replacing the current pendulum with a longer one would give the system more time to control the circuit and decreasing the force needed to counteract the falling of the pendulum. If increasing the current is not enough to stabilize the pendulum then no more work is possible with the current motor, and it will need to be replaced with another motor. Minimal changes would need to be made to the circuit to run a motor with lower inertia and a gearbox to increase the torque to enable the lower current motor to better control the pendulum, with an increase in the length of the pendulum and a lower current motor the second stage of the push-pull amplifier may prove unnecessary, the 2N3904 and 2N3906 transistors can switch up to 200 mA in current, this would reduce the turn on voltage of motor. We estimate between 3 and 4 weeks more time on this project would need to be spent to test these possibilities and achieve control of the inverted pendulum.

Sources

[1] X. Diao, "Modular Control of a Rotary Inverted Pendulum System," in *Jazzed about Engineering Education*, New Orleans, 2016.

[2] On Semiconductor, "General Purpose Transistors NPN Silicon 2N3903, 2N3904," August 2021. [Online]. Available: https://www.onsemi.com/pdf/datasheet/2n3903-d.pdf. [Accessed 9 November 2021].

[3] On Semiconductor, "2N3906 General Purpose Transistor," February 2010. [Online]. Available: https://www.onsemi.com/pdf/datasheet/2n3906-d.pdf. [Accessed 9 November 2021].

[4] On Semiconductor, "2N3055(NPN), MJ2955(PNP) Complementary Silicon Power Transistors," December 2005. [Online]. Available: https://www.onsemi.com/pdf/datasheet/2n3055-d.pdf. [Accessed 13 December 2021].

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Appendix

This appendix contains datasheets for all components utilized in the final circuit that are not resistors. It also information on the circuit trainer the prototype circuit was constructed on, and the power supplies used to power the circuit. These datasheets are listed in the same order that they are cited in the sources section above.

DATA SHEET
www.onsemi.com

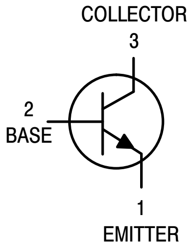
General Purpose Transistors

NPN Silicon

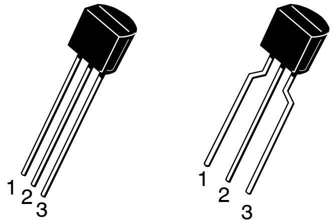
2N3903, 2N3904

Features

- Pb−Free Packages are Available*



TO−92
CASE 29
STYLE 1



STRAIGHT LEAD
BULK PACK

BENT LEAD
TAPE & REEL
AMMO PACK

MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Collector − Emitter Voltage	V_{CEO}	40	Vdc
Collector − Base Voltage	V_{CBO}	60	Vdc
Emitter − Base Voltage	V_{EBO}	6.0	Vdc
Collector Current − Continuous	I_C	200	mAdc
Total Device Dissipation @ T_A = 25°C Derate above 25°C	P_D	625 5.0	mW mW/°C
Total Device Dissipation @ T_C = 25°C Derate above 25°C	P_D	1.5 12	W mW/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	−55 to +150	°C

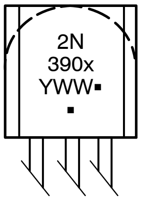
THERMAL CHARACTERISTICS (Note 1)

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction−to−Ambient	$R_{\theta JA}$	200	°C/W
Thermal Resistance, Junction−to−Case	$R_{\theta JC}$	83.3	°C/W

Stresses exceeding those listed in the Maximum Ratings table may damage the device. If any of these limits are exceeded, device functionality should not be assumed, damage may occur and reliability may be affected.

1. Indicates Data in addition to JEDEC Requirements.

MARKING DIAGRAMS



x = 3 or 4
Y = Year
WW = Work Week
▪ = Pb−Free Package
(Note: Microdot may be in either location)

ORDERING INFORMATION

See detailed ordering and shipping information in the package dimensions section on page 3 of this data sheet.

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*For additional information on our Pb−Free strategy and soldering details, please download the **onsemi** Soldering and Mounting Techniques Reference Manual, SOLDERRM/D.

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
OFF CHARACTERISTICS				
Collector – Emitter Breakdown Voltage (Note 2) (I_C = 1.0 mAdc, I_B = 0)	$V_{(BR)CEO}$	40	–	Vdc
Collector – Base Breakdown Voltage (I_C = 10 μAdc, I_E = 0)	$V_{(BR)CBO}$	60	–	Vdc
Emitter – Base Breakdown Voltage (I_E = 10 μAdc, I_C = 0)	$V_{(BR)EBO}$	6.0	–	Vdc
Base Cutoff Current (V_{CE} = 30 Vdc, V_{EB} = 3.0 Vdc)	I_{BL}	–	50	nAdc
Collector Cutoff Current (V_{CE} = 30 Vdc, V_{EB} = 3.0 Vdc)	I_{CEX}	–	50	nAdc
ON CHARACTERISTICS				
DC Current Gain (Note 2)	h_{FE}			–
(I_C = 0.1 mAdc, V_{CE} = 1.0 Vdc) 2N3903		20	–	
2N3904		40	–	
(I_C = 1.0 mAdc, V_{CE} = 1.0 Vdc) 2N3903		35	–	
2N3904		70	–	
(I_C = 10 mAdc, V_{CE} = 1.0 Vdc) 2N3903		50	150	
2N3904		100	300	
(I_C = 50 mAdc, V_{CE} = 1.0 Vdc) 2N3903		30	–	
2N3904		60	–	
(I_C = 100 mAdc, V_{CE} = 1.0 Vdc) 2N3903		15	–	
2N3904		30	–	
Collector – Emitter Saturation Voltage (Note 2)	$V_{CE(sat)}$			Vdc
(I_C = 10 mAdc, I_B = 1.0 mAdc)		–	0.2	
(I_C = 50 mAdc, I_B = 5.0 mAdc		–	0.3	
Base – Emitter Saturation Voltage (Note 2)	$V_{BE(sat)}$			Vdc
(I_C = 10 mAdc, I_B = 1.0 mAdc)		0.65	0.85	
(I_C = 50 mAdc, I_B = 5.0 mAdc)		–	0.95	
SMALL– SIGNAL CHARACTERISTICS				
Current – Gain – Bandwidth Product	f_T			MHz
(I_C = 10 mAdc, V_{CE} = 20 Vdc, f = 100 MHz) 2N3903		250	–	
2N3904		300	–	
Output Capacitance (V_{CB} = 5.0 Vdc, I_E = 0, f = 1.0 MHz)	C_{obo}	–	4.0	pF
Input Capacitance (V_{EB} = 0.5 Vdc, I_C = 0, f = 1.0 MHz)	C_{ibo}	–	8.0	pF
Input Impedance	h_{ie}			k Ω
(I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz) 2N3903		1.0	8.0	
2N3904		1.0	10	
Voltage Feedback Ratio	h_{re}			X 10^{-4}
(I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz) 2N3903		0.1	5.0	
2N3904		0.5	8.0	
Small–Signal Current Gain	h_{fe}			–
(I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz) 2N3903		50	200	
2N3904		100	400	
Output Admittance (I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	h_{oe}	1.0	40	μmhos
Noise Figure	NF			dB
(I_C = 100 μAdc, V_{CE} = 5.0 Vdc, R_S = 1.0 k Ω, f = 1.0 kHz) 2N3903		–	6.0	
2N3904		–	5.0	

SWITCHING CHARACTERISTICS

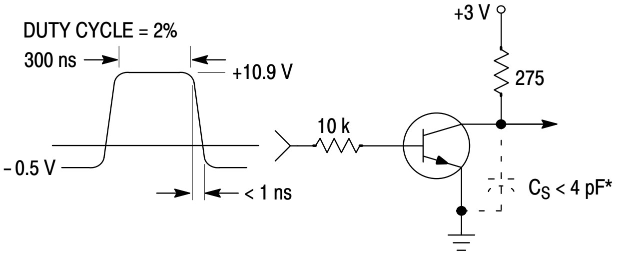
		Symbol	Min	Max	Unit
Delay Time	(V_{CC} = 3.0 Vdc, V_{BE} = 0.5 Vdc, I_C = 10 mAdc, I_{B1} = 1.0 mAdc)	t_d	–	35	ns
Rise Time		t_r	–	35	ns
Storage Time	(V_{CC} = 3.0 Vdc, I_C = 10 mAdc, I_{B1} = I_{B2} = 1.0 mAdc) 2N3903	t_s	–	175	ns
	2N3904		–	200	
Fall Time		t_f	–	50	ns

2. Pulse Test: Pulse Width ≤ 300 μs; Duty Cycle ≤ 2%.

ORDERING INFORMATION

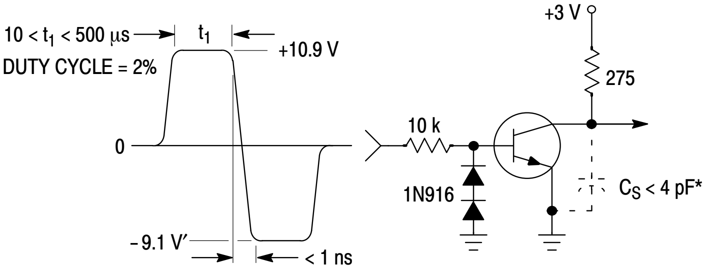
Device	Package	Shipping†
2N3903RLRM	TO−92	2000 / Ammo Pack
2N3904	TO−92	5000 Units / Bulk
2N3904G	TO−92 (Pb−Free)	5000 Units / Bulk
2N3904RLRA	TO−92	2000 / Tape & Reel
2N3904RLRAG	TO−92 (Pb−Free)	2000 / Tape & Reel
2N3904RLRM	TO−92	2000 / Ammo Pack
2N3904RLRMG	TO−92 (Pb−Free)	2000 / Ammo Pack
2N3904RLRP	TO−92	2000 / Ammo Pack
2N3904RLRPG	TO−92 (Pb−Free)	2000 / Ammo Pack
2N3904RL1G	TO−92 (Pb−Free)	2000 / Tape & Reel
2N3904ZL1	TO−92	2000 / Ammo Pack
2N3904ZL1G	TO−92 (Pb−Free)	2000 / Ammo Pack

†For information on tape and reel specifications, including part orientation and tape sizes, please refer to our Tape and Reel Packaging Specifications Brochure, BRD8011/D.



* Total shunt capacitance of test jig and connectors

Figure 1. Delay and Rise Time Equivalent Test Circuit



* Total shunt capacitance of test jig and connectors

Figure 2. Storage and Fall Time Equivalent Test Circuit

TYPICAL TRANSIENT CHARACTERISTICS

—— $T_J = 25°C$
– – $T_J = 125°C$

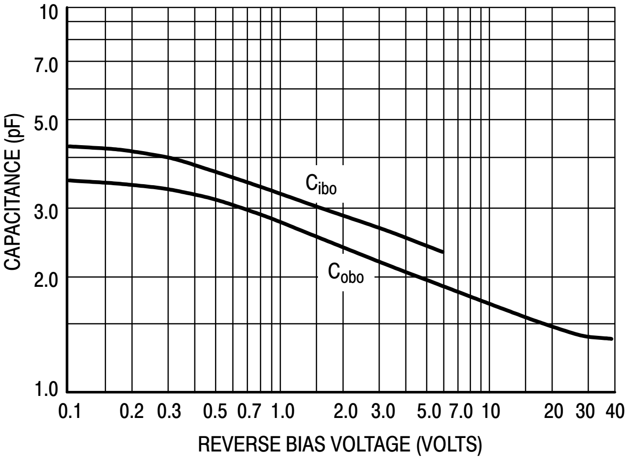


Figure 3. Capacitance

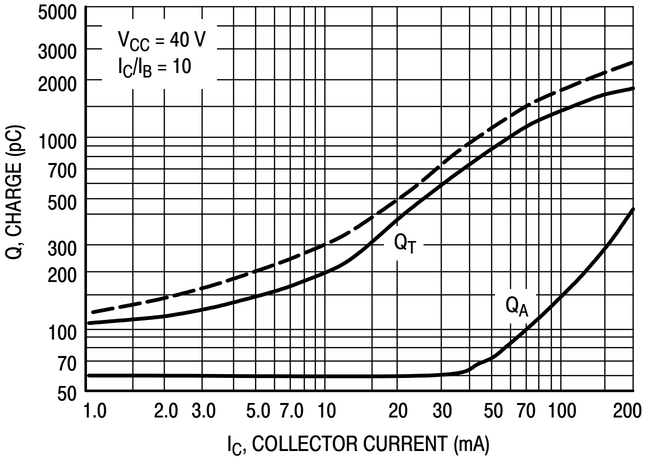


Figure 4. Charge Data

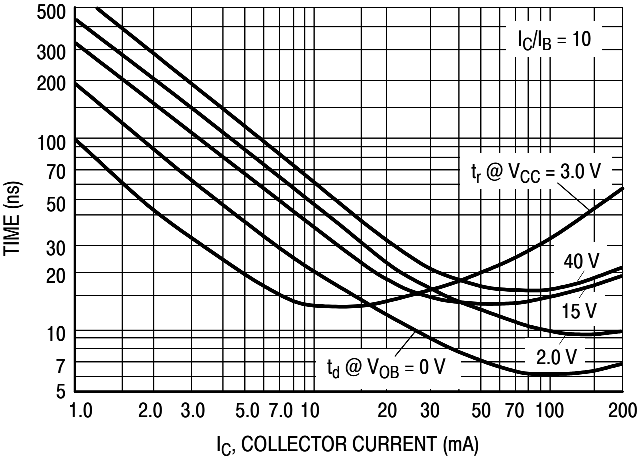


Figure 5. Turn−On Time

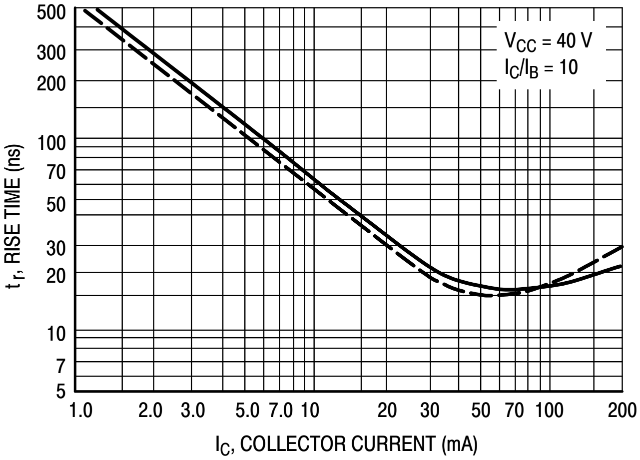


Figure 6. Rise Time

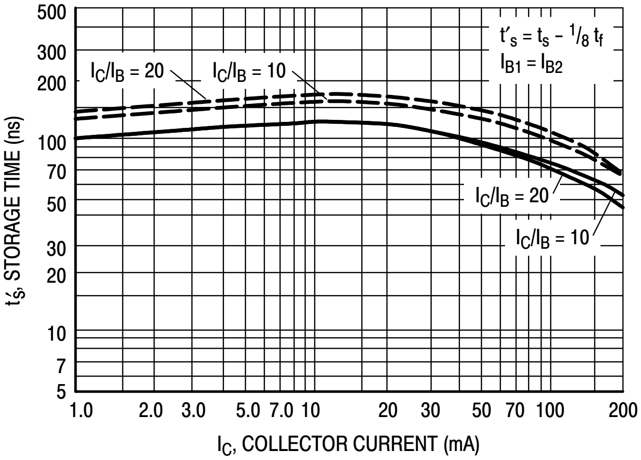


Figure 7. Storage Time

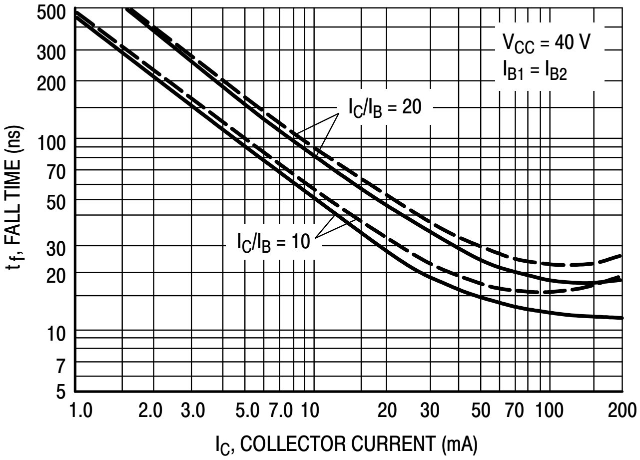


Figure 8. Fall Time

TYPICAL AUDIO SMALL–SIGNAL CHARACTERISTICS
NOISE FIGURE VARIATIONS

(V_{CE} = 5.0 Vdc, T_A = 25°C, Bandwidth = 1.0 Hz)

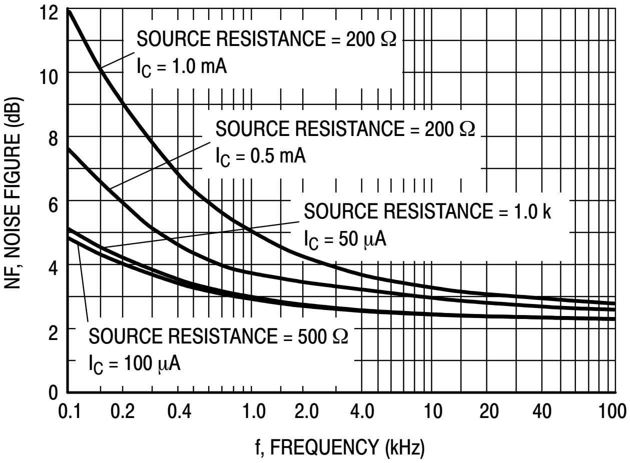


Figure 9.

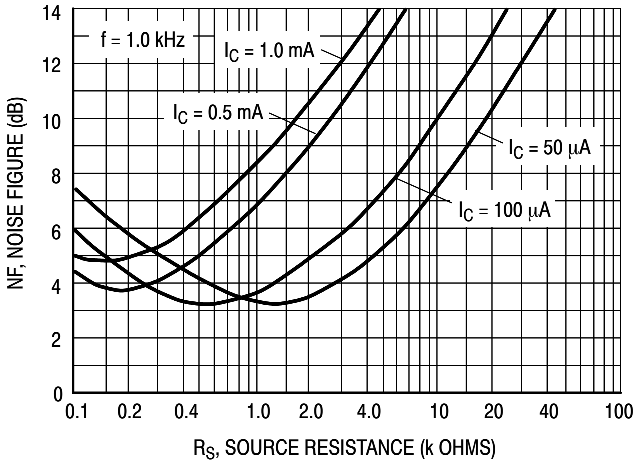


Figure 10.

h PARAMETERS

(V_{CE} = 10 Vdc, f = 1.0 kHz, T_A = 25°C)

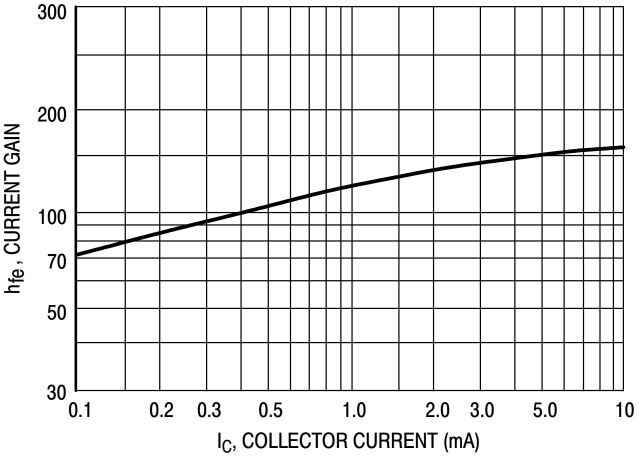


Figure 11. Current Gain

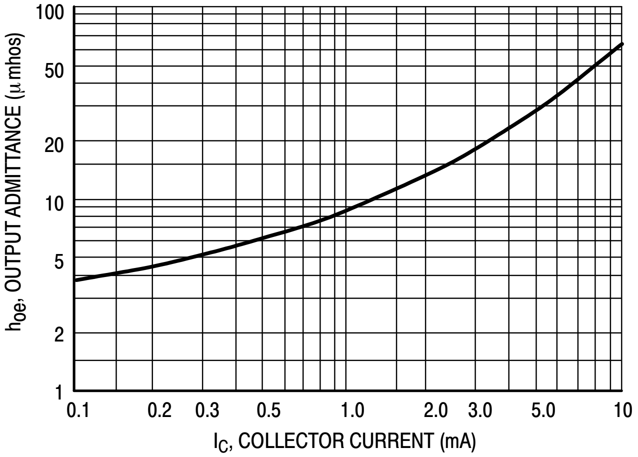


Figure 12. Output Admittance

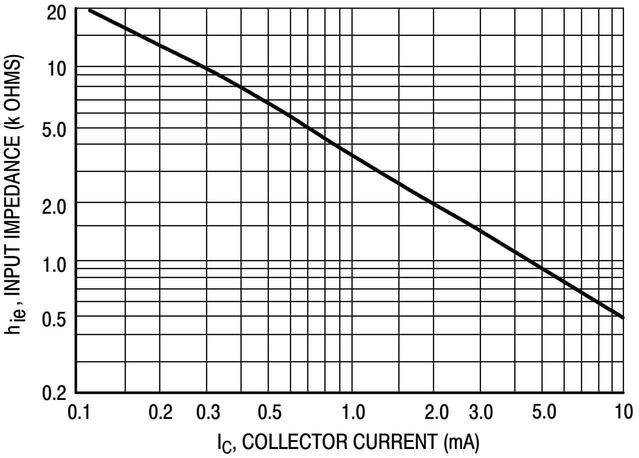


Figure 13. Input Impedance

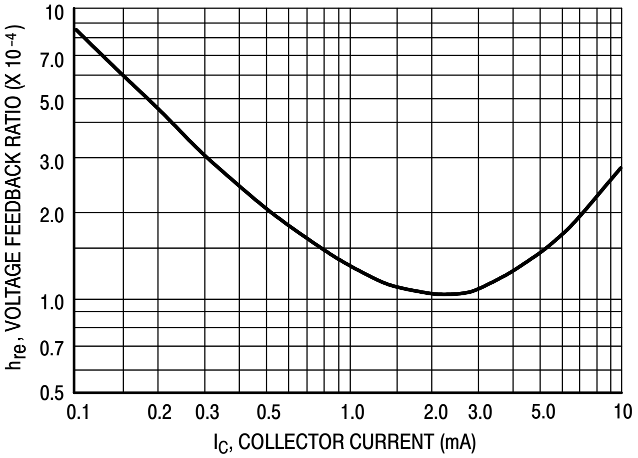


Figure 14. Voltage Feedback Ratio

TYPICAL STATIC CHARACTERISTICS

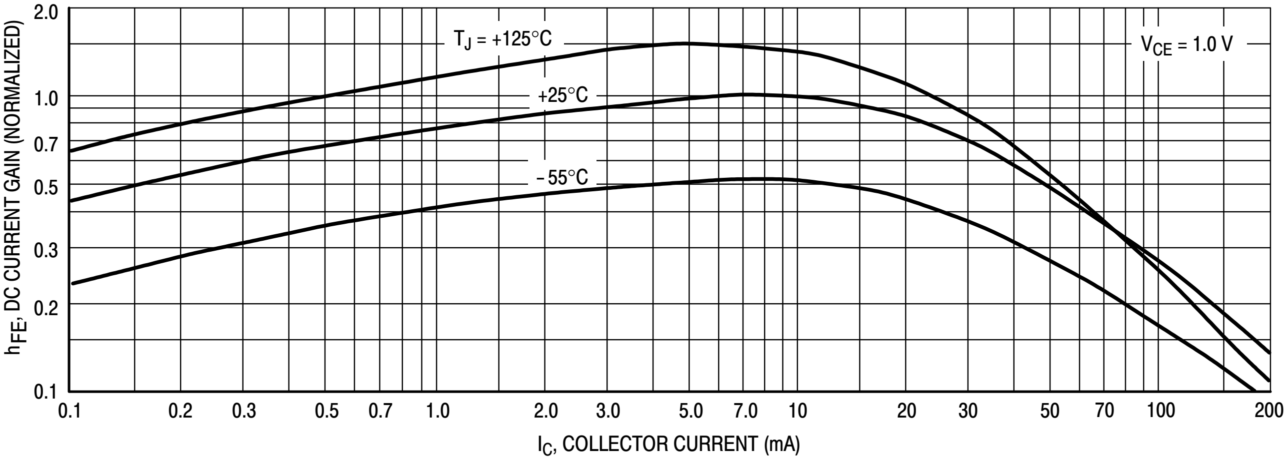


Figure 15. DC Current Gain

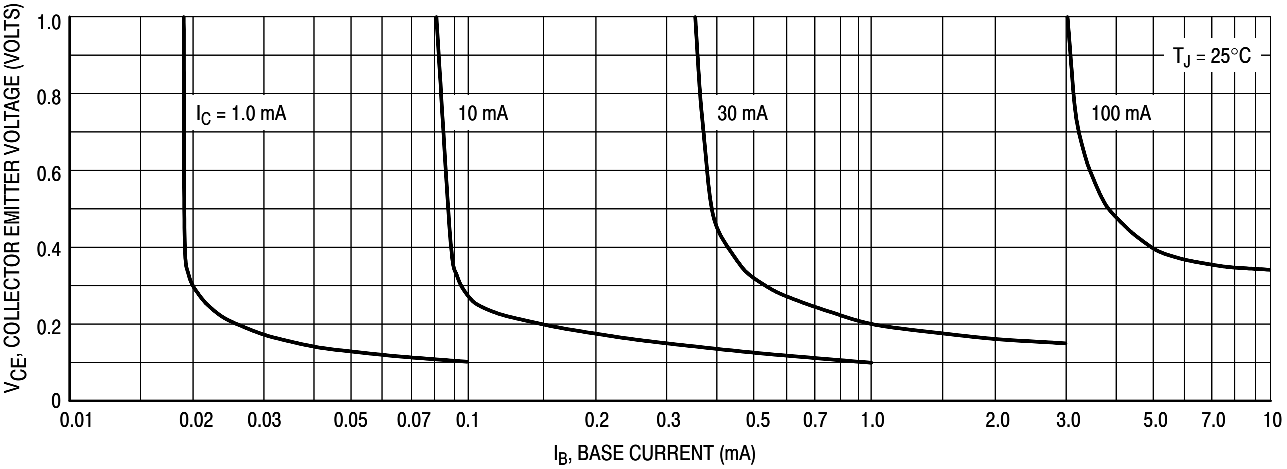


Figure 16. Collector Saturation Region

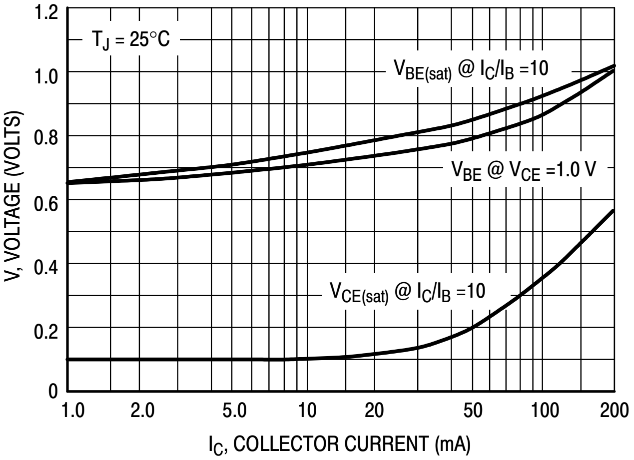


Figure 17. “ON” Voltages

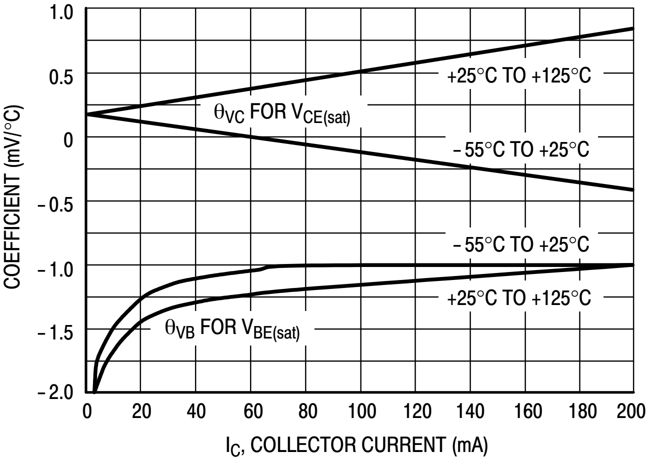
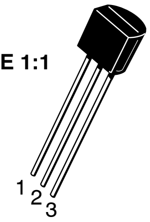
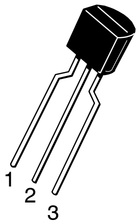


Figure 18. Temperature Coefficients

SCALE 1:1



STRAIGHT LEAD
BULK PACK

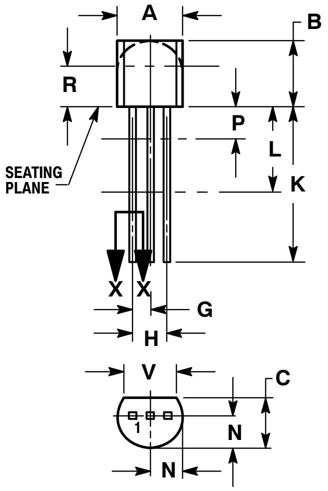


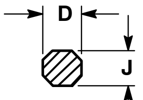
BENT LEAD
TAPE & REEL
AMMO PACK

TO−92 (TO−226)
CASE 29−11
ISSUE AM

DATE 09 MAR 2007

STRAIGHT LEAD
BULK PACK



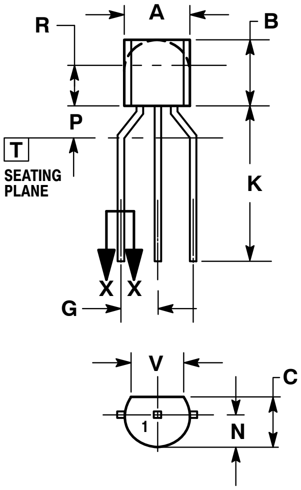


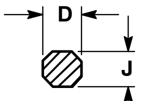
SECTION X−X

NOTES:
1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION: INCH.
3. CONTOUR OF PACKAGE BEYOND DIMENSION R IS UNCONTROLLED.
4. LEAD DIMENSION IS UNCONTROLLED IN P AND BEYOND DIMENSION K MINIMUM.

	INCHES		MILLIMETERS	
DIM	MIN	MAX	MIN	MAX
A	0.175	0.205	4.45	5.20
B	0.170	0.210	4.32	5.33
C	0.125	0.165	3.18	4.19
D	0.016	0.021	0.407	0.533
G	0.045	0.055	1.15	1.39
H	0.095	0.105	2.42	2.66
J	0.015	0.020	0.39	0.50
K	0.500	---	12.70	---
L	0.250	---	6.35	---
N	0.080	0.105	2.04	2.66
P	---	0.100	---	2.54
R	0.115	---	2.93	---
V	0.135	---	3.43	---

BENT LEAD
TAPE & REEL
AMMO PACK





SECTION X−X

NOTES:
1. DIMENSIONING AND TOLERANCING PER ASME Y14.5M, 1994.
2. CONTROLLING DIMENSION: MILLIMETERS.
3. CONTOUR OF PACKAGE BEYOND DIMENSION R IS UNCONTROLLED.
4. LEAD DIMENSION IS UNCONTROLLED IN P AND BEYOND DIMENSION K MINIMUM.

	MILLIMETERS	
DIM	MIN	MAX
A	4.45	5.20
B	4.32	5.33
C	3.18	4.19
D	0.40	0.54
G	2.40	2.80
J	0.39	0.50
K	12.70	---
N	2.04	2.66
P	1.50	4.00
R	2.93	---
V	3.43	---

STYLES ON PAGE 2

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NEW STANDARD:		
DESCRIPTION:	**TO−92 (TO−226)**	**PAGE 1 OF 3**

TO−92 (TO−226)
CASE 29−11
ISSUE AM

DATE 09 MAR 2007

STYLE 1:
PIN 1. EMITTER
2. BASE
3. COLLECTOR

STYLE 2:
PIN 1. BASE
2. EMITTER
3. COLLECTOR

STYLE 3:
PIN 1. ANODE
2. ANODE
3. CATHODE

STYLE 4:
PIN 1. CATHODE
2. CATHODE
3. ANODE

STYLE 5:
PIN 1. DRAIN
2. SOURCE
3. GATE

STYLE 6:
PIN 1. GATE
2. SOURCE & SUBSTRATE
3. DRAIN

STYLE 7:
PIN 1. SOURCE
2. DRAIN
3. GATE

STYLE 8:
PIN 1. DRAIN
2. GATE
3. SOURCE & SUBSTRATE

STYLE 9:
PIN 1. BASE 1
2. EMITTER
3. BASE 2

STYLE 10:
PIN 1. CATHODE
2. GATE
3. ANODE

STYLE 11:
PIN 1. ANODE
2. CATHODE & ANODE
3. CATHODE

STYLE 12:
PIN 1. MAIN TERMINAL 1
2. GATE
3. MAIN TERMINAL 2

STYLE 13:
PIN 1. ANODE 1
2. GATE
3. CATHODE 2

STYLE 14:
PIN 1. EMITTER
2. COLLECTOR
3. BASE

STYLE 15:
PIN 1. ANODE 1
2. CATHODE
3. ANODE 2

STYLE 16:
PIN 1. ANODE
2. GATE
3. CATHODE

STYLE 17:
PIN 1. COLLECTOR
2. BASE
3. EMITTER

STYLE 18:
PIN 1. ANODE
2. CATHODE
3. NOT CONNECTED

STYLE 19:
PIN 1. GATE
2. ANODE
3. CATHODE

STYLE 20:
PIN 1. NOT CONNECTED
2. CATHODE
3. ANODE

STYLE 21:
PIN 1. COLLECTOR
2. EMITTER
3. BASE

STYLE 22:
PIN 1. SOURCE
2. GATE
3. DRAIN

STYLE 23:
PIN 1. GATE
2. SOURCE
3. DRAIN

STYLE 24:
PIN 1. EMITTER
2. COLLECTOR/ANODE
3. CATHODE

STYLE 25:
PIN 1. MT 1
2. GATE
3. MT 2

STYLE 26:
PIN 1. V_{CC}
2. GROUND 2
3. OUTPUT

STYLE 27:
PIN 1. MT
2. SUBSTRATE
3. MT

STYLE 28:
PIN 1. CATHODE
2. ANODE
3. GATE

STYLE 29:
PIN 1. NOT CONNECTED
2. ANODE
3. CATHODE

STYLE 30:
PIN 1. DRAIN
2. GATE
3. SOURCE

STYLE 31:
PIN 1. GATE
2. DRAIN
3. SOURCE

STYLE 32:
PIN 1. BASE
2. COLLECTOR
3. EMITTER

STYLE 33:
PIN 1. RETURN
2. INPUT
3. OUTPUT

STYLE 34:
PIN 1. INPUT
2. GROUND
3. LOGIC

STYLE 35:
PIN 1. GATE
2. COLLECTOR
3. EMITTER

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	PAGE 3 OF 3

ISSUE	REVISION	DATE
AM	ADDED BENT−LEAD TAPE & REEL VERSION. REQ. BY J. SUPINA.	09 MAR 2007

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2N3906

General Purpose Transistors

PNP Silicon

Features

- Pb−Free Packages are Available*

MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Collector − Emitter Voltage	V_{CEO}	40	Vdc
Collector − Base Voltage	V_{CBO}	40	Vdc
Emitter − Base Voltage	V_{EBO}	5.0	Vdc
Collector Current − Continuous	I_C	200	mAdc
Total Device Dissipation @ T_A = 25°C Derate above 25°C	P_D	625 5.0	mW mW/°C
Total Power Dissipation @ T_A = 60°C	P_D	250	mW
Total Device Dissipation @ T_C = 25°C Derate above 25°C	P_D	1.5 12	W mW/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	−55 to +150	°C

THERMAL CHARACTERISTICS (Note 1)

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction−to−Ambient	$R_{\theta JA}$	200	°C/W
Thermal Resistance, Junction−to−Case	$R_{\theta JC}$	83.3	°C/W

Stresses exceeding Maximum Ratings may damage the device. Maximum Ratings are stress ratings only. Functional operation above the Recommended Operating Conditions is not implied. Extended exposure to stresses above the Recommended Operating Conditions may affect device reliability.

1. Indicates Data in addition to JEDEC Requirements.

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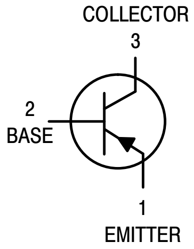
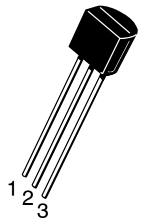
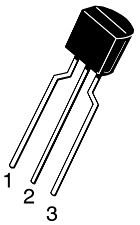


TO−92
CASE 29
STYLE 1

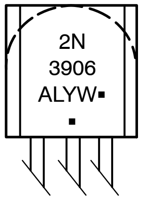


STRAIGHT LEAD
BULK PACK



BENT LEAD
TAPE & REEL
AMMO PACK

MARKING DIAGRAM



A = Assembly Location
L = Wafer Lot
Y = Year
W = Work Week
▪ = Pb−Free Package
(Note: Microdot may be in either location)

ORDERING INFORMATION

See detailed ordering and shipping information in the package dimensions section on page 3 of this data sheet.

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*For additional information on our Pb−Free strategy and soldering details, please download the ON Semiconductor Soldering and Mounting Techniques Reference Manual, SOLDERRM/D.

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

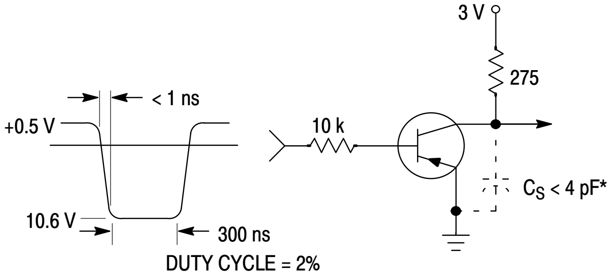
Characteristic		Symbol	Min	Max	Unit
OFF CHARACTERISTICS					
Collector – Emitter Breakdown Voltage (Note 2)	(I_C = 1.0 mAdc, I_B = 0)	$V_{(BR)CEO}$	40	–	Vdc
Collector – Base Breakdown Voltage	(I_C = 10 µAdc, I_E = 0)	$V_{(BR)CBO}$	40	–	Vdc
Emitter – Base Breakdown Voltage	(I_E = 10 µAdc, I_C = 0)	$V_{(BR)EBO}$	5.0	–	Vdc
Base Cutoff Current	(V_{CE} = 30 Vdc, V_{EB} = 3.0 Vdc)	I_{BL}	–	50	nAdc
Collector Cutoff Current	(V_{CE} = 30 Vdc, V_{EB} = 3.0 Vdc)	I_{CEX}	–	50	nAdc
ON CHARACTERISTICS (Note 2)					
DC Current Gain	(I_C = 0.1 mAdc, V_{CE} = 1.0 Vdc) (I_C = 1.0 mAdc, V_{CE} = 1.0 Vdc) (I_C = 10 mAdc, V_{CE} = 1.0 Vdc) (I_C = 50 mAdc, V_{CE} = 1.0 Vdc) (I_C = 100 mAdc, V_{CE} = 1.0 Vdc)	h_{FE}	60 80 100 60 30	– – 300 – –	–
Collector – Emitter Saturation Voltage	(I_C = 10 mAdc, I_B = 1.0 mAdc) (I_C = 50 mAdc, I_B = 5.0 mAdc	$V_{CE(sat)}$	– –	0.25 0.4	Vdc
Base – Emitter Saturation Voltage	(I_C = 10 mAdc, I_B = 1.0 mAdc) (I_C = 50 mAdc, I_B = 5.0 mAdc)	$V_{BE(sat)}$	0.65 –	0.85 0.95	Vdc
SMALL– SIGNAL CHARACTERISTICS					
Current – Gain – Bandwidth Product	(I_C = 10 mAdc, V_{CE} = 20 Vdc, f = 100 MHz)	f_T	250	–	MHz
Output Capacitance	(V_{CB} = 5.0 Vdc, I_E = 0, f = 1.0 MHz)	C_{obo}	–	4.5	pF
Input Capacitance	(V_{EB} = 0.5 Vdc, I_C = 0, f = 1.0 MHz)	C_{ibo}	–	10	pF
Input Impedance	(I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	h_{ie}	2.0	12	kΩ
Voltage Feedback Ratio	(I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	h_{re}	0.1	10	X 10^{-4}
Small–Signal Current Gain	(I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	h_{fe}	100	400	–
Output Admittance	(I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	h_{oe}	3.0	60	µmhos
Noise Figure	(I_C = 100 µAdc, V_{CE} = 5.0 Vdc, R_S = 1.0 kΩ, f = 1.0 kHz)	NF	–	4.0	dB
SWITCHING CHARACTERISTICS					
Delay Time	(V_{CC} = 3.0 Vdc, V_{BE} = 0.5 Vdc, I_C = 10 mAdc, I_{B1} = 1.0 mAdc)	t_d	–	35	ns
Rise Time		t_r	–	35	ns
Storage Time	(V_{CC} = 3.0 Vdc, I_C = 10 mAdc, I_{B1} = I_{B2} = 1.0 mAdc)	t_s	–	225	ns
Fall Time	(V_{CC} = 3.0 Vdc, I_C = 10 mAdc, I_{B1} = I_{B2} = 1.0 mAdc)	t_f	–	75	ns

2. Pulse Test: Pulse Width ≤ 300 µs; Duty Cycle ≤ 2%.

ORDERING INFORMATION

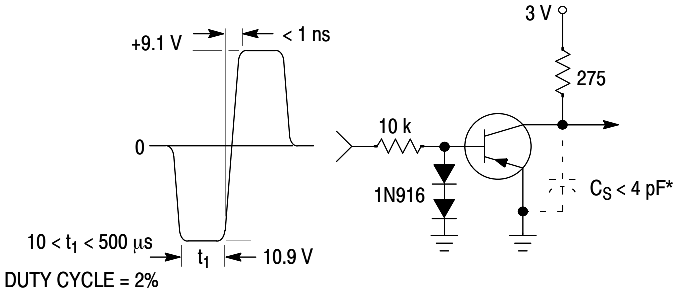
Device	Package	Shipping†
2N3906	TO−92	5000 Units / Bulk
2N3906G	TO−92 (Pb−Free)	5000 Units / Bulk
2N3906RL1	TO−92	2000 / Tape & Reel
2N3906RL1G	TO−92 (Pb−Free)	2000 / Tape & Reel
2N3906RLRA	TO−92	2000 / Tape & Reel
2N3906RLRAG	TO−92 (Pb−Free)	2000 / Tape & Reel
2N3906RLRM	TO−92	2000 / Tape & Ammo Box
2N3906RLRMG	TO−92 (Pb−Free)	2000 / Tape & Ammo Box
2N3906RLRP	TO−92	2000 / Tape & Ammo Box
2N3906RLRPG	TO−92 (Pb−Free)	2000 / Tape & Ammo Box

†For information on tape and reel specifications, including part orientation and tape sizes, please refer to our Tape and Reel Packaging Specifications Brochure, BRD8011/D.



* Total shunt capacitance of test jig and connectors

Figure 1. Delay and Rise Time Equivalent Test Circuit



* Total shunt capacitance of test jig and connectors

Figure 2. Storage and Fall Time Equivalent Test Circuit

TYPICAL TRANSIENT CHARACTERISTICS

——— $T_J = 25°C$
— — $T_J = 125°C$

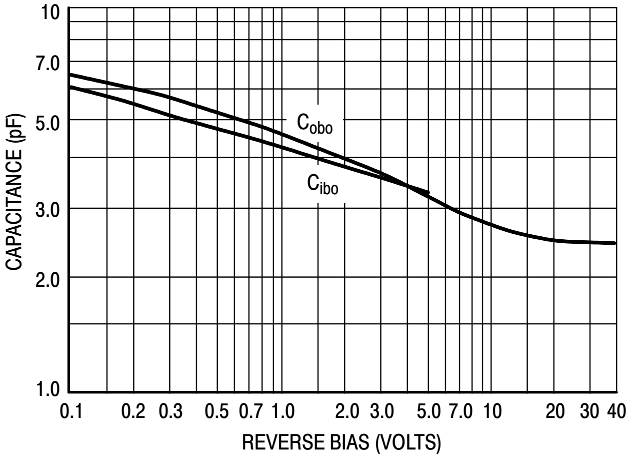


Figure 3. Capacitance

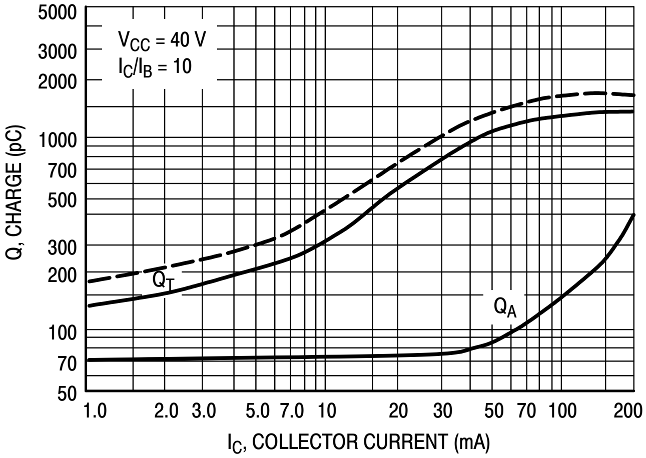


Figure 4. Charge Data

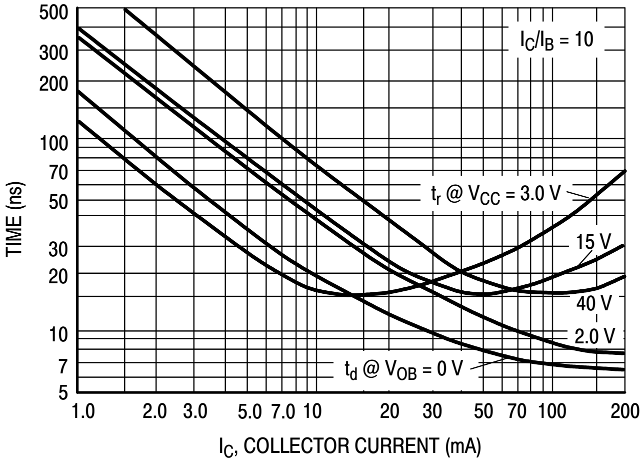


Figure 5. Turn-On Time

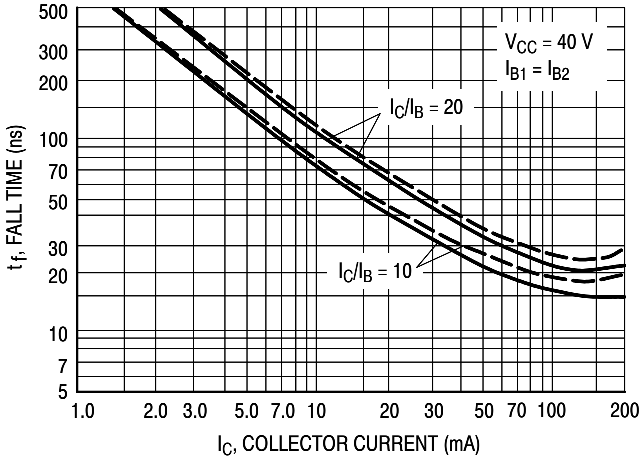


Figure 6. Fall Time

TYPICAL AUDIO SMALL–SIGNAL CHARACTERISTICS
NOISE FIGURE VARIATIONS

(V_{CE} = −5.0 Vdc, T_A = 25°C, Bandwidth = 1.0 Hz)

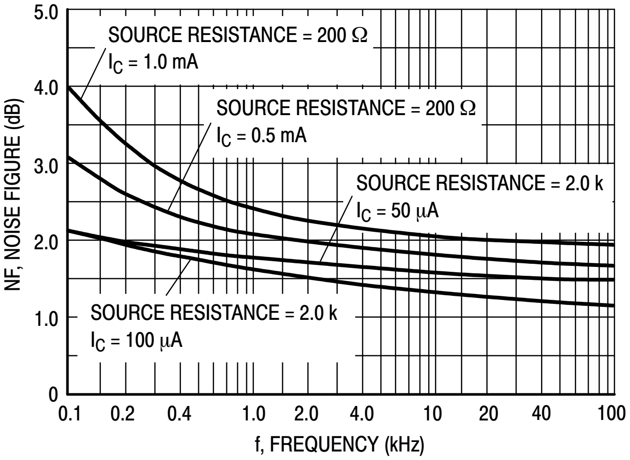


Figure 7.

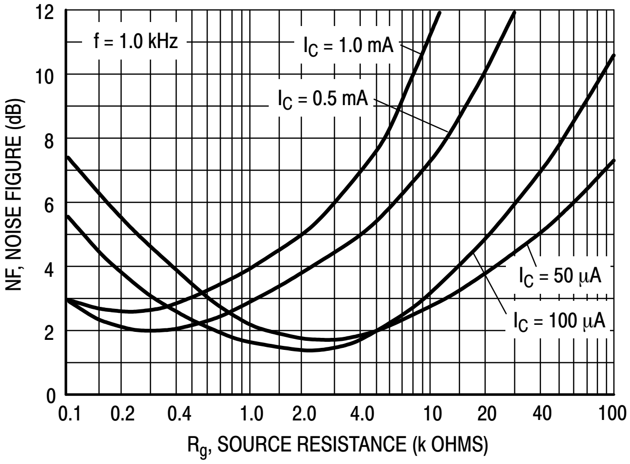


Figure 8.

h PARAMETERS

(V_{CE} = −10 Vdc, f = 1.0 kHz, T_A = 25°C)

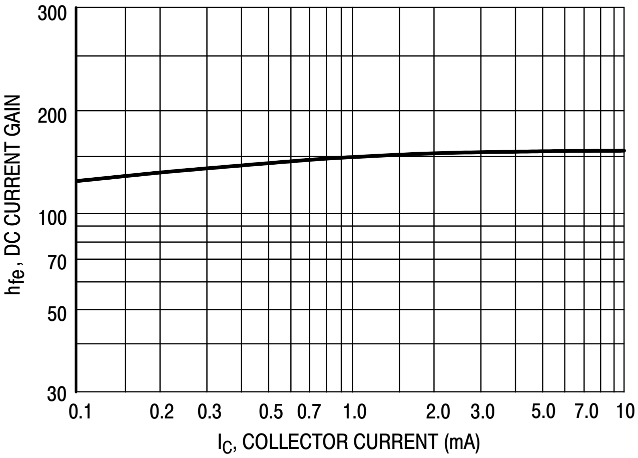


Figure 9. Current Gain

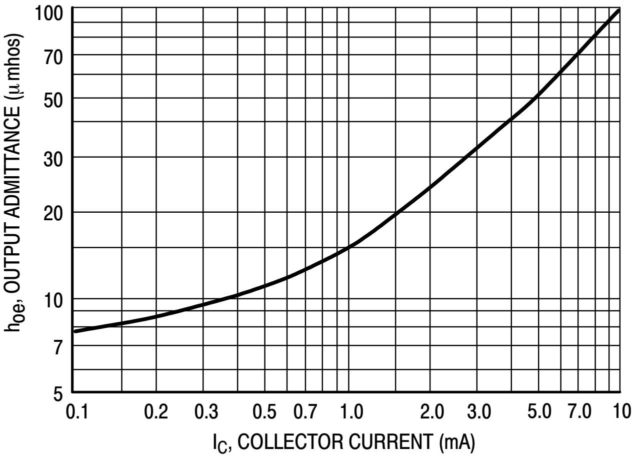


Figure 10. Output Admittance

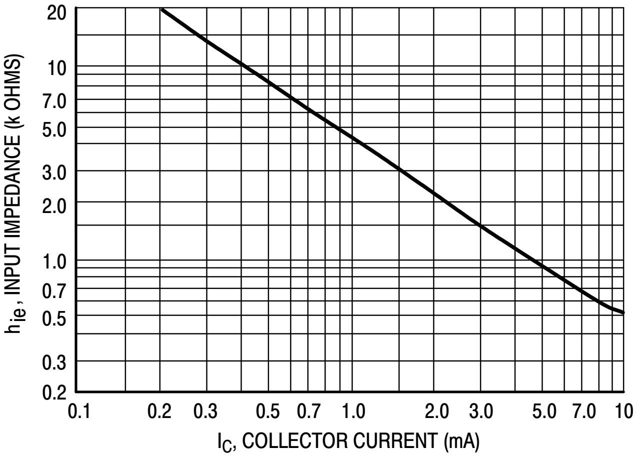


Figure 11. Input Impedance

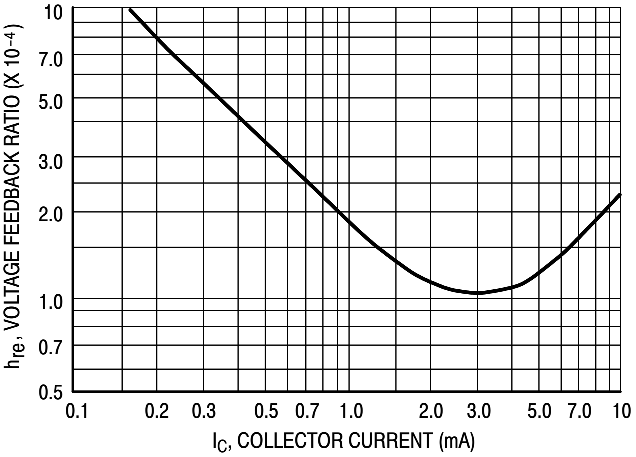


Figure 12. Voltage Feedback Ratio

TYPICAL STATIC CHARACTERISTICS

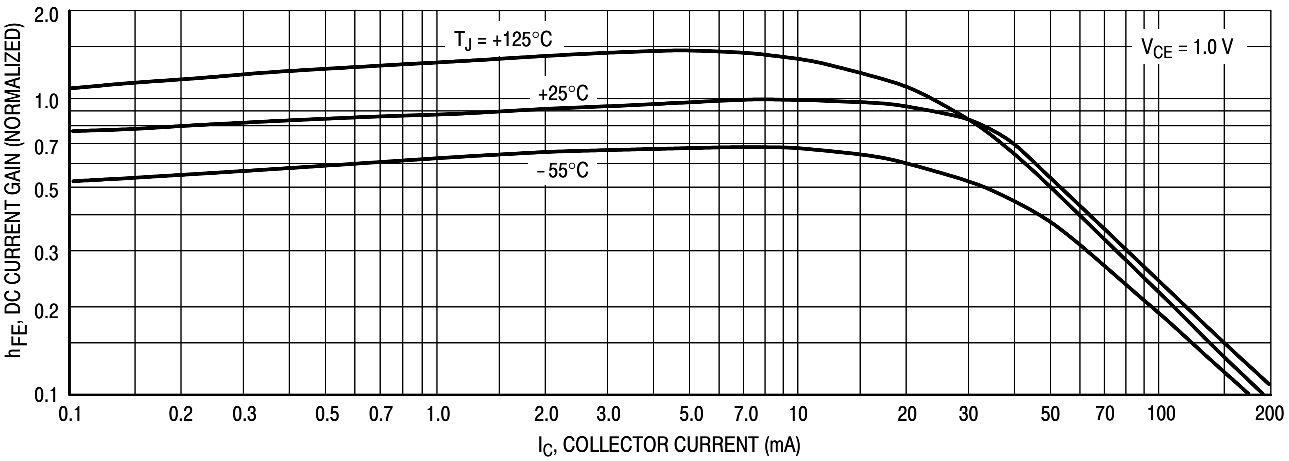


Figure 13. DC Current Gain

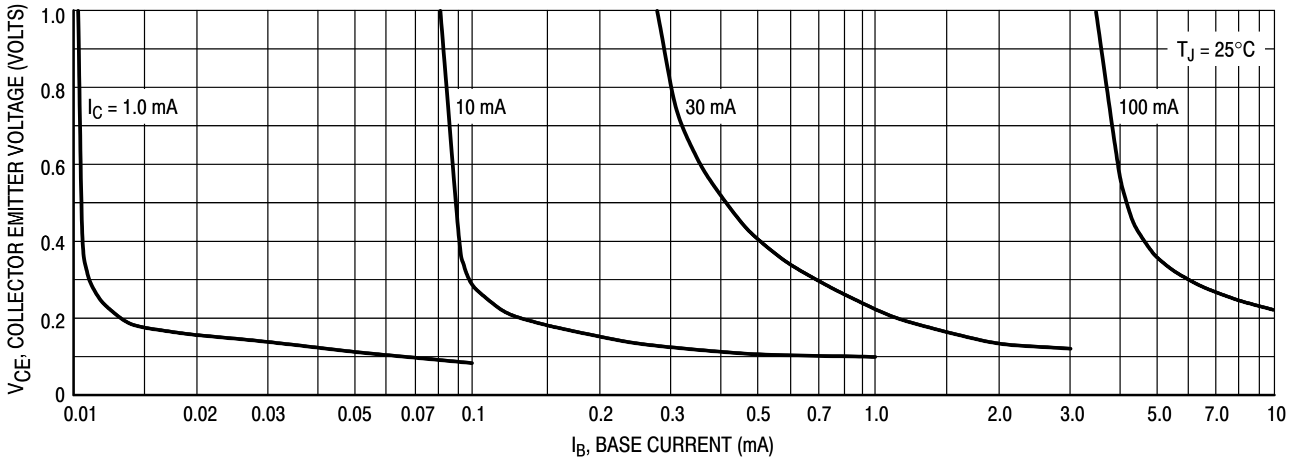


Figure 14. Collector Saturation Region

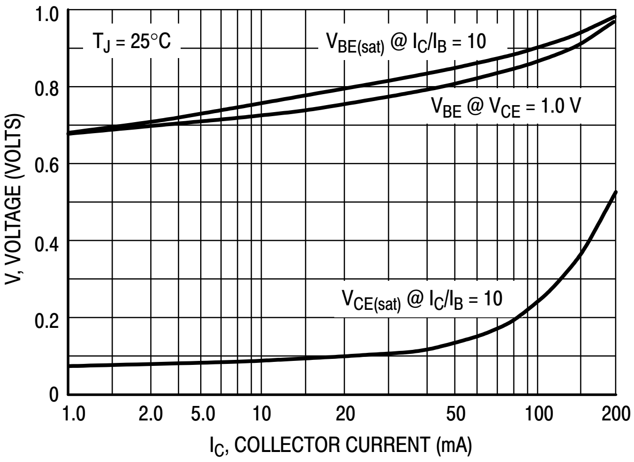


Figure 15. "ON" Voltages

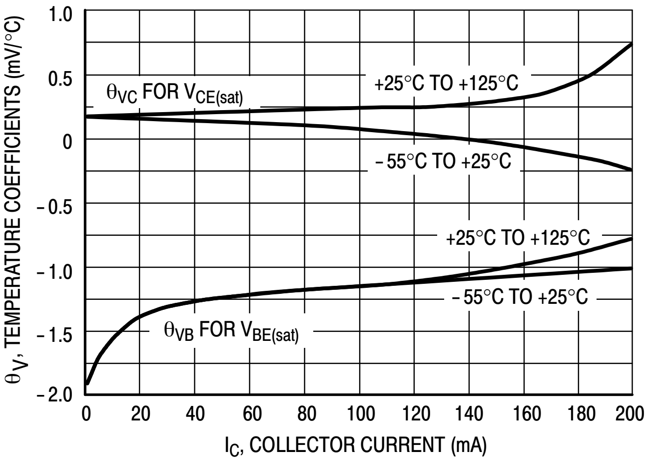
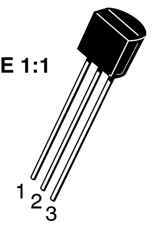


Figure 16. Temperature Coefficients

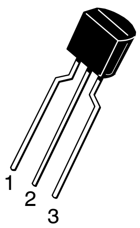
MECHANICAL CASE OUTLINE
PACKAGE DIMENSIONS

ON Semiconductor®

SCALE 1:1



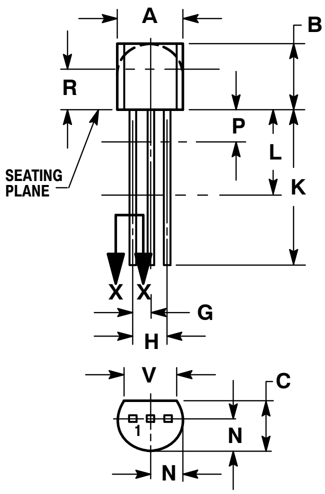
STRAIGHT LEAD
BULK PACK



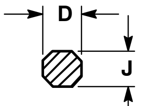
BENT LEAD
TAPE & REEL
AMMO PACK

TO–92 (TO–226)
CASE 29–11
ISSUE AM

DATE 09 MAR 2007



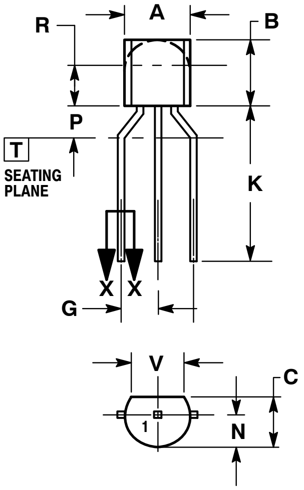
STRAIGHT LEAD
BULK PACK



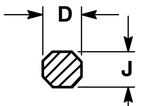
SECTION X–X

NOTES:
1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION: INCH.
3. CONTOUR OF PACKAGE BEYOND DIMENSION R IS UNCONTROLLED.
4. LEAD DIMENSION IS UNCONTROLLED IN P AND BEYOND DIMENSION K MINIMUM.

	INCHES		MILLIMETERS	
DIM	**MIN**	**MAX**	**MIN**	**MAX**
A	0.175	0.205	4.45	5.20
B	0.170	0.210	4.32	5.33
C	0.125	0.165	3.18	4.19
D	0.016	0.021	0.407	0.533
G	0.045	0.055	1.15	1.39
H	0.095	0.105	2.42	2.66
J	0.015	0.020	0.39	0.50
K	0.500	---	12.70	---
L	0.250	---	6.35	---
N	0.080	0.105	2.04	2.66
P	---	0.100	---	2.54
R	0.115	---	2.93	---
V	0.135	---	3.43	---



BENT LEAD
TAPE & REEL
AMMO PACK



SECTION X–X

NOTES:
1. DIMENSIONING AND TOLERANCING PER ASME Y14.5M, 1994.
2. CONTROLLING DIMENSION: MILLIMETERS.
3. CONTOUR OF PACKAGE BEYOND DIMENSION R IS UNCONTROLLED.
4. LEAD DIMENSION IS UNCONTROLLED IN P AND BEYOND DIMENSION K MINIMUM.

	MILLIMETERS	
DIM	**MIN**	**MAX**
A	4.45	5.20
B	4.32	5.33
C	3.18	4.19
D	0.40	0.54
G	2.40	2.80
J	0.39	0.50
K	12.70	---
N	2.04	2.66
P	1.50	4.00
R	2.93	---
V	3.43	---

STYLES ON PAGE 2

TO−92 (TO−226)
CASE 29−11
ISSUE AM

DATE 09 MAR 2007

STYLE 1:
PIN 1. EMITTER
2. BASE
3. COLLECTOR

STYLE 2:
PIN 1. BASE
2. EMITTER
3. COLLECTOR

STYLE 3:
PIN 1. ANODE
2. ANODE
3. CATHODE

STYLE 4:
PIN 1. CATHODE
2. CATHODE
3. ANODE

STYLE 5:
PIN 1. DRAIN
2. SOURCE
3. GATE

STYLE 6:
PIN 1. GATE
2. SOURCE & SUBSTRATE
3. DRAIN

STYLE 7:
PIN 1. SOURCE
2. DRAIN
3. GATE

STYLE 8:
PIN 1. DRAIN
2. GATE
3. SOURCE & SUBSTRATE

STYLE 9:
PIN 1. BASE 1
2. EMITTER
3. BASE 2

STYLE 10:
PIN 1. CATHODE
2. GATE
3. ANODE

STYLE 11:
PIN 1. ANODE
2. CATHODE & ANODE
3. CATHODE

STYLE 12:
PIN 1. MAIN TERMINAL 1
2. GATE
3. MAIN TERMINAL 2

STYLE 13:
PIN 1. ANODE 1
2. GATE
3. CATHODE 2

STYLE 14:
PIN 1. EMITTER
2. COLLECTOR
3. BASE

STYLE 15:
PIN 1. ANODE 1
2. CATHODE
3. ANODE 2

STYLE 16:
PIN 1. ANODE
2. GATE
3. CATHODE

STYLE 17:
PIN 1. COLLECTOR
2. BASE
3. EMITTER

STYLE 18:
PIN 1. ANODE
2. CATHODE
3. NOT CONNECTED

STYLE 19:
PIN 1. GATE
2. ANODE
3. CATHODE

STYLE 20:
PIN 1. NOT CONNECTED
2. CATHODE
3. ANODE

STYLE 21:
PIN 1. COLLECTOR
2. EMITTER
3. BASE

STYLE 22:
PIN 1. SOURCE
2. GATE
3. DRAIN

STYLE 23:
PIN 1. GATE
2. SOURCE
3. DRAIN

STYLE 24:
PIN 1. EMITTER
2. COLLECTOR/ANODE
3. CATHODE

STYLE 25:
PIN 1. MT 1
2. GATE
3. MT 2

STYLE 26:
PIN 1. V_{CC}
2. GROUND 2
3. OUTPUT

STYLE 27:
PIN 1. MT
2. SUBSTRATE
3. MT

STYLE 28:
PIN 1. CATHODE
2. ANODE
3. GATE

STYLE 29:
PIN 1. NOT CONNECTED
2. ANODE
3. CATHODE

STYLE 30:
PIN 1. DRAIN
2. GATE
3. SOURCE

STYLE 31:
PIN 1. GATE
2. DRAIN
3. SOURCE

STYLE 32:
PIN 1. BASE
2. COLLECTOR
3. EMITTER

STYLE 33:
PIN 1. RETURN
2. INPUT
3. OUTPUT

STYLE 34:
PIN 1. INPUT
2. GROUND
3. LOGIC

STYLE 35:
PIN 1. GATE
2. COLLECTOR
3. EMITTER

ON Semiconductor®	**DOCUMENT NUMBER:** **98ASB42022B**
	PAGE 3 OF 3

ISSUE	REVISION	DATE
AM	ADDED BENT−LEAD TAPE & REEL VERSION. REQ. BY J. SUPINA.	09 MAR 2007

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◊

2N3055(NPN), MJ2955(PNP)

Preferred Device

Complementary Silicon Power Transistors

Complementary silicon power transistors are designed for general−purpose switching and amplifier applications.

Features

- DC Current Gain − h_{FE} = 20−70 @ I_C = 4 Adc
- Collector−Emitter Saturation Voltage − $V_{CE(sat)}$ = 1.1 Vdc (Max) @ I_C = 4 Adc
- Excellent Safe Operating Area
- Pb−Free Packages are Available*

MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Collector−Emitter Voltage	V_{CEO}	60	Vdc
Collector−Emitter Voltage	V_{CER}	70	Vdc
Collector−Base Voltage	V_{CB}	100	Vdc
Emitter−Base Voltage	V_{EB}	7	Vdc
Collector Current − Continuous	I_C	15	Adc
Base Current	I_B	7	Adc
Total Power Dissipation @ T_C = 25°C Derate Above 25°C	P_D	115 0.657	W W/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	−65 to +200	°C

Maximum ratings are those values beyond which device damage can occur. Maximum ratings applied to the device are individual stress limit values (not normal operating conditions) and are not valid simultaneously. If these limits are exceeded, device functional operation is not implied, damage may occur and reliability may be affected.

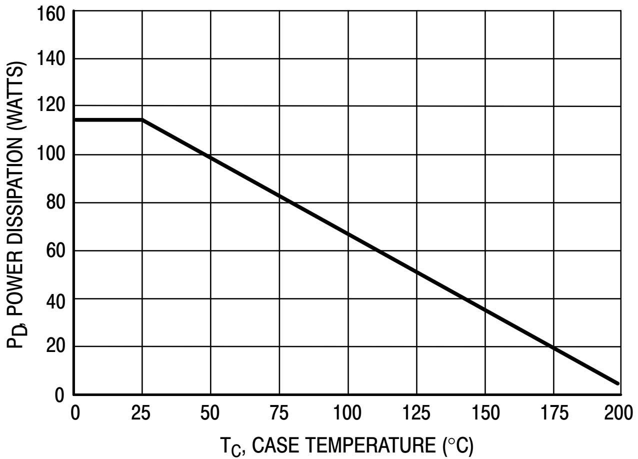
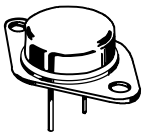


Figure 1. Power Derating

ON Semiconductor®

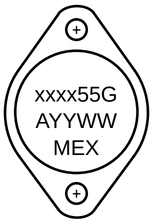
http://onsemi.com

15 AMPERE
POWER TRANSISTORS
COMPLEMENTARY SILICON
60 VOLTS, 115 WATTS



TO−204AA (TO−3)
CASE 1−07
STYLE 1

MARKING DIAGRAM



xxxx55 = Device Code
xxxx = 2N30 or MJ20
G = Pb−Free Package
A = Location Code
YY = Year
WW = Work Week
MEX = Country of Orgin

ORDERING INFORMATION

Device	Package	Shipping
2N3055	TO−204AA	100 Units / Tray
2N3055G	TO−204AA (Pb−Free)	100 Units / Tray
MJ2955	TO−204AA	100 Units / Tray
MJ2955G	TO−204AA (Pb−Free)	100 Units / Tray

Preferred devices are recommended choices for future use and best overall value.

---

*For additional information on our Pb−Free strategy and soldering details, please download the ON Semiconductor Soldering and Mounting Techniques Reference Manual, SOLDERRM/D.

December, 2005 − Rev. 6

THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction−to−Case	$R_{\theta JC}$	1.52	°C/W

ELECTRICAL CHARACTERISTICS (T_C = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
OFF CHARACTERISTICS*				
Collector−Emitter Sustaining Voltage (Note 1) (I_C = 200 mAdc, I_B = 0)	$V_{CEO(sus)}$	60	−	Vdc
Collector−Emitter Sustaining Voltage (Note 1) (I_C = 200 mAdc, R_{BE} = 100 Ω)	$V_{CER(sus)}$	70	−	Vdc
Collector Cutoff Current (V_{CE} = 30 Vdc, I_B = 0)	I_{CEO}	−	0.7	mAdc
Collector Cutoff Current (V_{CE} = 100 Vdc, $V_{BE(off)}$ = 1.5 Vdc) (V_{CE} = 100 Vdc, $V_{BE(off)}$ = 1.5 Vdc, T_C = 150°C)	I_{CEX}	− −	1.0 5.0	mAdc
Emitter Cutoff Current (V_{BE} = 7.0 Vdc, I_C = 0)	I_{EBO}	−	5.0	mAdc
ON CHARACTERISTICS* (Note 1)				
DC Current Gain (I_C = 4.0 Adc, V_{CE} = 4.0 Vdc) (I_C = 10 Adc, V_{CE} = 4.0 Vdc)	h_{FE}	20 5.0	70 −	−
Collector−Emitter Saturation Voltage (I_C = 4.0 Adc, I_B = 400 mAdc) (I_C = 10 Adc, I_B = 3.3 Adc)	$V_{CE(sat)}$	−	1.1 3.0	Vdc
Base−Emitter On Voltage (I_C = 4.0 Adc, V_{CE} = 4.0 Vdc)	$V_{BE(on)}$	−	1.5	Vdc
SECOND BREAKDOWN				
Second Breakdown Collector Current with Base Forward Biased (V_{CE} = 40 Vdc, t = 1.0 s, Nonrepetitive)	$I_{s/b}$	2.87	−	Adc
DYNAMIC CHARACTERISTICS				
Current Gain − Bandwidth Product (I_C = 0.5 Adc, V_{CE} = 10 Vdc, f = 1.0 MHz)	f_T	2.5	−	MHz
*Small−Signal Current Gain (I_C = 1.0 Adc, V_{CE} = 4.0 Vdc, f = 1.0 kHz)	h_{fe}	15	120	−
*Small−Signal Current Gain Cutoff Frequency (V_{CE} = 4.0 Vdc, I_C = 1.0 Adc, f = 1.0 kHz)	f_{hfe}	10	−	kHz

*Indicates Within JEDEC Registration. (2N3055)

1. Pulse Test: Pulse Width ≤ 300 μs, Duty Cycle ≤ 2.0%.

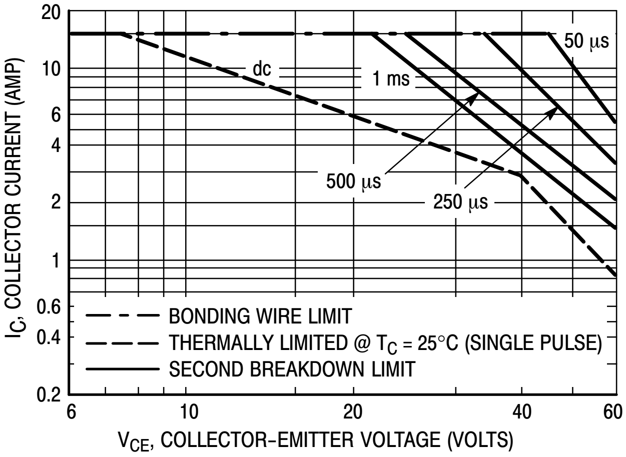


Figure 2. Active Region Safe Operating Area

There are two limitations on the power handling ability of a transistor: average junction temperature and second breakdown. Safe operating area curves indicate $I_C - V_{CE}$ limits of the transistor that must be observed for reliable operation; i.e., the transistor must not be subjected to greater dissipation than the curves indicate.

The data of Figure 2 is based on T_C = 25°C; $T_{J(pk)}$ is variable depending on power level. Second breakdown pulse limits are valid for duty cycles to 10% but must be derated for temperature according to Figure 1.

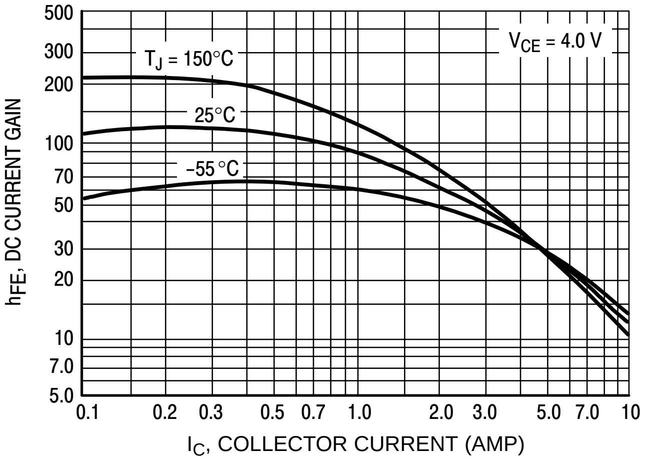


Figure 3. DC Current Gain, 2N3055 (NPN)

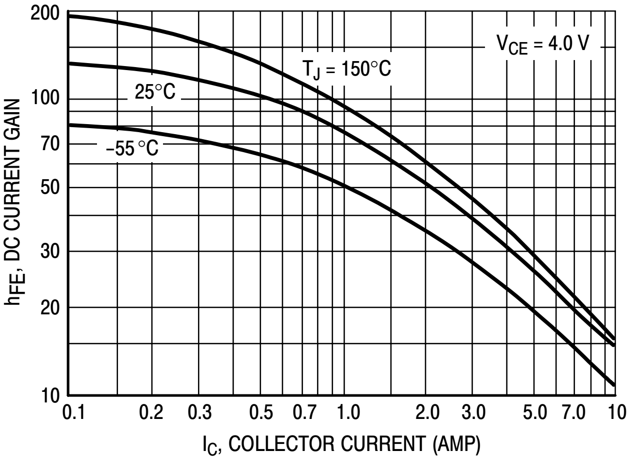


Figure 4. DC Current Gain, MJ2955 (PNP)

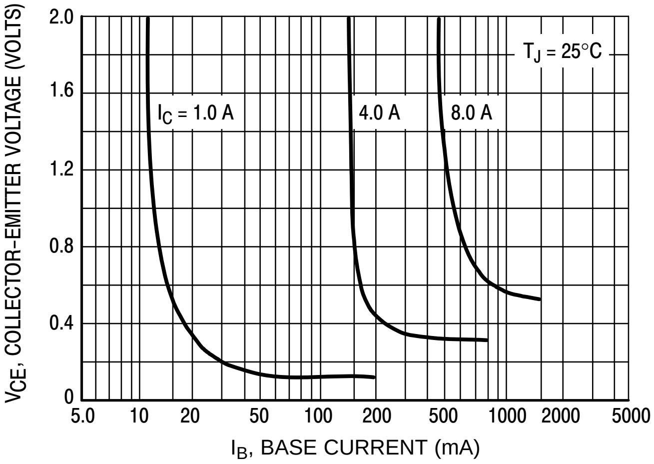


Figure 5. Collector Saturation Region, 2N3055 (NPN)

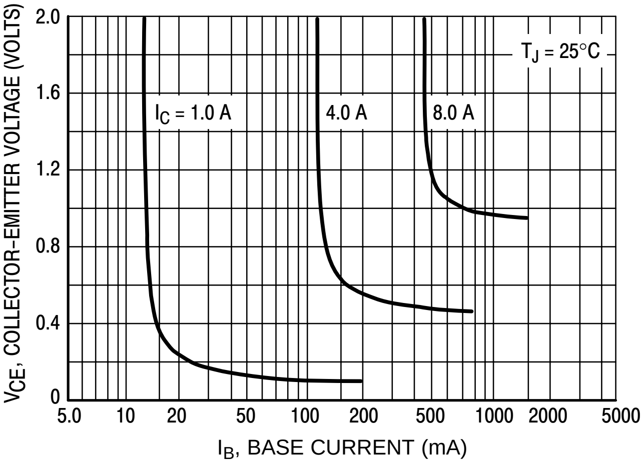


Figure 6. Collector Saturation Region, MJ2955 (PNP)

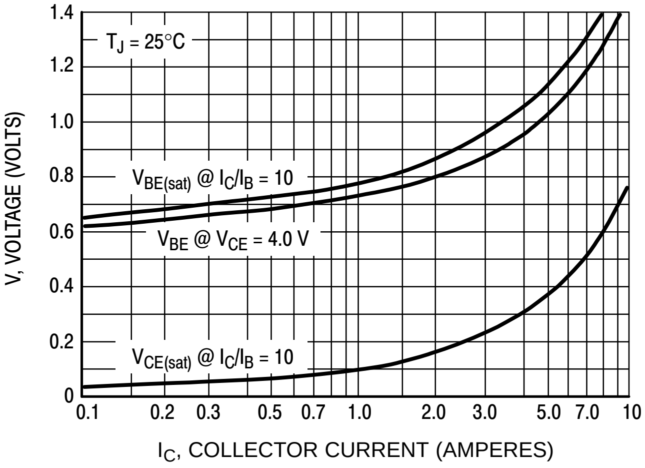


Figure 7. “On” Voltages, 2N3055 (NPN)

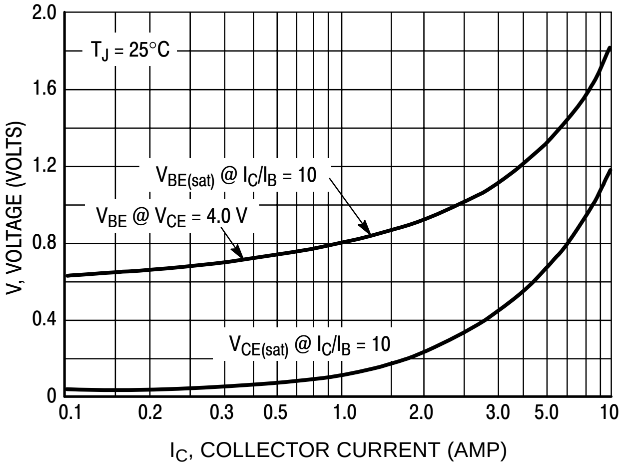
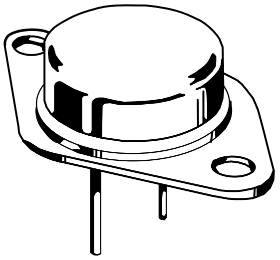


Figure 8. “On” Voltages, MJ2955 (PNP)

MECHANICAL CASE OUTLINE

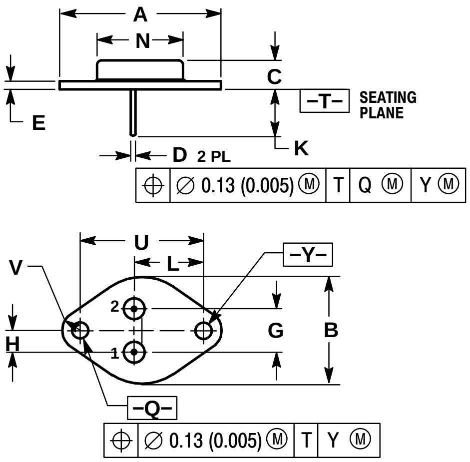
PACKAGE DIMENSIONS



SCALE 1:1

TO−204 (TO−3)
CASE 1−07
ISSUE Z

DATE 05/18/1988



NOTES:
1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION: INCH.
3. ALL RULES AND NOTES ASSOCIATED WITH REFERENCED TO−204AA OUTLINE SHALL APPLY.

	INCHES		MILLIMETERS	
DIM	**MIN**	**MAX**	**MIN**	**MAX**
A	1.550 REF		39.37 REF	
B	---	1.050	---	26.67
C	0.250	0.335	6.35	8.51
D	0.038	0.043	0.97	1.09
E	0.055	0.070	1.40	1.77
G	0.430 BSC		10.92 BSC	
H	0.215 BSC		5.46 BSC	
K	0.440	0.480	11.18	12.19
L	0.665 BSC		16.89 BSC	
N	---	0.830	---	21.08
Q	0.151	0.165	3.84	4.19
U	1.187 BSC		30.15 BSC	
V	0.131	0.188	3.33	4.77

STYLE 1:
PIN 1. BASE
2. EMITTER
CASE: COLLECTOR

STYLE 2:
PIN 1. BASE
2. COLLECTOR
CASE: EMITTER

STYLE 3:
PIN 1. GATE
2. SOURCE
CASE: DRAIN

STYLE 4:
PIN 1. GROUND
2. INPUT
CASE: OUTPUT

STYLE 5:
PIN 1. CATHODE
2. EXTERNAL TRIP/DELAY
CASE: ANODE

STYLE 6:
PIN 1. GATE
2. EMITTER
CASE: COLLECTOR

STYLE 7:
PIN 1. ANODE
2. OPEN
CASE: CATHODE

STYLE 8:
PIN 1. CATHODE #1
2. CATHODE #2
CASE: ANODE

STYLE 9:
PIN 1. ANODE #1
2. ANODE #2
CASE: CATHODE

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Agilent E36XX-Series Manual dc Power Supplies

Data Sheet

- **Linear power supply**
- **Single, dual or triple output**
- **10-turn voltage and current controls**
- **Digital voltage and current meters**
- **Low noise and excellent regulation**

Affordable, full-featured benchtop power supplies provide excellent performance and flexibility

A whole family of low-cost power supplies to meet your needs

The E3600-series of low-cost benchtop power supplies give you the performance of system power supplies without the high price. All E3600 family members give you clean power with dependable regulation and fast transient response. E3600-series single-output models are described on this page. See page 2 for information on dual- and triple-output models.

Single-output models

All E3600-series single-output power supplies feature separate digital-panel meters for monitoring voltage and current simultaneously, giving you precise reading and control capability. All models except the E3630A also feature 10-turn potentiometers for accurate adjustment of voltage and current output settings.

With 0.01 percent load and line regulation, these instruments keep the output steady when power line and load changes occur. The low normal-mode noise specification of less than 200μVrms ensures clean power for precision circuitry.

In all single-output models, either the positive or negative terminal can be connected to ground, providing a positive or negative voltage output. Outputs can also be floated up to 240V from ground.

These instruments also feature adjustable current limits, letting you set the safest current limit without having to short the output.

E3610A, E3611A, and E3612A single-output models

These popular 30-watt bench supplies are designed for general laboratory use. The constant-voltage, constant-current output allows operation as either a voltage or current source. The changeover occurs automatically, based on the load. Each of these models has two ranges, allowing more current at a lower voltage. For higher output voltages, supplies can be connected in series.

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E3614A, E3615A, E3616A and E3617A models feature overvoltage protection

These flexible 60-watt, single-range power supplies can be used as either voltage or current sources. When output terminal voltage increases to a preset shut-down level, an overvoltage protection circuit disables the output to protect the device under test (DUT) from damage. The overvoltage protection feature is easily monitored and adjusted from the front panel.

Using remote sensing capability, these instruments automatically compensate for voltage drop in the load leads, so you get accurate voltage at the DUT.

You can combine multiple units in auto-parallel, auto-series and auto-tracking configurations for greater output voltage or current capacity. Front and rear output terminals allow flexible configuration. Output voltage and current can be controlled with external 0- to10-volt analog voltage or variable resistance.

Multi-output models

With multiple supplies in a compact unit, the E3620A and E3630A give you excellent performance while saving space on your bench. Both instruments feature tight 0.01 percent line and load regulation and a low normal-mode noise specification of less than 0.35mV to ensure clean power for precision circuitry. With a common-mode current specification of less than 1uA, both multiple-output power supplies minimize power line current injection.

Like the single-output models in the E3600 series, the E3620A and E3630A feature separate digital panel meters so you can monitor voltage and current simultaneously. They also protect your DUT against overload and short-circuit damage. Smooth turn-on and turn-off transitions keep power spikes out of your circuits.

E3620A dual-output power supply

The 50-watt E3620A dual-output power supply provides two 0 V to 25 Vdc outputs with the maximum current of 1 A to satisfy most bench requirements. The outputs are completely independent and isolated.

E3630A triple-output power supply

The 35-watt E3630A triple- output power supply provides three dc outputs: 0 to 6 V with a maximum current of 1 to 2.5A and 0 to 20 V and 0 to -20 V with a maximum current of 0.5A. An autotracking feature lets you use one voltage control to adjust the +20 V and -20 V outputs simultaneously. The outputs track each other to within 1 percent, making it easy to adjust the power supply for circuits requiring balanced voltages.

Specifications

	E3610A	E3611A	E3612A	E3614A	E3615A	E3616A	E3617A	E3620A	E3630A
Features	Dual range, 10 turn pots, Constant Voltage (CV), Constant Current (CC) modes.			Adjustable overvoltage protection, voltage & resistance programming, remote sense, rear outputs, ten turn pots, CV, CC modes. Multiple supplies can be connected for tracking or higher power.				Isolated dual outputs, 10 turn pots CV, CL	Tracking, CV, CL (±20 V) CV, CF (+6 V)
Number of outputs	1							2	3
Number of output Ranges	2	2	2	1	1	1	1	1	1
dc Output Rating	8 V, 3 A 15 V, 2 A	20 V, 1.5 A 35 V, 0.85 A	60 V, 0.5 A 120 V, 0.25 A	8 V, 6 A	20 V, 3 A	35 V, 1.7 A	60 V, 1 A	25 V, 1 A 25 V, 1 A	+6 V, 2.5 A +20 V, 0.5 A -20 V, 0.5 A
Load and Line Regulation	<0.01% + 2 mV								
Ripple and Noise (20 Hz to 20 MHz)									
Normal mode voltage	<200 µVrms, <2 mVpp			<200 µVrms, <1 mVpp				<350 µVrms, <1.5 mVpp	
Normal mode current	<200 µVrms / 1 mApp			<0.02%+ 3 mA	<0.02%+ 1.5 mA	<0.02%+ 1 mA	<0.02%+ 0.5 mA	–	
Common mode current	not specified							<1 µArms	
Transient Response Time:	<50 µsec following change in output current from full load to half load for output to recover to within:								
	10 mV			15 mV					
Meter Accuracy	±0.5% + 2 counts at 25°C ±5°C								
Meter Resolution									
Voltage	10 mV	100 mV	100 mV	10 mV	10 mV (0-20 V), 100 mV (>20 V)				10 mA
Current	10 mA	10 mA	1 mA	10 mA	10 mA	1 mA	1 mA	1 mA	10 mA
Isolation	240 Vdc								

Supplemental Characteristics

	E3610A	E3611A	E3612A	E3614A	E3615A	E3616A	E3617A	E3620A	E3630A
Control Mode	CV/CC							CV/CL	CV/CL (±20 V) CV/CF (+6 V)
Temperature Coefficient per °C									
Voltage	<0.02% + 1 mV			<0.02% + 500 µV				<0.02% + 1 mV	
Current	<0.02% + 2 mA			<0.02% + 3 mA	<0.02% + 1.5 mA	<0.02% + 1 mA	<0.02% + 0.5 mA	–	
Output Drift									
Voltage	Less than 0.1% + 5 mV total drift for 8 hours after an initial warm-up of 30 minutes.								
Current	Less than 0.1% + 10 mA total drift for 8 hours after an initial warm-up of 30 minutes.								
Temperature Range									
	0 to 40°C for full rated output. Derate output current 1% per °C between 40°C and 55°C							Derate output current 3.3% per °C	
Cooling	Convection cooling								
Isolation	±240 Vdc								
AC Input	100 Vac ±10%, 47– 63 Hz (opt. 0E9) 115 Vac ±10%, 47– 63 Hz (std) 230 Vac ±10%, 47– 63 Hz (opt. 0E3)								
Weight	3.8 kg (8.4 lb.) net, 5.1 kg (11.3 lbs) shipping			5.5 kg (12.1 lb.) net, 6.75 kg (14.9 lbs) shipping					Same as E3610A
Size	91 mm H x 213 mm W x 319 mm D 3.6" H x 8.4" W x 12.6" D			91 mm H x 213 mm W x 373 mm D 3.6" H x 8.4" W x 14.7" D					
Warranty	1 year								
Product Regulation	Certified to CSA 22.2 No. 231; conforms to IEC 1010-1; carries CE mark; complies with CISPR-11, Group 1, Class A								

www.agilent.com

Ordering Information

E3600-Series Power Supplies

E3610A 30-Watt Power Supply
E3611A 30-Watt Power Supply
E3612A 30-Watt Power Supply
E3614A 48-Watt Power Supply
E3615A 60-Watt Power Supply
E3616A 60-Watt Power Supply
E3617A 60-Watt Power Supply
E3620A Dual-output Power Supply
E3630A Triple-output Power Supply

Accessories included

Operating and service manuals and AC power cord

Power Options

Opt. 0E3 230 Vac ±10%
Opt. 0EM 115 Vac ±10%
Opt. 0E9 100 Vac ±10%

Other Options

Opt. 1CM Rack-mount kit* (E3614A, E3615A, E3616A, E3617A, E3620A)
Opt. 0L2 Extra Manual

Extra manual sets

E3610A/11A/12A Manual (P/N 5959-5304)
E3614A/15A/16A /17A Manual (P/N 5959-5310)
E3620A Manual (P/N E3620-90001)
E3630A Manual (P/N 5959-5329)

Rack Mount Kits*

E3610A/11A/12A/30A
(P/N 5063-9767)

E3614A/15A/16A/17A/20A

To rack mount instruments side by side
- Lock-link Kit (P/N 5061-9694)
- Flange Kit (P/N 5063-9212)

To rack mount one or two instruments in a sliding support shelf
- Support Shelf (P/N 5063-9255)
- Slide Kit (P/N 1494-0015) required for support shelf
- For a single instrument, also order filler panel (P/N 5002-3999)

*Rackmounting with 1CM or lock-link/flange kit requires Agilent or customer supplied support rails
Agilent Support Rails - E3663AC

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Our Promise
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LA6500

Monolithic Linear IC

Power Operational Amplifier

Overview

The LA6500 is a power operational amplifier.

Features

- High output current (I_O max = 1.0A)
- High gain
- With current limiter
- Capable of being operated from single supply

Specifications

Maximum Ratings at Ta = 25°C

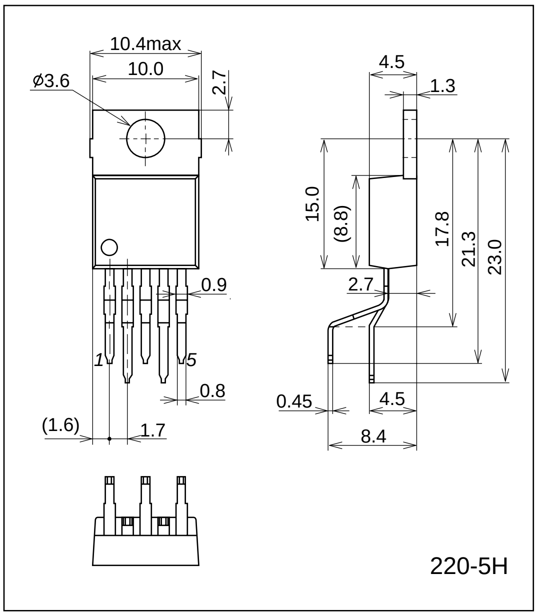
Parameter	Symbol	Conditions	Ratings	Unit
Maximum supply voltage	V_{CC}/V_{EE}		±18	V
Differential input voltage	V_{ID}		30	V
Common-mode input voltage	V_{IN}		±15	V
Output current	I_O max		1.0	A
Allowable power dissipation	Pd max1	With infinity large heat sink	20	W
	Pd max2	Independent IC	1.75	W
Operating temperature	Topr		-20 to +75	°C
Storage temperature	Tstg		-55 to +150	°C

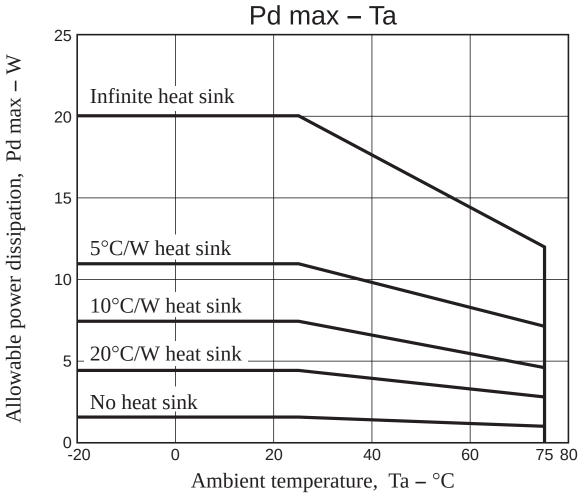
Electrical Characteristics at Ta = 25°C, V_{CC} /V_{EE} = ±15V

Parameter	Symbol	Conditions	Ratings			Unit
			min	typ	max	
Quiescent current dissipation	I_{CCO}			6.0	12.0	mA
Input offset voltage	V_{IO}			2	6	mV
Input offset current	I_{IO}			10	200	nA
Input bias current	I_B			100	700	nA
Common-mode input voltage range	V_{ICM}		-15		+13	V
Common-mode rejection	CMR		70	80		dB
Maximum output voltage	V_O	R_L = 33Ω	±12	±13		V
Voltage gain	VG_O			100		dB
Slew rate	SR	G_V = 0, R_L = 33Ω, R = 2.2Ω, L = 0.1µF		0.15		V/µs
Equivalent input noise voltage	V_{NI}	Rg = 1kΩ, DIN AUDIO		2		µV
Supply voltage rejection	SVR			30	150	µV/V
Limiting current	I_{SC}			1.0		A

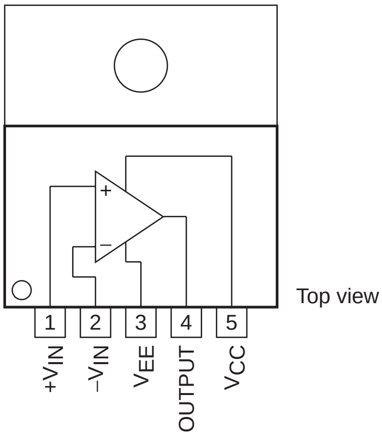
Package Dimensions

unit : mm (typ)
3079C

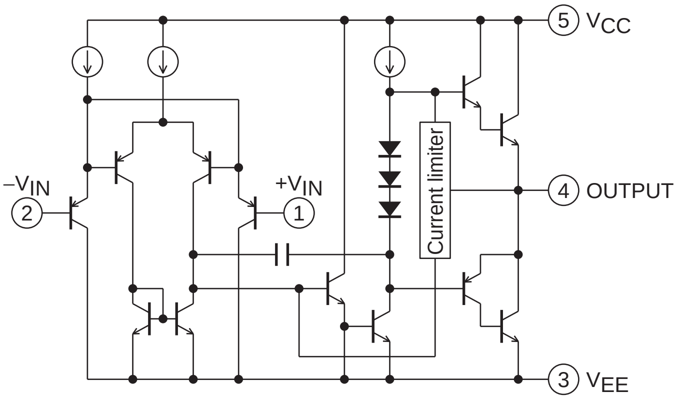




Pin Assignment

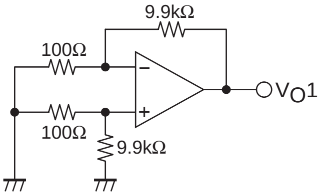


Equivalent Circuit



Test Circuit

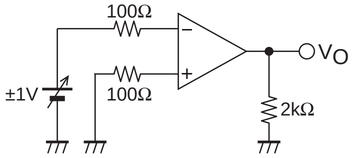
(1) V_{IO}, SVRR



· V_{IO} is $V_{CC}/V_{EE} = \pm 15V$

· SVRR is $\begin{cases} V_{CC} = 15, 5V \\ V_{EE} = -5, -15V \end{cases}$

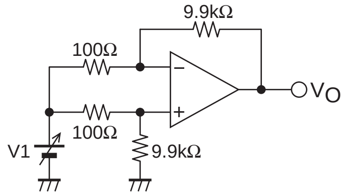
(2) V_O



· $V_{IO} = V_O1/100$

$\left.\begin{matrix} SVR(+) \\ SVR(-) \end{matrix}\right\} = \left| \frac{\Delta V_O1}{100 \times 10V} \right|$

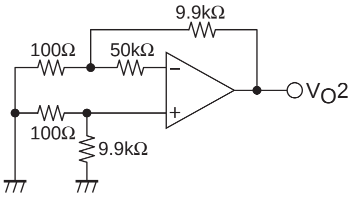
(3) CMMR, V_{ICM}



· CMRR V1 = ±7.5V

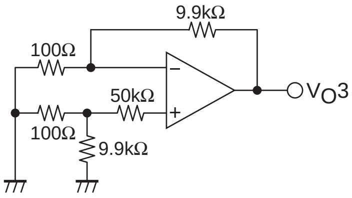
· CMR = 20log $\frac{15 \times 100}{|\Delta V_O|}$

(3) $I_B(+)$



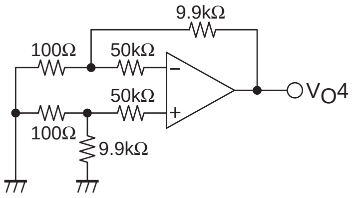
· $I_B(+) = \frac{|V_O2 - V_O1|}{50k\Omega \times 100}$

(4) $I_B(-)$



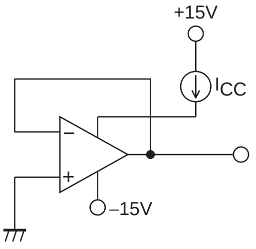
· $I_B(-) = \frac{|V_O3 - V_O1|}{50k\Omega \times 100}$

(5) I_{IO}

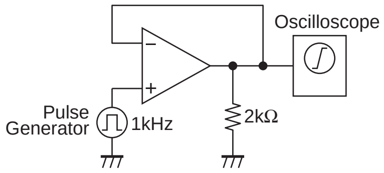


· $I_{IO} = \frac{|V_O4 - V_O1|}{50k\Omega \times 100}$

(7) I_{CC}

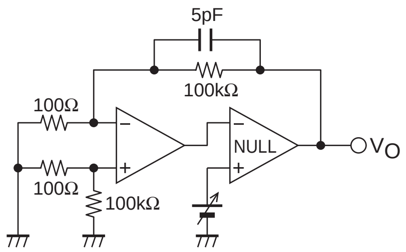


(8) SR



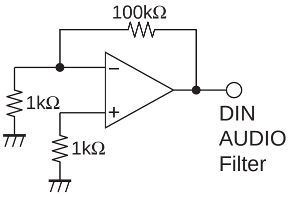
10Vp-p Square wave

(9) VG_O

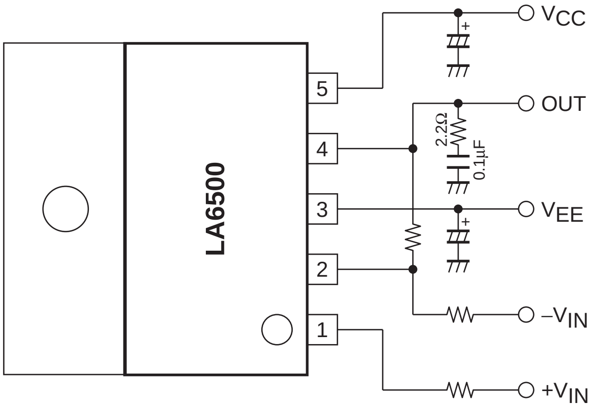


$$\cdot\ VG_O = 20\log\frac{1000\times20}{\Delta V_O}$$

(10) V_{NI}



Application Circuit Example



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PB-503 **Analog & Digital Design Workstation**

Global Specialties Model PB-503 is an Analog & Digital Design Workstation. The PB-503's newly updated, robust design makes it a trainer suitable for all levels of electronics instruction and design.

The PB-503's breadboarding area is comprised of Global's "Premium" solderless breadboards and is backed by an industry leading 3-year warranty.

The PB-503 can be used to construct basic series and parallel circuits up to the most complicated multi-stage microcomputer circuits, incorporating the latest in industrial technology.

The PB-503 allows students to learn valuable hands-on lab experience by employing necessary breadboarding techniques, which provide a solid foundation in circuit experimentation, analyzing and troubleshooting.

Experienced designers will also find the PB-503 an invaluable, capable and reliable instrument, suitable for the most advanced and demanding design applications.

Global Specialties trainers provide the most complete platform required to enable engineers and technicians to train for careers in the rapidly growing field of electronics technology.

Use the PB-503 to construct a wide variety of experiments, including but not limited to:

- Opto-Device Circuits
- Clocks
- Multivibrators
- Oscillator Circuits
- Timers
- Function Generator Circuits
- Logic Circuits
- Gates
- Counters
- Flip-Flops
- Analog-to-Digital Converters
- Digital-to-Analog Converters
- Medium Scale Integration Circuits
- Phase Lock Loops
- Operational Amplifier

Features:

- Ideal for analog, digital and microprocessor circuits
- Includes built-in Function Generator with continuously variable waveforms
- Triple output power supply for a variety of DC voltage levels
- Two Digital Pulsers for logic test circuits
- High & low buffered logic indicators
- 8 channel logic monitor
- Audio experimentation speaker
- Removable breadboard plate allows the flexibility of building circuits away from the lab
- Analog & Digital optional courseware available
- 3-year warranty on all parts and workmanship.

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PB-503

Trainer Series

Electronic Trainers

Analog & Digital Design Workstation

Specifications

Model	**PB-503**
Input power Source	AC Line: 115VAC @ 60Hz (typical)
Power Supplies	Fixed DC: +5VDC 1.0A max, current limited Ripple, <5mV Variable + DC: +1.3V @150mA to +15VDC @ 500mA , Ripple < 5mV Variable - DC: -1.3VDC @ 150mA to -15VDC @ 500mA, Ripple < 5mV
Binding Posts	(4) Ground, +5 VDC, Variable + DC & Variable - DC Power Supply Outputs
Pulsers	(2) Pushbutton-operated, open-collector output pulsers. Each with 1 normally-open, 1 normally-closed output. Each output sinks up to 250 mA
Function Generator	Frequency Range: 0.1Hz to 100KHz, six ranges Output Voltage: 0 to ± 10Vp-p into 50 Ω Load (20Vp-p in open circuit), short circuit protected Output Impedance: 600Ω except TTL Output waveforms: Sine, Square, Triangle & TTL Sine Wave Distortion: <3% @ 1Khz Typical TTL Pulse: Rise & fall time: <25ns, drive 100 TTL Loads *(TTL is available when the function generator is set to Square Wave Mode)* Square Wave: Rise and fall times <0.5µs
Logic Switches	(8) Logic Switches select Logic High and Logic Low Logic Low Level: Ground Logic High Level: Switchable between +5V and the variable positive power supplies.
Switches	(2) Single Pull Double Throw (SPDT) - uncommitted
Logic Indicators	LEDs: 16 LEDs; (8) red to indicate logic high and (8) green to indicate logic low Logic High Threshold: 2.2V (nominal) in TTL/+5V mode, 70% (nominal) of selected operating voltage in CMOS mode Logic Low Threshold: 0.8V (nominal) in TTL/+5V mode, 30% (nominal) of selected operating voltage in CMOS mode
Connectors	2 ea BNC - uncommitted
Potentiometers	2: 1 kΩ and 10 kΩ - uncommitted
Speaker	8 Ω, 0.25 W - uncommitted
Breadboards	Removable Plexiglas Socket Plate (PB-3) with 2520 Tie points with 200 additional buss strip tie points internally connected to power supply outputs and ground
Weight	7 lbs (3.2 kg)
Dimensions	6.5 x 16 x 11.5" (165 x 406 x 292 mm)

Technical data subject to change without notice.

Optional Accessories

Courseware: Available separately or as a package (Model PB-503 Lab).
WK-1: Jumper Wire Kit, 350 pieces
WK-2: Jumper Wire Kit, 140 pieces
WK-3: Jumper Wire Kit, 70 pieces
WK-4: Wire Jumper Kit, 100 wires with machined tips
GSPA Series: Prototyping adapters
GSPA-K1: Surface mount to DIP adapter kit, 6 adapter boards
GSPA-K2: Surface mount to DIP adapter kit, 11 adapter boards
GSA-3185: Minipro Test Clip Set
PRO-50A: Digital Multimeter

The **PB-503 Lab** package offers comprehensive course instruction covering the following areas:

Electronic Fundamentals

Fundamentals of Electricity
Ohm's Law
Series Circuits, Parallel Circuits
Combinational Circuits
Current Control
Closed, open, shorts
Switches
Thevenin's Theorem
Wheatstone Bridge
Capacitors, Inductors
Phase Shift Circuits
Impedance
Resonant Circuits
Transformers
Rectifiers & Filtering
Integrated Circuits
Transistor Amplifiers
Oscillators
Power Control Circuits

Digital Electronics

Number Systems & Codes
Binary, Decimal, Hexadecimal, Octal & ASCII
Logic Gates & Boolean Algebra
Combinational Logic Circuits
Flip-Flops
Digital Arithmetic
Counters & Registers
Integrated Circuit Logic Families
TTL Logic
MOSFETS
CMOS
Interfacing CMOS & TTL
Medium Scale Integration
Decoders
Encoders
Data Conversion & Acquisition
Microcomputer Concepts

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