ENGINE SPEED CONTROL

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ABSTRACT: This is one of a series of white papers on systems modelling, analysis and control, prepared by Control Systems Principles.co.uk to give insights into important principles and processes in control. In control systems there are a number of generic systems and methods which are encountered in all areas of industry and technology. These white papers aim to explain these important systems and methods in straightforward terms. The white papers describe what makes a particular type of system/method important, how it works and then demonstrates how to control it. The control demonstrations are performed using models of real systems that Control Systems Principles partners designed to teach control ideas and that are now manufactured by TQ Education and Training Ltd in their CE range of equipment. This white paper is about one of the most historically important control problems - engine speed control and regulation.

1. Why is Engine Speed Control Important?

1.1. Some History

The speed control of engines is intimately associated with the origins of control theory. There are many examples in the ancient times [1] of devices that could be said to incorporate feedback or regulation, and most basic control textbooks [e.g.2] will have some discussion of the ancient origins of feedback mechanisms. However, for the true beginnings of modern feedback control analysis we must look to the practical problem of regulating the speed of engines and the centifugal governor (Figure 1).

Figure 1. A Simple Centrifugal Speed Governor.

In the beginning of mechanisation, the engine power was supplied by water wheels and wind mills – but the really big change occurred when the steam engine arrived in the early 18th century. The development of the steam engine in a useful form was crucial to the success of the Industrial Revolution. Equally important for the success of the steam engine was the development of the fly-ball or centrifugal speed governor in the last quarter of the 18th century. James Watt is normally associated with this invention, but as so often happens, Watt's innovation was built upon the work of many other engineers and inventors,[3]. In fact there had been many forms of speed governer before Watt, but the simplicity and effectiveness of his design, combined with new steam engine developments, gave a centrifugal device that could regulate speed reliably. It did this via a steam valve connected to a pair of rotating weights. As the engine speed increased, the centrifugal force on the weights increased, and lifted a collar on the regulator shaft. The collar was connected to a valve in a way that reduced steam flow into the cylinders of a steam engine when the speed increased, and increased the steam flow as the engine speed decreased. Figure 1 shows a picture of a very simple centrifugal governor from our development workshop. The centrifugal governor and the linkage to the steam valve gave a negative feedback loop with which to control the engine speed.

Watt's centrifugal speed governer gave factory and mill owners a reliable and practical way in which to regulate the speed of all forms of rotating machines, ranging from water wheels to steam engines and in all forms of industry that required a constancy of operating conditions. The development of the centrifugal governor was in fact a sideshow to the Industrial Revolution, Nevertheless, its invention – followed by its mathematical analysis - is at the heart of much of today's control engineering theory and practice. This was enabled by the Industrial Revolution, when a group of highly intelligent men who mixed scientific curiosity with commercial energy came into being and formed a conduit between new practical engineering problems and mathematical tools of analysis [4]. During the 18^{th} century many scientists and engineers contributed to the improvement of the centrifugal governer with excellent results and amazing analysis. However these people were outside the British educational establishment represented by Oxford, London and Cambridge, and so it waited until a centrifugal governor found its way to Cambridge in the late 19^{th} century before its dynamical analysis gained scientific respectability and wide publicity in Britain through Maxwell's paper 'On Governors' for the Royal Society of London.

The 18^{th} century developments in the industrial midlands of England attracted wide attention from other countries. Vistors from continental Europe - including many important scientists from France and Germany - would by-pass the stagnant South East of England and travel direct to centres of industry such as Birmingham and Manchester where they were welcomed by the Dissenter scientists and engineers. Through this route knowledge of the centrifugal governor and its practical development spread. Its analysis was widely taken up, with the most well known work being from the Russian, Wischnegradski, but with other important and excellent technical developments from Germany and France. However, if we lay aside questions of 'who did what, where and first', the important fact is that the centrifugal speed governor for engines led to the important theoretical step that showed that the dynamic behaviour of a system is associated with the roots of a polynomial equation. We now call this the characteristic equation of a system, the roots of the equation are called the poles of the system transfer function or the eigenvalues of the system. These concepts lie at the heart of all linear control systems analysis and design.

1.2. The Relevance of Engine Speed Control Today

To see why engine speed control remains an important issue, we fast forward from the regulation of steam engine speed to the control of the automobile engine. The petrol (gasoline if you are from the USA) and diesel motor for cars and lorries are the most important engines of our age. For the control engineer they are intensely interesting to work with and challenging to control. In addition to speed, the petrol engine has a number of other control aspects, starting from ignition timing control, through fuel-air ratio control to the growing number of emissions and efficiency requirements that all require yet more complex control strategies. The modern car is in fact controlled by electronic control units (ECU's), Figure 2, which contains more computing power than was used to take man to the Moon and back.

Figure 2. An Engine Control Unit (ECU) – photograph by permission of Lucas Industries.

The control of diesel engines has followed a similar trend – with the historical connection that until quite recently centrifugal governers were used to limit the maximum and control the minimum speeds of diesel engines. The modern automotive diesel engine has an ECU of similar complexity to the petrol engine device. And all this complexity to control engines. This is why engine speed control remains relevant today – it is the application that gave rise to the theoretical analysis and design of control systems. Moreover, engine speed control still lies at the heart of some of the most sophisticated control systems in the world. Now read on.

2. A Standard Engine Speed Control System

The basic elements of an engine control system of the kind that led to the development of regulators are:

- A valve with which to change the supply rate of the fuel source
- A reciprocating engine
- An output shaft with flywheel and the engine load.

In a standard system, especially one which students might use, a safe fuel source is compressed air. This gives similar results to steam but without the extremes of temperature or energy. A standard engine speed control system using compressed air is shown in Figure 3.

The inlet valve is a very important part of this system – the valve is non-linear with a dead-zone in its input characteristics. This is important because the input valve dead-zone, usually caused by static friction, was a significant feature in the design of centrifugal speed governers. Actuator dead-zone remains a problematic feature of engine control and to emphasize this problem, a large amount of dead-zone is designed into the standard system. The input valve in the standard system is also motorized so that a constant control input to the valve motor causes a constant rate of change of the valve position. The airflow rate/ valve position characteristic is also non-linear so that the control of the air flow into the engine is itself a problem.

The design and layout of the engine is typical of a four cylinder steam engine with an inertial load in the form of a flywheel, and variable load in the form of an electrical generator. To vary the electrical load a load control voltage is used. The appendix shows a more detailed schematic layout for a standard engine speed control system.

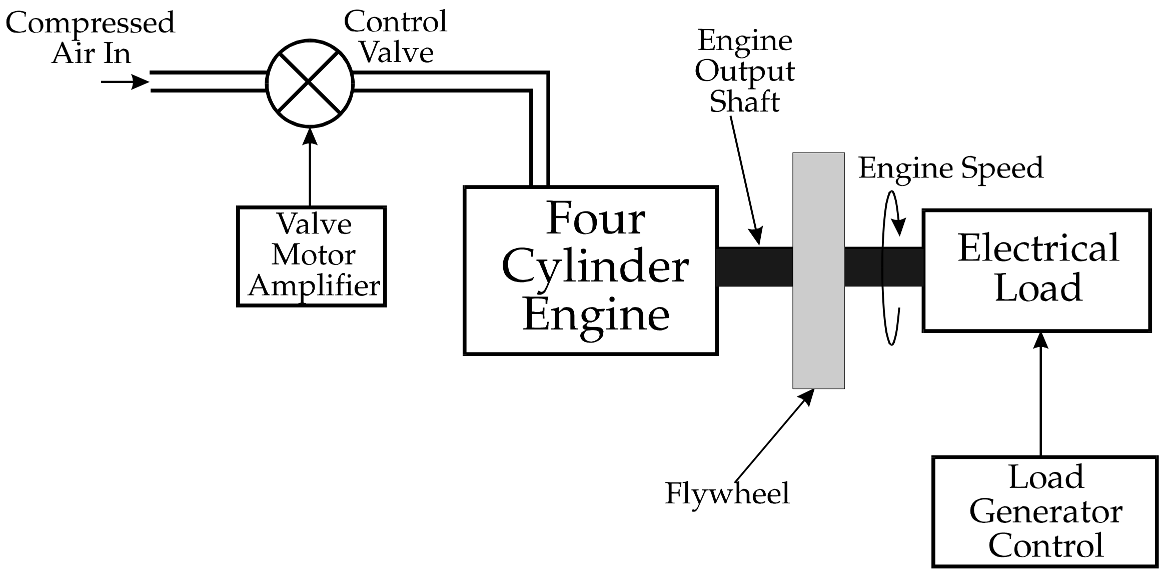

Figure 3. A Standard Engine Speed Control System

3. Modeling.

The components of the standard engine control system are the air control valve, the engine and the load. The air control valve in turn has two parts, the drive motor and the valve. The drive motor gives a rate of change of valve position $\dot{y}(t)$ proportional to the motor input signal $u(t)$, so it can be modelled as an integrator with gain g_m. The valve output pressure $P(t)$ is proportional to the valve position $y(t)$ – so it can be modelled as a gain g_v.

$$\frac{dy(t)}{dt} = g_m u(t), \qquad P(t) = g_v y(t) \tag{1}$$

The engine torque $\tau_e(t)$ is proportional to the air pressure.

$$\tau_e(t) = g_e P(t) \tag{2}$$

The engine torque is used to supply the engine load, frictional losses and to accelerate the engine flywheel inertia I. If the engine speed is ω then we can write;

$$\begin{pmatrix}\text{Rate of change of}\\ \text{Flywheel Momentum}\end{pmatrix} = \begin{pmatrix}\text{Engine}\\ \text{Torque}\end{pmatrix} - \begin{pmatrix}\text{Frictional}\\ \text{Torque}\end{pmatrix} - \begin{pmatrix}\text{Load}\\ \text{Torque}\end{pmatrix}$$

$$I\frac{d\omega(t)}{dt} = \tau_e - \tau_f - \tau_l \tag{3}$$

The torque required to overcome friction is $\tau_f = b\omega(t)$, where b is the friction coefficient. The load torque τ_l is proportional to the load demand voltage $d_l(t)$ such that; $\tau_l = g_l d_l(t)$.Combining these equations gives:

$$I\frac{d\omega(t)}{dt} + b\omega(t) = g_e g_v y(t) - g_l d_l(t) \tag{4}$$

Equations (1) and (4) are the differential equation model of the standard engine speed control system. In transfer function form these are:

$$
\begin{aligned}
y(s) &= \frac{g_m u(s)}{s} \\
\omega(s) &= \frac{g_e g_v y(s)}{b+Is} - \frac{g_l d(s)}{b+Is}
\end{aligned}
\qquad (5)
$$

Because the input valve has a dead-zone, the gain g_m is non-linear with a characteristic as shown in Figure 4. The air flow gain g_v is also non-linear but with a smooth characteristic, usually power law. In normal operation the valve characteristic is locally linearised about the normal operating speed of the engine, and the dead-zone is compensated for as described in section 4.1. below.

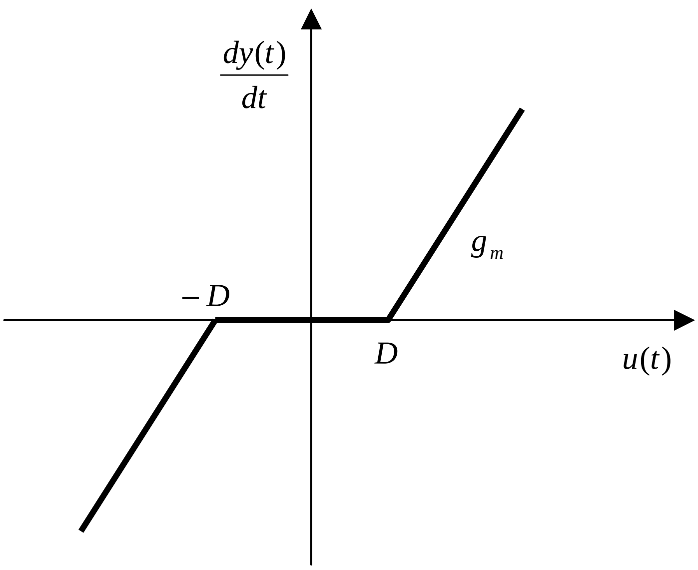

Figure 4. Dead-zone Characteristic.

4. Control Problems for a Standard Engine Speed System.

The standard engine control problem as shown in Figure 3 has two main components that are found in many engine control situations. They are:

- The requirement to control a non-linear input actuator (the air flow control valve)
- The requirement to regulate the speed of the engine when the load on its output shaft changes

The solution to these control problems requires some standard and important control techniques:

- Compensation for dead-zone in the actuator. A local feedback loop is used, together with some non-linear compensating mechanism to reduce the actuator dead-zone and to give direct control over the valve position.
- The use of cascade control. An inner feedback loop gives control over the position of the air flow valve and an outer feedback loop does the speed regulation.
- The use of feed forward of the load demand. When a signal is available which is proportional to the load, then the signal (the load generator demand voltage in this case) can be fed forward to the input of the control system to anticipate changes in load.

4.1. Dead-zone Compensation

A typical actuator dead-zone characteristic is shown in Figure 4. For input signals smaller than the dead-zone width, D, the actuator output response is zero and no actuation signal is sent to the system. This can be compensated for in several ways. If the actuator position is measured (as in the standard engine speed control system) then high gain feedback around the actuator can reduce the effective dead-zone by a factor equal to the feedback gain. A further common procedure is to use a technique called dither. In this a periodic signal is added to the actuator input signal. The frequency of the dither signal should be higher than the bandwith of the system dynamics, and the amplitude should be approximately *D*. The effect of this is to give an effective gain characteristic as shown in Figure 5.

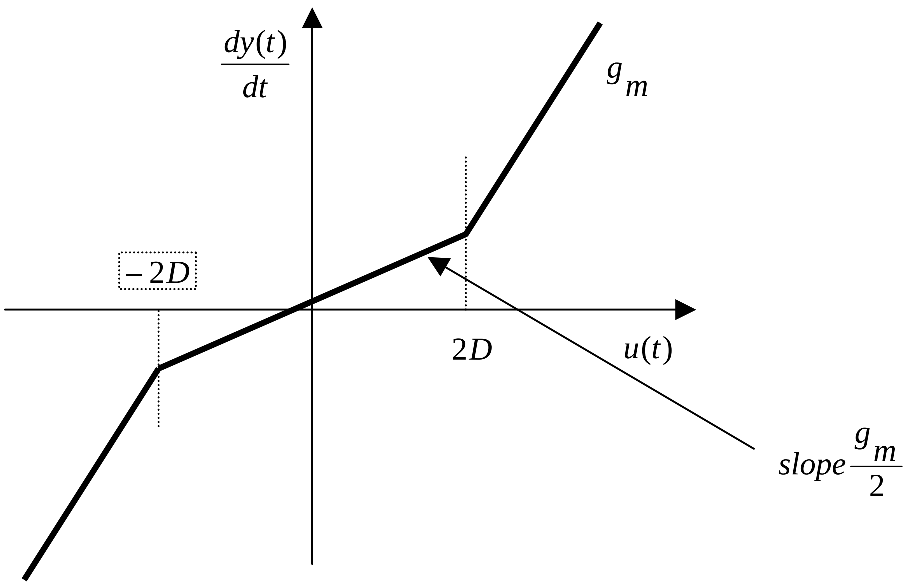

Figure 5. Dither Compensated Dead-zone Characteristic.

The problem caused by dead-zone is that when the control signal falls within the dead-zone band, then no control signal is fed to the system. This causes a servo tracking error proportional to the size of the dead-zone. The advantage of dither is that the valve dead-zone as shown in Figure 4 is replaced by the non-zero gain of $\frac{g_m}{2}$. In this case there is always a corrective control signal being fed to the system and the servo tracking error can be control by normal means. There are other dead-zone compensation methods, (see the Servo Systems white paper for details of this).

4.2. Cascade Control

The engine speed control system is an example of a process in which we must first control the actuator (the air valve) before the main system (the engine) can be controlled. This is a common ocurence in industry and leads to what is known as cascade control. Figure 6 illustrates a cascade control system for the engine speed control system. The cascade control system consists of an inner loop (or slave controller) which controls the valve position $y(t)$ to a reference valve position $y_r(t)$. The outer loop (or master controller) controls the engine speed $\omega(t)$ The outer loop is termed the master control loop because it supplies the reference valve position which the inner (slave) loop must follow.

Cascade control systems are widely used in industrial systems, where it is important to proceed step by step through a complex system. The aim is to start with the inner most blocks of a system, place them under control and then work outwards to the next level of control. In the engine speed control system the procedure is to close the valve position control loop using non-linear compensation, (e.g. dither), and obtain good accurate valve position control. The valve reference position then becomes the system input for the master controller design. The master controller design would use three-term control as described in Elke's white paper (see the down load page at www.control-systems-principles.co.uk).

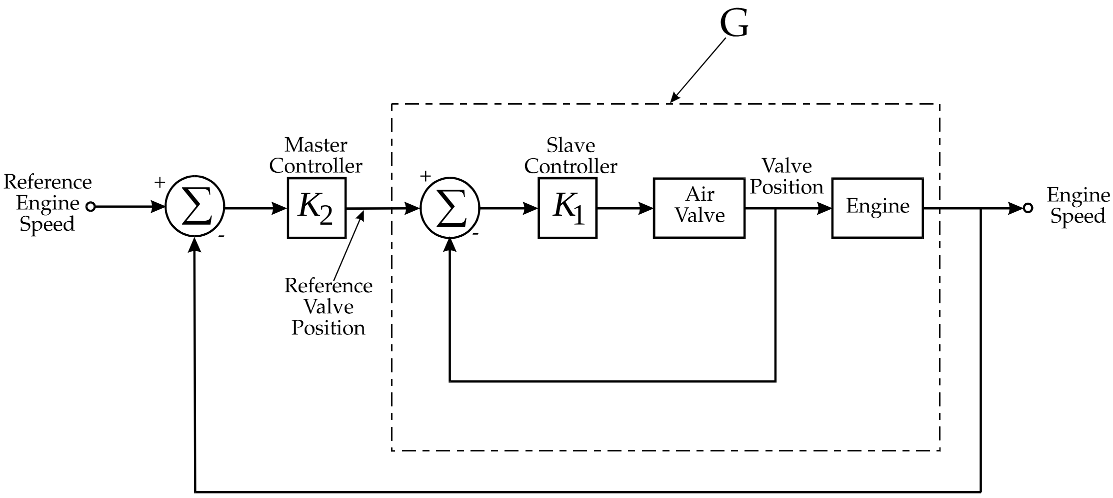

Figure 6. Cascade Control Structure for the Standard Engine Speed Control System.

4.3. Feed Forward Control

An external load will influence the quality of control when it changes. A good feedback controller with integral action can compensate for this external disturbance. However, if the disturbance can be measured, then better control can be achieved by using the measured disturbance in the control system. This is called **Feedforward Control**. In the standard engine speed control system the disturbance signal, $d_l(t)$, can be measured. This measurement is used to assist the feedback controller action. The signal $d_l(t)$ is fed through a feedforward controller $F(s)$ and added (or subtracted as appropriate) from the output of the feedback controller. By correct choice of $F(s)$ the feedforward signal will exactly compensate for the influence of the disturbance.

5. An Engine Speed Control System

Figure 7 shows a commercial version of the standard engine control problem produced by TQ Education and Training Ltd. It uses compressed air to drive the system and the engine is a scale model of a steam engine. All other aspects of the system follow the 'standard' model that was described in Section 2 of this white paper. We will use a model of this hardware to illustrate the control experiments – in a later white paper we will use the real system and compare results.

Figure 7. The TQ CE107 Engine Speed Control System.

6. Control Examples for the Standard Engine Speed Control System

In this section we use simulation to demonstrate dead-zone compensation using dither and cascade compensation. Feedforward compensation is used to demonstrate load disturbance rejection. The simulation model is shown below where the motor dynamics are represented by a simple 1st order lag. The actuator includes an integrator as described above. The inputs are the reference, dither and disturbance signals.

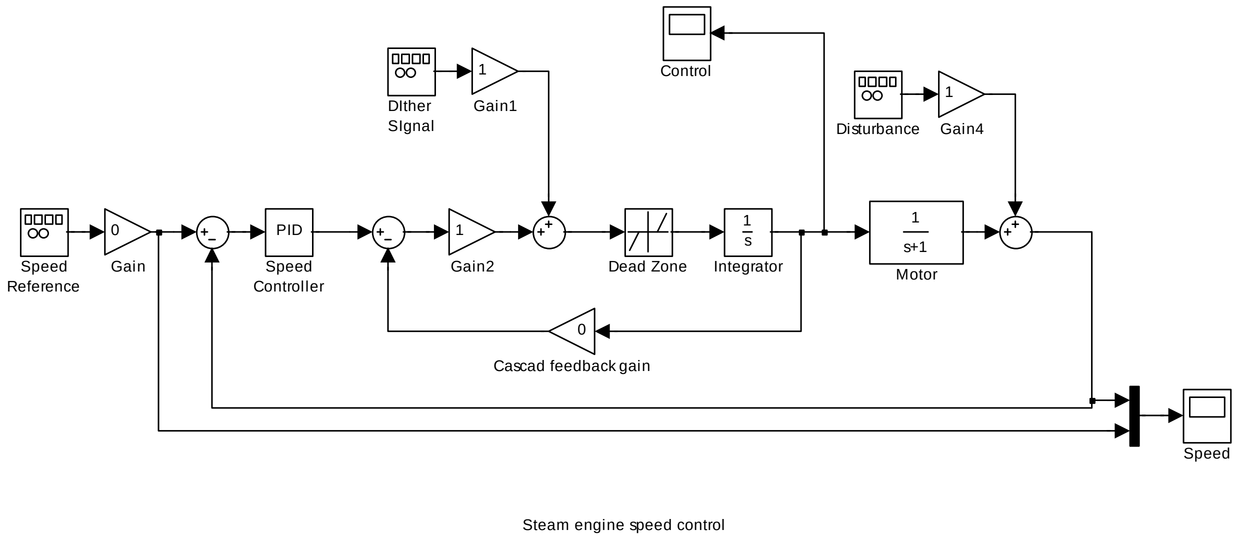

Figure 8. Simulation of Engine Speed Control System.

6.1. Dead-zone Compensation

In this section we compare speed control of the steam engine with and without dither compensation of the actuator. The dither signal is inserted into the feedback loop just before the input to the actuator. The amplitude of the dither signal should exceed the dead-zone and the frequency of the dither should be higher than the closed loop bandwidth of the system. Because the actuator already contains an integrator, only proportional control is required to track a step change in speed. The simulation results shown below compares control of the shaft speed with and without dither. The only difference between these signals is the presence of dither on the lower trace. The dither signal has an amplitude of 1volt and a frequency of 10Hz. This is well above the closed loop bandwidth of the system. Notice the improvement in steady steady state error and dynamic response when the dither signal is added. Also note that the dither signal has no visible effect on the control signal. This is important. The dither signal should linearize the system but have as little effect a possible on the controlled variables. An accessible control orientated dicussion on the use of dither can be found in reference [9].

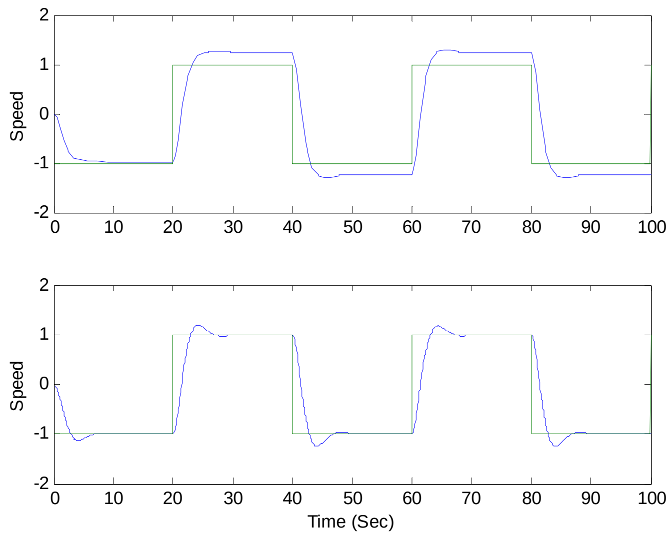

Figure 9. Dead-zone Compensation Using A Dither Signal.

6.2. Cascade Control

In this section the dead-zone is compensated for by using feedback. Feedback can have a strong linearizing effect. To demonstrate this in the simulation the dither signal is turned off by reducing the gain in the dither channel to zero. Feedback is now introduced around the actuator. This has the efffect of linearizing the actuator dynamics but also results in a type '0' system[1]. Therefore the PID controller for the shaft speed now has to include integral action to compensate for the steady state error.

[1] The type of a system tells us how many integrators there are in the closed loop. A type '0' system has none, a type '1' system has one, and so on. The type of a servo system is important because it tells the designer with what input signal he/she can hope to have zero steady state errors.

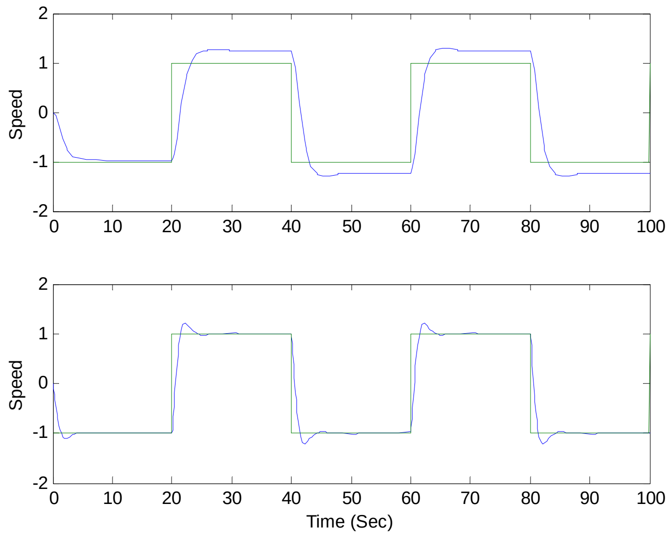

Figure 10. Dead-zone Compensation Using Cascade Control.

6.3. Load Feed Forward

A solution to disturbance rejection is to use feedforward control. With feedforward control it is assumed that a signal related to (idealy proportional to) the disturbance is available. For example with a steam engine a generator connected to the output might supply electrical power to a load. Measuring the load current as the load varies gives a measure of the disturbance signal. This signal can the be used to generate a control signal that will cancel or reduce the effect of the disturbance. In the simulation below a triangular load disturbance is injected into the feedback loop. The effect of feedforward is clearly seen in Figure 12. Without compensation this load disturbance causes a large steady-state error (blue plot). With feedforward compensation this error is clearly reduced (red plot).

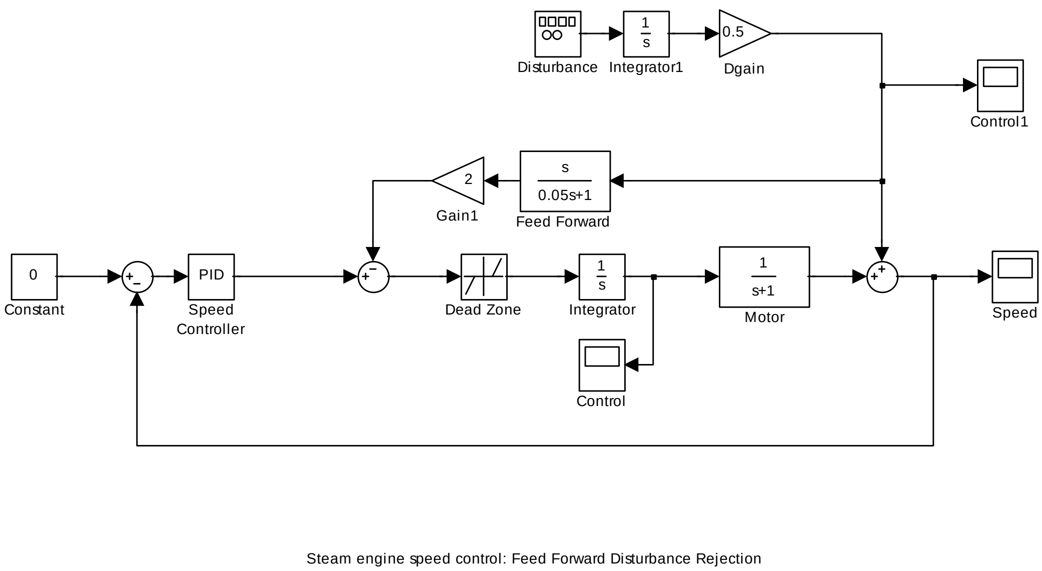

Figure 11. Feed Forward Simulation

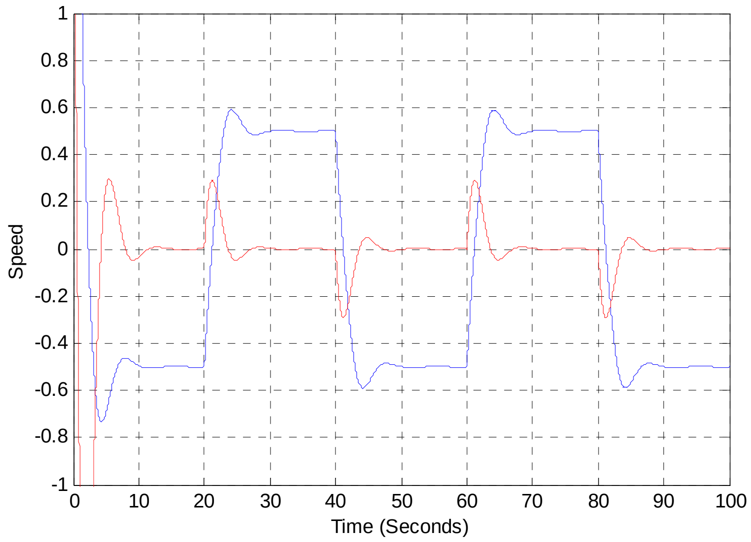

Figure 12. Feed Forward Disturbance Rejection.

7. A Final Word

We are sorry to say that it is not possible to answer general questions about the contents of our white papers, unless we have a contract with your organisation. For more information about speed control of engines and the CE107 Engine Speed Control System go to the TQ Education and Training web site using the links on our web site www.control-systems-principles.co.uk or use the email info@tq.com.

The history of control systems is a rich one in the area of engine speed control. For example, look at references [1, 3] for the details of how speed controllers were developed in the industrial revolution. Control Systems Principles have especially enjoyed Jenny Uglow's book [4] because it paints a picture of the complex social and scientific changes that were occuring at the time and gives a wider understanding of the atmosphere in which engine control was born. For IEEE members the special issue of the IEEE Control Systems Magazine [5] is a good read. We also recommends the web sites [6,7] and industrial museum web sites in general . The Manchester Museum of Science and Industry [8] is especially good.

References

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Appendix – Schematic of the Standard Speed Control System