Precision temperature measurement and control using the LM335

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Measuring temperature for its own sake or in a control application requires a suitable 'transducer' to provide an accurately known relationship between temperature and output. That's just what the LM335 does.

THERE ARE MANY ways of measuring temperature, but the familiar mercury-in-glass thermometer does have the disadvantage that it is not easily read and remote readout is impossible. The circular clock-face type of thermometers based on bimetallic strip in the form of a coil are very convenient for hanging on the wall in the home or greenhouse, but have a very limited accuracy. Electronic thermometers providing a very accurate digital indication of temperature are very convenient, although the commercially available types are necessarily moderately expensive.

This article describes the use of a device specially developed by National Semiconductor for the precision measurement of temperature which can be used in circuits whose output is usually fed to a digital voltmeter so that a digital indication of temperature can be obtained.

The LM335

The LM335 is an integrated circuit temperature sensor for use over the range 0° C to +100° C. It is available in economical plastic packaging with the connections shown in Figure 1, although a similar device is available in a TO-46 metal transistor type package with the connections of Figure 2.

The LM335 is a relatively economical device, but the LM235 is a similar product with the same internal circuitry designed for use over the −25° C to +100° C range and the LM135 can operate over the military temperature range of −53° C to +150° C; these last two devices have narrower tolerance than the LM335 specifications. Suffix 'A' versions, such as the LM335A, are also manufactured with more closely specified characteristics. However, it will be assumed that readers will employ the most economical device in the range, the LM335, although the circuits can be used with any of the devices named.

Basically, the LM335 is operated in the same way as a zener diode, as shown in the circuit of Figure 3. The breakdown voltage (that is, the output voltage from this circuit) is directly proportional to the absolute temperature and is 10 mV/K over the specified working temperature range.

The value of R1 in Figure 3 determines the current flowing through the device, but as the dynamic impedance at 1 mA is typically 0.6 Ohm, the device can be operated over the current range of 400 μA to 5 mA with virtually no change in its performance. It should be noted that the absolute maximum forward or reverse current which may safely be passed through the device (even momentarily) is only 10 mA; higher currents may cause irreversible damage to the LM335.

At 25° C and a reverse current of 1 mA, the operating output voltage from the Figure 3 circuit is typically 2.98 V with minimum and maximum limits of 2.92 V and 3.04 V. The value chosen for R1 may be calculated for a current through the LM335 of 1 mA using the equation R1 = $(V+ - V_{out})/0.001$ which equals approximately (V+ - 3) kilohm.

Linear output

A particular advantage of the LM335 is the linear output provided by its circuit, unlike the output of most other temperature sensors which is not linearly related to temperature. Indeed, if the output voltage is plotted against temperature over the working range and the graph is extrapolated back to the absolute zero of temperature, the output read from the graph at the latter temperature will be zero.

Although the LM335 output from the Figure 3 circuit is within the limits stated a calibration connection is included on the chip. It is only necessary to connect a potentiometer across the LM335, as shown in Figure 4, and adjust this potentiometer to 2.982 V output when the device is at 25° C in order to obtain higher accuracy over the whole temperature range.

The single calibration temperature over the whole working range is possible because the output is accurately proportional to the absolute temperature with the extrapolated output falling to 0 V at the absolute zero of temperature. Variations from one LM335 to another are only in the slope of the voltage/temperature graph, so a slope calibration at one temperature corrects for all others. Thus, calibration is far easier than with a non-linear device such as a thermocouple.

Self heating

As with any temperature sensing system, any heat generated by the current passing through the sensing device will affect its temperature and hence the output voltage. The LM335 should therefore be operated at the lowest current which is adequate to drive its internal circuitry. When calculating the value of R1 allowance should be

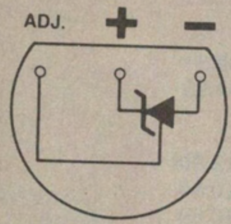


Figure 1. The TO-92 plastic encapsulated LM335.

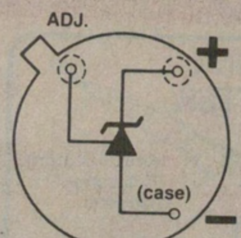
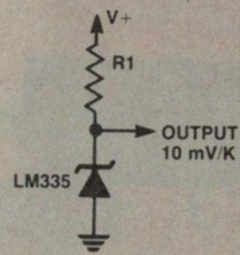


Figure 2. The TO-48 metal encapsulated LM335.

Figure 3. The basic LM332 circuit.



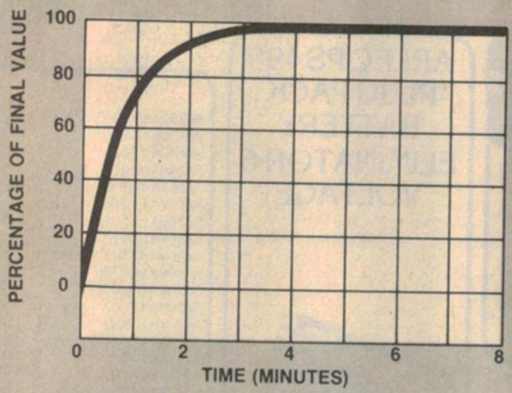


Figure 5. Response time of the LM335 to a temperature change in free air.

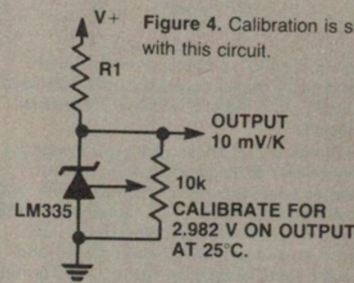


Figure 4. Calibration is simple with this circuit.

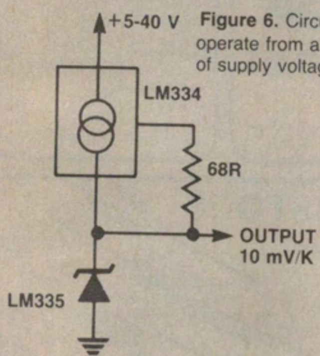
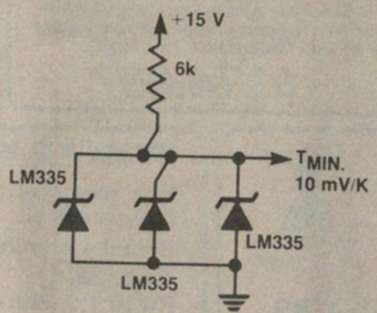


Figure 6. Circuit able to operate from a wide range of supply voltages.

Figure 7. This circuit records the minimum temperature of any of the devices.



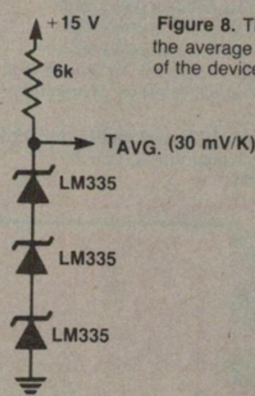


Figure 8. This circuit records the average temperature of the devices.

made for the current passing through any calibrating potentiometer in parallel with the device and for any output current. A current of about 400 μA is about the normal minimum.

If the sensor is used in a situation where the thermal resistance to the surroundings is constant, self-heating errors can be calibrated out, provided the device is operated with a constant current independent of temperature. Heating of the device will then be proportional to the zener voltage and to the absolute temperature; thus, the self-heating error is proportional to the absolute temperature and temperature scale linearity is preserved.

Performance

In a typical LM335 circuit which has not been calibrated, operating at 1 mA, the temperature error is 2° C (maximum 6° C) at 25° C or 4° C (maximum 9° C) over the whole working range. When calibrated the typical error at the temperature limits is 2° C. Non-linearity at 1 mA is typically 0.3° C over the range.

In still air the device requires about three minutes to reach its final temperature after a temperature change has occurred (Figure 5), the time constant being typically 80 seconds. In stirred oil the final temperature is reached within about three seconds (time constant typically one second). The device is stable to 0.2° C (typical) over 1000 hours, even at 125° C.

The dynamic impedance is less than one Ohm at frequencies up to more than 1 kHz (typical), but increases to 20 to 30 Ohms at 100 kHz.

Circuits

The circuits of Figures 3 and 4 are suitable for use when the supply voltage is reasonably constant. If wide variations in the supply voltage are expected to occur, the LM334 constant current device may be used with the external resistor to set the LM335 current at about 1 mA for all supply voltages. (Figure 6.)

If a number of LM335 ICs are connected in parallel, as in Figure 7, the output will correspond to that of the device which is at the minimum temperature. Thus a minimum indication of the temperatures at three locations is easily obtained.

Similarly, a number LM335 devices may be connected in series, as in Figure 8, in which case the output will represent the average temperature of the devices, but will be increased by a factor equal to the number of devices used.

Centigrade Thermometer

The circuits discussed previously are basic ones which provide an output voltage directly proportional to the absolute temperature, but this is not very consistent for feeding to a digital voltmeter to produce a reading directly in ° C. The additional operational amplifier circuit of Figure 9 is required for this purpose.

In this circuit the LM336 provides a precise 5 V reference voltage to pin 3 of the LM308 operational amplifier. The negative feedback to pin 2 is adjusted by means of the 2k potentiometer so that the output of the amplifier is at a potential of 2.73 V. The voltage difference between this output and that from the LM335 circuit is then a measure of the Centigrade ▶

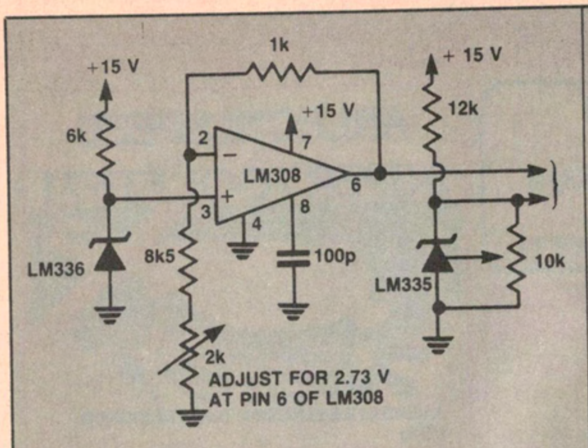


Figure 9. A centigrade thermometer circuit.

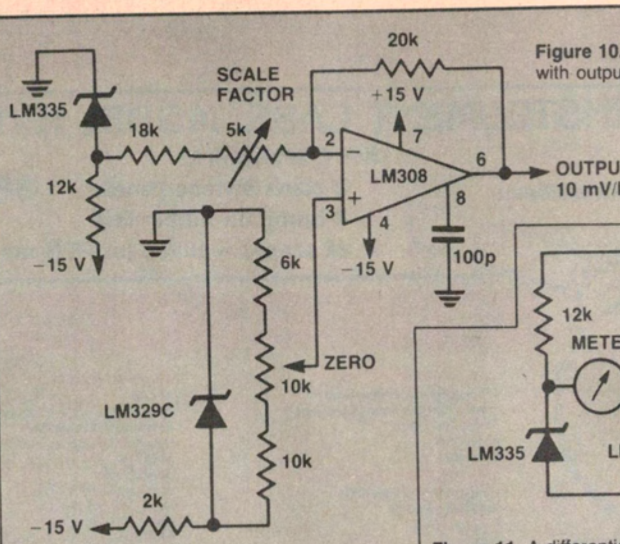


Figure 10. A centigrade thermom with output referenced to ground.

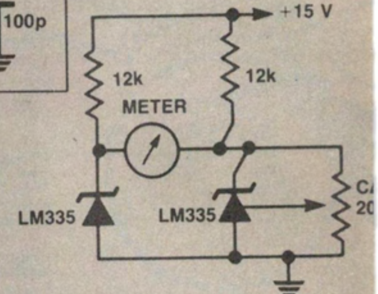


Figure 11. A differential temperature sensor.

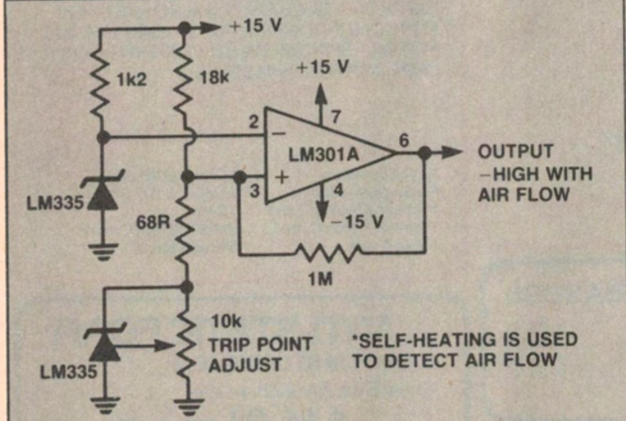


Figure 12. A differential temperature sensor with amplifier gain of ten.

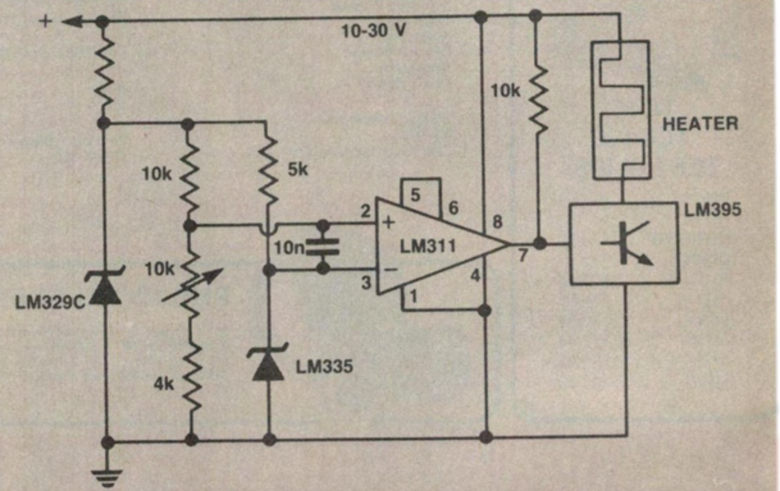


Figure 13. A thermostatic heater controller.

temperature; the 2.73 V reference effectively subtracts 273° C from the absolute temperature indicated by the output from the LM335 circuit to leave the Centigrade temperatures to be displayed by a digital voltmeter set to an appropriate scale.

Neither of the outputs from the circuit of Figure 9 are at ground potential. The slightly more complex circuit of Figure 10 provides an output of 10 mV/° C referred to ground. It employs an LM329C 6.9 V precision reference voltage device to provide a variable preset voltage to the non-inverting input of the LM308 operational amplifier. The latter takes its inverting input to a feedback network involving the LM335 temperature sensing device.

Differential sensors

Two LM335 devices in different positions can be used in the simple circuit of Figure 11 to measure the temperature difference between the two positions. Only one calibration control is required to give a zero difference when the two devices are at the same temperature.

In Figure 12 an operational amplifier is used to compare the outputs of two LM335 devices connected as in Figure 11, but the negative feedback circuit is arranged to provide a gain of ten so that the output from the amplifier is the Centigrade temperature difference in 100 mV/° C.

Temperature controller

A simple temperature control circuit which adjusts the current through a heater to maintain the temperature at some constant desired value is shown in Figure 13. The LM329C provides a precision 6.9 V reference, the fraction of this reference voltage which is tapped off and fed to the non-inverting input of the LM311 being adjusted by the temperature setting potentiometer.

If the temperature of the LM335 is high enough for the voltage from it (which is fed to the inverting input of the LM311) to exceed that of the non-inverting input, the output of the amplifier will be low so that the LM395 passes only a very small current through the heater. If the LM335 temperature falls, the LM311 output rises and switches on the LM395 so that current passes through the heater. The LM395 is actually an IC which behaves like a very high gain power transistor.

Air flow detector

In the circuit of Figure 14, a fairly high current is passed through the upper LM335 so that the device becomes warm. If air flows fairly quickly past this device, it will be cooled and its output voltage will fall. As this voltage is connected to the inverting input of the LM301A device, the output of the latter will become 'high' when such a fast air flow occurs. the lower LM335 (not in the air flow) is used to provide a comparison voltage by keeping the ambient temperature around the two LM335 devices the same.

Fast NiCad charger

Nickel cadmium cells can be fast charged only if precautions are taken to ensure that the temperature of the cells does not rise above a permissible limit. In the circuit of Figure 15, the LM335 diode D2 is placed in close thermal contact with the Nickel Cadmium cells being charged. If the temperature of the cells rises, the output from D2 rises and, as this output is

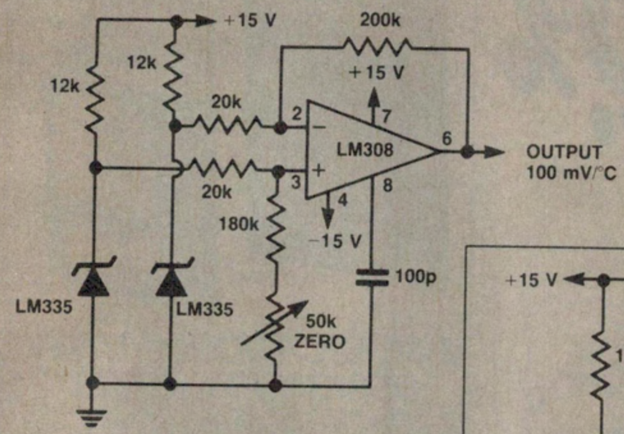


Figure 14. An air-flow detector.

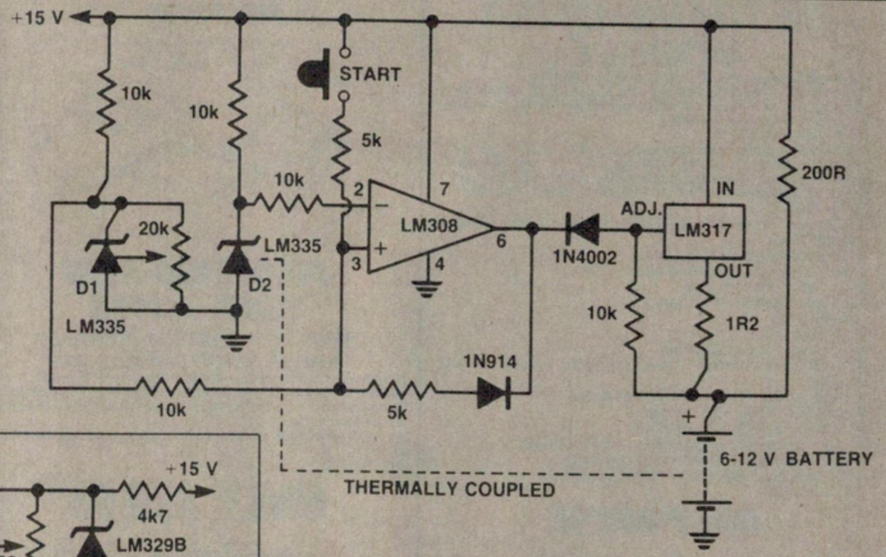
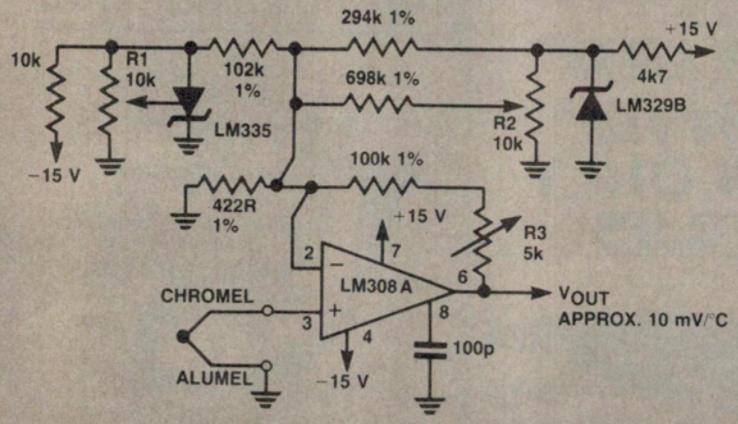


Figure 15. A fast charging circuit for Nickel Cadmium batteries with temperature monitoring and automatic switch-off in the event of over heating.

Figure 16. A centigrade calibrated thermocouple electronic thermometer.



fed to the inverting input of the LM308, the output of this operational amplifier falls.

Current passing from the 'ADJ' terminal of the LM317 regulator to the LM308 causes the potential at this terminal to fall so that the regulator no longer passes the charging current to the nickel cadmium cells. The non-inverting input potential is derived from the other LM335 which is at the ambient temperature. Thus the temperature of the cells is compared with the ambient temperature, as required. The calibration potentiometer across D1 may be adjusted so that the voltage across this LM335 is 50 mV greater than that across D2. The charging will then be terminated when the temperature of the cells rises by 5° C above ambient.

Thermocouple application

Thermocouples are much used for making temperature measurements over a much wider range than is possible with the LM335, partly because they are very cheap and simple. Although thermocouples can be used for measuring temperatures of up to some thousands of degrees Centigrade using a junction of two different materials, a cold reference junction is required, often an ice bath, except when differential measurements are being made.

Rather than use an ice bath it is often more convenient to employ a technique known as cold junction compensation in which a compensating voltage is added to the output of the thermocouple so that the reference junction potential seems to be at 0° C, although it is actually at another temperature. The added voltage can be made proportional to temperature with the same constant of proportionality as the thermocouple so that changes in ambient temperature have no effect on the output voltage.

The LM335 temperature sensor is very suitable for use in the cold junction compensating circuit owing to its very linear voltage/temperature characteristics. In addition, as the LM335 voltage extrapolates to zero at the absolute zero of temperature, the temperature coefficient of the compensation circuit can be adjusted to room temperature without any temperature cycling.

A thermocouple thermometer calibrated in degrees centigrade is shown in Figure 16. The thermocouple reference junction should be terminated in close proximity to the LM335 so that their temperatures do not differ appreciably. Initially a signal should be applied in place of the thermocouple and R3 adjusted for a gain of 245.7. The non-inverting input of the LM308A should be shorted to ground and R1 adjusted so that the output voltage is 2.982 V at 25° C. The short should now be removed from the non-inverting input and R2 adjusted for an output of 246 mV at 25°C. The thermocouple connections should now be replaced.

Electronic thermometers of this general type can provide a 10 mV/° C output over a 0° C to 1300° C range, but it is important to use good quality cermet trimmers and stable components.

Further thermocouple circuits together with practical information on their construction using LM335 cold junction compensation is available in the *National Semiconductor Linear Applications Handbook*, as Application Note AN-225, April 1979.