2.6 PID CONTROL

The Model 340 temperature controller uses a algorithm called PID control. The control equation for the PID algorithm has three variable terms, a P or proportional term, an I or integral term, and a D or derivative term. See Figure 2-3. Changing these variables for best control of a system is called tuning. The PID equation in the Model 340 is:

$$\text{Heater Output} = P\left[e + I\int(e)\,dt + D\frac{de}{dt}\right]$$ where **error (e) = Setpoint - Feedback Reading.**

Proportional (P) is discussed in Paragraph 2.6.1. Integral (I) is discussed in Paragraph 2.6.2. Derivative (D) is discussed in Paragraph 2.6.3. Finally, the manual heater output is discussed in Paragraph 2.6.4.

2.6.1 Proportional (P)

The Proportional term, also called gain, must have a value greater than zero for the control loop to operate. The value of the proportional term is multiplied by the error (e) which is defined as the difference between the setpoint and feedback temperatures, to generate the proportional contribution to the output: Output (P) = Pe. If proportional is acting alone, with no integral, there must always be an error or the output will go to zero. great deal must be known about the load, sensor, and controller to compute a proportional setting (P). Most often, the proportional setting is determined by trial and error. The proportional setting is part of the overall control loop gain, and so are the heater range and cooling power. The proportional setting will need to change if either of these change.

2.6.2 Integral (I)

In the control loop, the integral term, also called reset, looks at error over time to build the integral contribution to the output:

$$Output\ (I) = PI\int(e)\,dt.$$

By adding the integral to proportional contributions, the error that is necessary in a proportional only system can be eliminated. When the error is at zero, controlling at the setpoint, the output is held constant by the integral contribution. The integral setting (I) is more predictable than the gain setting. It is related to the dominant time constant of the load. As discussed in Paragraph 2.7.3, measuring this time constant allows a reasonable calculation of the integral setting. In the Model 340, the integral term is not set in seconds like some other systems. The integral setting can be derived by dividing 1000 by the integral seconds: Isetting = 1000 / Iseconds.

3 Derivative (D)

The derivative term, also called rate, acts on the change in error with time to get its contribution to the output:

$$Output\ (D) = PD\frac{de}{dt}.$$

By reacting to a fast changing error signal the derivative can work to boost the output when the setpoint changes quickly, reducing the time it takes for temperature to reach the setpoint. It can also see the error decreasing rapidly when the temperature nears the setpoint and reduce the output for less overshoot. The derivative term can be useful in fast changing systems but it is often turned off during steady state control because it reacts too strongly to small disturbances. The derivative setting (D) is related to the dominant time constant of the load similar to the I setting. The derivative term is set in seconds.

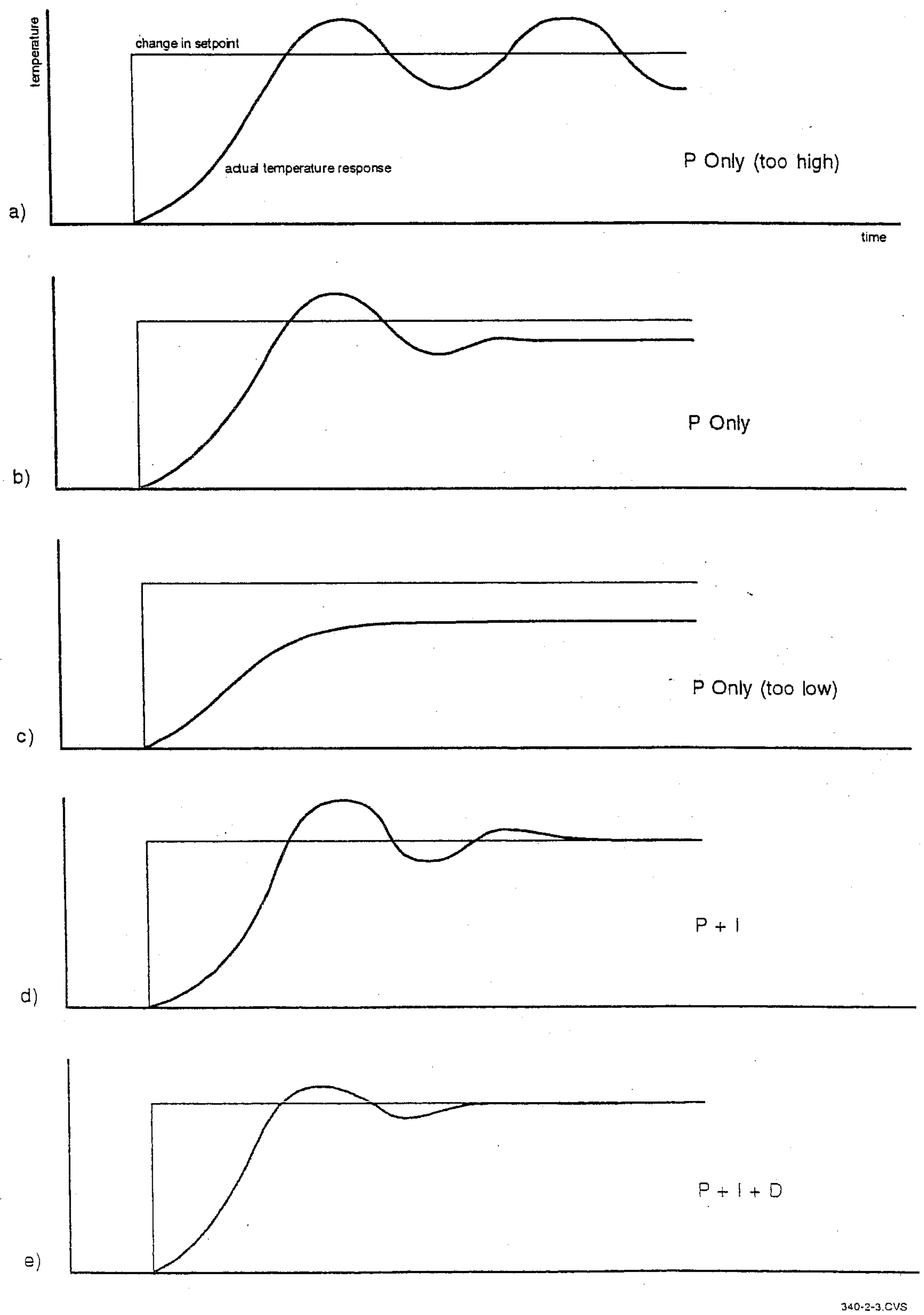

Figure 2-3 Examples of PID Control

2.6.4 Manual Heater Output

The Model 340 has a control setting that is not a normal part of a PID control loop. Manual heater output can be used for open loop control, meaning feedback is ignored and the heater output stays at the users manual setting. This is a good way to put constant heating power into a load when needed. The manual output term can also be added to the PID output. Some users prefer to set a power near that necessary to control at a setpoint and let the closed loop make up the small difference. Manual output is set in percent of full scale current or power for a given heater range.

2.7 MANUAL TUNING

There has been a lot written about tuning closed loop control systems and specifically PID control loops. This section does not attempt to compete with control theory experts. It describes a few basic rules of thumb to help less experienced users get started. This technique will not solve every problem, but it has worked for many others in the field. This section assumes the user has worked through the operation sections of this manual, has a good temperature reading from the sensor chosen as a control sensor, and is operating Loop 1. It is also a good idea to begin at the center of the temperature range of the cooling system (not close to its highest or lowest temperature). AutoTune (Paragraph 2.8) is another good place to begin, and do not forget the power of trial and error.

Setting the heater range is discussed in Paragraph 2.7.1. Manually tuning Proportional (P) is discussed in Paragraph 2.7.2. Manually tuning Integral (I) is discussed in Paragraph 2.7.3. Finally, manually tuning Derivative (D) is discussed in Paragraph 2.7.4.

2.7.1 Setting Heater Range

Setting an appropriate heater output range is an important first part of the tuning process. *The heater range should allow enough heater power to comfortably overcome the cooling power of the cooling system.* If the heater range will not provide enough power, the load will not be able to reach the setpoint temperature. If the range is set too high, the load may have very large temperature changes that take a long time to settle out. Delicate loads can even be damaged by too much power.

Often there is little information on the cooling power of the cooling system at the desired setpoint. If this is the case, try the following: Allow the load to cool completely with the heater off. Set manual heater output to 50% while in Open Loop control mode. Turn the heater to the lowest range and write down the temperature rise (if any). Select the next highest heater range and continue the process until the load warms up to room temperature. If the load never reaches room temperature, some adjustment may be needed in heater resistance or maximum heater current.

The list of heater range versus load temperature is a good reference for selection the proper heater range. It is common for systems to require two or more heater ranges for good control over their full temperature. Lower heater ranges are normally needed for lower temperature. The Model 340 is of no use controlling at or below the temperature reached when the heater was off. Many systems can be tuned to control within a degree or two above that temperature.

2.7.2 Tuning Proportional

The proportional setting is so closely tied to heater range that it can be thought of as fine and course adjustments of the same setting. An appropriate heater range must be known before moving on to the proportional setting.

Begin this part of the tuning process by letting the cooling system cool and stabilize with the heater off. Place the Model 340 in Manual PID control mode, then turn integral, derivative and manual output settings off. Enter a setpoint several degrees above the cooling systems lowest temperature. Enter a low proportional setting of approximately 5 or 10 and then enter the appropriate heater range as described above. The heater display should show a value greater than zero and less than 100%. The load temperature should stabilize at a temperature below the setpoint. If the load temperature and heater meter swing rapidly, the heater range may be set too high and should be reduced. Very slow changes in load temperature that could be described as drifting are an indication of a proportional setting that is too low (which is addressed in the next step).

Gradually increase the proportional setting by doubling it each time. At each new setting, allow time for the temperature of the load to stabilize. As the proportional setting is increased, there should be a setting in which the load temperature begins a sustained and predictable oscillation rising and falling in a consistent period of time. See Figure 2-3a. The goal is to find the proportional value in which the oscillation begins, do not turn the setting so high that temperature and heater output changes become violent.

Record the proportional setting and the amount of time it takes for the load change from one temperature peak to the next. The time is called the oscillation period of the load and it helps describe the dominant time constant of the load which is used in setting integral. If all has gone well, the appropriate proportional setting is *one half* of the value required for sustained oscillation. See Figure 2-3b.

If the load does not oscillate in a controlled manner, the heater range could be set too low. A constant heater reading of 100% on the display would be an indication of a low range setting. The heater range could also be too high, indicated by rapid changes in the load temperature or heater output with a proportional setting of less than 5. There are a few systems that will stabilize and not oscillate with a very high proportional setting and a proper heater range setting. For these systems, setting a proportional setting of one half of the highest setting is the best choice.

2.7.3 Tuning Integral

When the proportional setting is chosen and the integral is set to zero (off), the Model 340 controls the load ꞏnperature below the setpoint. Setting the integral allows the Model 340 control algorithm to gradually eliminate the difference in temperature by integrating the error over time. See Figure 2-3d. An integral setting that is too low causes the load to take too long to reach the setpoint. An integral setting that is too high creates instability and cause the load temperature to oscillate.

Begin this part of the tuning process with the system controlling in proportional only mode. Use the oscillation period of the load that was measured above in seconds. *Divide 1000 by the period to get the integral setting.* Enter the integral setting into the Model 340 and watch the load temperature approach the setpoint. If the temperature does not stabilize and begins to oscillate around the setpoint, the integral setting is too high and should be reduced by one half. If the temperature is stable but never reaches the setpoint, the integral setting is too low and should be doubled.

To verify the integral setting make a few small (2 to 5 degree) changes in setpoint and watch the load temperature react. Trial and error can help improve the integral setting by optimizing for experimental needs. Faster integrals, for example, get to the setpoint more quickly at the expense of greater overshoot. In most systems, setpoint changes that raise the temperature act differently than changes that lower the temperature.

If it was not possible to measure the oscillation period of the load during proportional setting, start with an integral setting of 20. If the load becomes unstable reduce the setting by half. If the load is stable make a series of small, two to five degree, changes in the setpoint and watch the load react. Continue to increase the integral setting until the desired response is achieved.

2.7.4 Tuning Derivative

If an experiment requires frequent changes in setpoint or data taking between changes in the setpoint, derivative should be considered. See Figure 2-3e. A derivative setting of zero, off, is recommended when the control system is seldom changed and data is taken when the load is at steady state.

Compute a derivative setting in seconds as one fourth the measured oscillation period of the load in seconds. If this period is unknown and the integral setting was determined experimentally, the derivative setting in seconds is calculated as:

$$D_{setting} = \frac{1000}{4 \times I_{setting}}.$$

Again, do not be afraid to make some small setpoint changes; halving or doubling this setting to watch the affect.

2.8 AUTOTUNING

Choosing appropriate PID control settings can become very tedious. Many systems can take several minutes to complete a setpoint change and it is hard to watch the display for that long looking for oscillation period and signs of instability. With the AutoTune feature, the Model 340 automates the tuning process by measuring system characteristics itself and, along with some assumptions about typical cryogenic systems, computes setting values for P, I, and D. AutoTune works only with Loop 1 and will not set manual heater output or heater range. Setting an inappropriate heater range is potentially dangerous to some loads so the Model 340 does not attempt to automate that step of the tuning process.

When the AutoTune mode is selected, the Model 340 evaluates the control loop similar to the manual tuning section described in Paragraph 2.7. One difference is that the Model 340 will not initiate changes to the control settings or setpoint for the purpose of tuning. *It only gathers data and change control settings after the user changes the setpoint.* Unexpected or unwanted disturbances to the control system can ruin experimental data being taken by the user.

When the user selects a new setpoint, the Model 340 logs the change in temperature at the load and the change in heater output that was required to make the load temperature change. The old control settings are used while data is being logged, so a good initial guess of settings can improve the efficiency of the AutoTune feature. Once the load temperature is at or near the new setpoint, the Model 340 looks at the logged data to calculate the best P, I and D settings values. Those values are then loaded and used as the control parameters so the control loop can stabilize at the new setpoint. AutoTune will not work during a ramp because the dominant time constant of the load is disguised by the ramp rate.

When the **TUNING** annunciator is displayed, this indicates that tuning data is being logged. When the annunciator returns to **TUNE**, the process is finished and will not begin again until the user changes the setpoint. If AutoTune does not give desired results the first time, make a few small, two to five degree, changes in setpoint and let the Model 340 go until the tune message returns. In many cases, AutoTune is able to arrive at a better set of control settings.

There are situations where AutoTune is not the answer. The algorithm can be fooled when cooling systems are very fast, have a large thermal lag, or are have an extremely nonlinear relationship between heater power and load temperature. If a load can reach a new setpoint in just under 10 seconds, the cooling system is too fast for AutoTuning. Systems with a very small thermal mass can be this fast. Adding mass is a solution but it is unappealing to users who need the speed for fast cycle times. Manual tuning is not difficult on these systems because new settings can be tested very quickly. Thermal lag can be improved by using the sensor and heater installation techniques discussed above. Lag times of a few seconds should be expected, much larger lags can be a problem. System nonlinearity is a problem for both AutoTune and manual tuning. It is most commonly noticed when controlling near the maximum or minimum temperature of a temperature control system. It is not uncommon; however, for a user to buy a cryogenic cooling system specifically to operate near its minimum temperature. If this is the case, try to tune the system at 5 degrees above the minimum temperature and gradually reduce the setpoint, manually adjusting the control settings with each step.

9 ZONE TUNING

nce the PID tuning parameters have been chosen for a given setpoint the whole process may have to be one again for other setpoints significantly far away that have different tuning needs. Trying to remember hen to use which set of tuning parameters can be frustrating. The Model 340 has a Zone feature as one of its uning modes that can help.

o use the Zone feature the user must determine the best tuning parameters for each part of the temperature ange of interest. These parameters are then entered into the Model 340 where up to ten zones can be efined with different P, I, D, heater output range and manual output. A setpoint setting is assigned as the naximum temperature for that zone. The minimum temperature for a zone is the setpoint for the previous one, 0 K is the starting point for the first zone. When the zone tuning mode is on, appropriate control arameters are chosen automatically, each time the setpoint is changed to a new temperature zone.

Control parameters can be determined manually or by using the AutoTune feature. AutoTune is a good way to letermined a set of tuning parameters for the control system that can then be entered as zones. Once the arameters are chosen, AutoTune is turned off and zone tuning takes over.

Zone tuning has advantages over AutoTune during normal operation. When a new setpoint is set the zone uning automatically sets the appropriate control parameters for the destination. Approach to the new setpoint s c ..rolled with the best parameters. AutoTune, on the other hand, is not able to learn enough about the system to change the control parameters until after the temperature gets near or to the new setpoint. Approach to the new setpoint is controlled with the old parameters because they are the best available.