FEED FORWARD ALGORITHMS IN WEB CONVEYANCE APPLICATIONS

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Abstract – *Web conveyance, as many manufacturer's know, can be a challenging task due to the difference among substrates and mechanical systems. Not only does the mechanical design need to accommodate these varying substrates, so does the automation design and subsequent software behind these designs. This session discusses software implementations for compensations such as static, dynamic and inertial compensations for roll friction and acceleration as well as torque, speed and position feed forward algorithms. The discussion compares the theoretical to the real world to substantiate the theory.*

Introduction

In any type of process, whether it's chemical, mechanical or electrical, there are controls that are in place that regulate the variables of that process. In the human body, it is the systems that regulate heart rate, breathing rate and metabolism. In a nuclear power stations, there are systems that regulate the rate of nuclear fission. In a car, there is a system in place that regulates the charging of a battery.
Generically speaking, there are many ways to achieve this control. Two general classes are:
feedback control and feed forward control. In a feedback system, you measure the variable you are trying to control, with subsequent action on the system if the variable is not where you want it. Feed forward control is predictive in nature, or in other words, when you know how external variable affects the control variable, and then you set those variables accordingly to achieve the desired output.
A practical real-world example that everyone is familiar with is a car's cruise control. If you engage cruise control, and you start going up a steep incline, the car starts to slow down. The cruise control system sees that the car has slowed down and then it increases the throttle to a point where the car is now going the correct speed. It may overshoot the speed a little bit, but eventually the speed settles in to the set point set by the driver. This is an example of a feedback control system.

A feed forward control system would be one that would anticipate the extra load required by the hill and adjust the throttle accordingly before car slows down. This could be the action of an experienced driver who sees the hill, and increases the throttle at the right time, thereby keeping the car at a constant speed throughout.[i]

Advantages of feed forward control

The advantage of a feed forward system is exactly as demonstrated above. By properly being able to adjust the control variables (in the above case, the throttle on the vehicle), the more precisely the process variables (the speed of the vehicle) can be maintained. This is especially important in certain conditions, such as in high inertia loads. Typically, by the time the deviation from the set-point is sensed, it will take too long for the control variables to react and correct for the deviation. Another application is where the stability of the system is critical. Again in the above example, you notice with a cruise control system the speed dips, and then overshoots before finally settling in to the correct speed. In many marginally stable systems, the oscillation that takes place is too great for the process to handle. In these systems feed forward can help.

Another important thing to note is that feed forward and feedback systems are not mutually exclusive, but rather can be effectively used in conjunction with each other. Again in the example of an experienced driver going up an incline, the driver may anticipate the extra throttle required as the car starts going up the hill (feed forward), but then may glance down at his speedometer and trim the throttle speed based on what driver sees (feedback). In almost all of the examples a feed forward term is used in conjunction with a feedback loop for the final control strategy.

Relevance to the converting operation

In any modern converting line, there can be hundreds of control loops that are involved in the process. The more tightly these variables can be controlled, the more consistent and repeatable the end product.

Simple feedforward and feedback systems in converting

A very simple example of a feed back and a feed forward system in a converting application can be demonstrated by some older, simple rewinds, on slower lines. There are installations where the regulation of the speed of the rewind is accomplished completely by the position of the dancer in front of it. When the dancer is fully tight the winder stops, conversely, when the dancer is completely loose, the winder goes to max speed. This is a 100% feedback control system. At the opposite end of the spectrum, there are applications in the paper industry where very elastic substrates can have no feedback at all. In these cases speed of the winder is set as a target of line speed, perhaps adjusted by the properties of the material. This is an example of a very simple feed forward system. Almost all of the winder applications though, are a hybrid of the two, whereby there is a main line speed signal that is followed by the winder, but is sped up or down (trimmed) by some feedback device, such as a dancer or a load cell. To aid in the stability of the system, the amount of trim (adjustment) is limited to some percentage.

Quick discussion on loops in a drive system

In several of the examples to be discussed, the drive loops end up interfacing to the loops that are built into an electrical drive system. It is therefore important to at least have a cursory knowledge of how a drive system operates in a typical converting line. There are *many* different ways to incorporate drives into a lineup but a majority of the drive systems are fundamentally set up in a similar fashion and will be discussed in more detail. Also, there is an underlying difference in the way that AC and DC drives achieve certain functions, so the discussion is held in more generic terms to try and blend both.

The innermost loop of the drive is the torque (current) loop. The torque loop actually generates the signal that is sent to the firing device (whether it's the SCR's in a DC drive or the transistors in an AC drive.) Whenever we talk of loops, we are referring to a set point that is coming from somewhere, then there is a variable that is controlled (i.e. motor torque) that is measured by a sensor. The control loop, usually a PID loop, automatically adjusts the output to get the controlled variable to equal the set point.

There are parameters called tuning parameters that regulate how the output reacts to a difference between the set point and the controlled variable. These tuning parameters determine how "aggressive" the loop reacts to the difference (SETPOINT minus FEEDBACK), and how quickly it tracks, etc. The parameters can be set to react quickly, but in most cases, there is a point at which the control system will actually cause the process to oscillate out of control due to over aggressive corrections. This can be just as detrimental as a loop that responds too slowly. Anyone that has tried to tune a system probably has had this occur, and the parameters must be adjusted to be less aggressive.

The set point to the torque loop on a drive is typically fed by the output of the speed loop. The speed loop controls how fast the motor spins and measures the speed feedback, usually from an encoder or tachometer and compares it to the desired speed set point. Usually the outer loop of a drive is the tension/position loop, which measures feedback via load cell/dancer of the web tension, and then sends a signal to the speed loop to either speed up or slow down based on the feedback.

The interesting point from above is that the variable that is of great concern to converters, the tension in the web, is a variable that is used to modulate the speed of the drive. In turn, the speed is used to modulate the torque sent to motor, which is what actually is used to regulate web tension. Several of the feed forward systems implemented, inject correction or compensating signals into the inner loops of the drive so that a tension upset doesn't have to occur before corrective action is taken.

Example of feed forward systems for mechanical losses

In an ideal world, the only amount of power required by a drive system would be the power to convey the web down the line and to exert tension on the web. However in the real world, the rolls that are used to transmit this energy to the web consume some of that energy. These energies are either losses (in terms or frictional losses) or energy transfer (translation from potential energy to kinetic energy)

In terms of losses, there are two basic types of losses that have to be overcome, static friction and dynamic friction. To overcome static friction, energy must be put into the system to get an object moving or sliding against the bearings or slides that support it. This “break away” force is dependent on the design of the system and factors such as the weight of the system, the types of bearings used, and whether grease or oil is used for lubrication, etc. Once the system is in motion, the amount of force that’s required to keep it in motion may very well be less than it took to get it to turn in the first place. Once the system is in motion, then dynamic frictional forces are at work. These dynamic frictional forces are in proportion to the velocity that the system to moving, (i.e. the dynamic frictional losses are greater the faster the system is moving). Again, the magnitude of these losses is very dependent on the design of the system.

In terms of energy transfer, as the machine starts to speed up, there is an energy transfer from potential energy (electrical energy through the drive system) to kinetic energy (energy that is stored in the rotation of the rolls). As per the Law of Conservation of Energy, the amount of energy that is in a closed system is constant. A good example of a system that requires a great deal of energy to affect motion would be a large diameter cooling drum. The energy required to get it to run at 2000 FPM can be very significant. It would be extremely advantageous to be able to anticipate this energy before an effect is seen on the web tension.

Simply written, the formula to compensate for these factors would be an equation that sums in the following torque compensations into the drive motor:

$$T_c = S + D*v + I*dv/dt$$

Where:

Tc = Compensating Torque
S = Static Compensation
D = Dynamic Compensation
v = Machine Velocity
I = Inertial Compensation
dv/dt = Acceleration

The above equation would add a compensating torque into the system, T_c , which is the sum of a static compensation S, added to a dynamic compensation D which is multiplied by the machine velocity, which is added to an inertial compensation that is multiplied by the rate of acceleration.

The above example of a feed forward system can be incorporated into a drive system at the time of setup. Certain elements of this type of feed forward system are built into more upper end drive systems and calculated automatically during an "auto-tune" cycle. Other elements may have to be manually programmed into the drive control system. Regardless of how it is added, if correctly implemented and tuned, this feed forward term can compensate for several aspects of the mechanical system before an effect is seen on the web tension.

<u>Example of feed forward systems for tension compensation</u>

Another easily understood example is the effect of the magnitude of web tension on the control system. On most web conveyance sections on a line, the tension from prior section to a section after it is relatively close. For example you may have a setting of 90lbs. of tension before a pull roll section and a setting of 100lbs. of tension right after it. Therefore the net tension that the pull roll sees is +10lbs. Assuming the pull roll is 1ft. in diameter, utlilizing the following formula:

T = F * r, where:

T = Torque (ft-lb)
F = Force (lbs)
R = radius

You get:

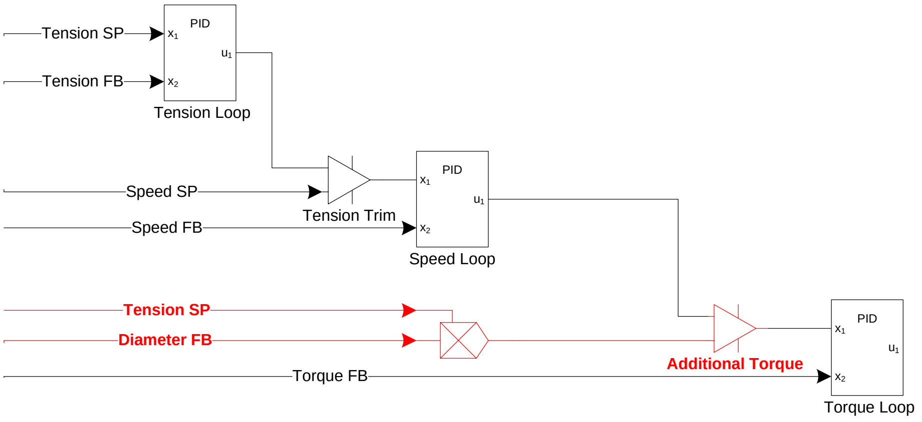
Radius = 0.5 * diameter = 0.5 ft
T = 10lbs * (0.5 ft)

The input of the roll journal only sees a 5ft-lb torque requirement due to tension. Now if you assume a gear in ratio of 10:1, the motor only sees a torque requirement of 0.5 ft-lbs. Now, let's say the tension set point is changed from 90 lbs to 100 lbs. Now the torque requirement of the motor due to tension went from 0.5 ft-lbs to 0 ft-lbs, since the tension before and after the pull roll are the same. This step change would hardly require a change in the internal loops of the drive to compensate for it. The advantage of using any feed forward term is now mitigated; hence using a feed forward term in this application would not be required.

Let's now look at the effect of an unwind spindle prior to a splice. Prior to a splice there is no torque requirement due to tension, since the roll about to be spliced in, is not yet attached to the web. The overall torque requirement due to spinning the roll in speed match is in the positive direction, since the power required is to overcome friction. At the moment of splice when tension control is transferred to the incoming spindle, the torque requirement due to tension instantaneously kicks in. A 6' diameter roll at

100 lbs. tension equals 300 ft-lbs at the core. Since the gear in ratio required is much smaller for unwinds than for sectional drives, this means that on a 2:1 gear ratio there would be an instantaneous step change of 150 ft-lbs of torque required at the motor shaft! Depending on the tuning of the drive, it could take quite a while for the system to recover from this, potentially resulting in a missed splice or the web breaking right after a splice.

A feed forward term in this case is extremely beneficial by anticipating the magnitude of the step change and immediately adjusting the torque output of the drive before the feedback terms see a dancer (position feedback) moving out of position or a motor spindle slowing down. Simply by injecting a (Tension * Diameter) term while the spindle is in tension control compensates for the component of torque due to tension and allows the drive to be tuned for more subtle changes than trying to control this large step change.



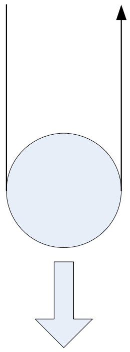
Example of Feedforward control in temperature control

Temperature control systems in converting systems are also prime examples of how systems can benefit from feed forward strategies. One of the best examples of this are extrusion systems where there is natural heating that occurs as an extrusion screw turns and works on the extradite as it’s being transported down the barrel. From a temperature control standpoint, the screw requires heating as the system is at standstill to keep the resin melted, but may very well require cooling once the line is up and running while the screw is putting work into the system. In this case, adding a feed forward term into the output of the temperature loop that is proportional to line speed is very beneficial. Many advanced algorithms take into account the type of resin being run, the design of the screw, etc. to more accurately hone in on this feed forward term. The result is more accurate and robust temperature control of the system.

Example of feed forward control for speed compensation

The last example to be discussed in feed forward control is compensation for speed variations. Consider a line is running at steady state, and the drive systems are properly tuned, the result is that all of the internal loops on a drive will settle into an equilibrium point. Now consider an event taking place such as a coating nip opening, or a turret indexing. In these cases the actual web length in the machine changes because you are modifying the web path. From the drives system standpoint, it will see a tension upset, which will cause the tension loop to change, modulating the speed loop set point. This in turn causes the torque loop to change, eventually compensating for the web length change. If you look at the overall line, you can see this tension ripple down the line as each subsequent section compensates for this change.

If you consider the movement of a linear nip with a 180 degree wrap, it should be fairly easy to see how to derive the feed forward term for this situation. Summing 2 * velocity of the moving roll into the speed set point of the drive controlling this web span's tension should compensate for the movement of the roll. Again, without adding this compensation term in, the system would not correct for this anomaly until the actual web tension upset is seen by the system.



Now consider the effect of indexing a turret on an unwind or a rewind, especially on a slow moving line. The web length change of an indexing turret can actually cause the spindles to change direction as the movement of the spindle can be opposite of the of the normal web flow. Conversely on slow moving lines, the spindle speed may need to double as the turret is rotating in the same direction as the web flow. This is extremely difficult for a normal feedback system to deal with and usually results from the operator's standpoint, in wild tension fluctuations or incorrect calculations such as diameter calculating incorrectly during turret index. The equation needed to calculate this additive feed forward velocity, however, is much more complicated than the linear nip example previously discussed. Velocity change is very non-linear. Below is a sample of the PLC code used to calculate the effective web length change based on the change in turret position:

Sample PLC Code to Compensate for Turret Rotation

```
//Find roll center position
WoundRollCenterX := TurretRadius*cos(TurretAngleRad);
WoundRollCenterY := TurretRadius*sin(TurretAngleRad);

//Determine the point of similitude between wound roll and surface roll
P3x := WoundRollCenterX;
P3y := WoundRollCenterY + WoundRollDiameter/2.0;

P4x := SurfaceRollX;
P4y := SurfaceRollY - SurfaceRollDiameter/2.0;

A1 := SurfaceRollY - WoundRollCenterY;
B1 := WoundRollCenterX - SurfaceRollX;
C1 := SurfaceRollX*WoundRollCenterY - WoundRollCenterX*SurfaceRollY;

A2 := P4y - P3y;
B2 := P3x - P4x;
C2 := P4x*P3y - P3x*P4y;

DENOM := A1*B2-A2*B1;
PsX := (B1*C2 - B2*C1)/DENOM;
PsY := (A2*C1 - A1*C2)/DENOM;

SurfCent_to_Ps := sqrt((PsX-SurfaceRollX)**2 + (PsY-SurfaceRollY)**2);
SurfTan_to_Ps := sqrt(SurfCent_to_Ps**2 - (SurfaceRollDiameter/2.0)**2);
Theta2 := acos((SurfaceRollDiameter/2.0)/SurfCent_to_Ps);

//Determine the length of the tangent portion of the web
Ltangent := (WoundRollDiameter+SurfaceRollDiameter)/SurfaceRollDiameter*SurfTan_to_Ps;

WoundCent_to_SurfCent := sqrt((WoundRollCenterX-SurfaceRollX)**2 + (WoundRollCenterY-SurfaceRollY)**2);

//Determine the length of web around surface and wound rolls
Theta3 := asin((WoundRollCenterY-SurfaceRollY)/WoundCent_to_SurfCent);
Theta4 :=   3.14159265358979/2.0 - Theta2 + Theta3;
WebAngle := Theta4;

SurfRollContactLength := 0.5*SurfaceRollDiameter * Theta4;
WoundRollContactLength := 0.5*WoundRollDiameter * Theta4;

//Determine total web length from starting point of surface roll to ending point on wound roll
WebPathLength := SurfRollContactLength + Ltangent + WoundRollContactLength;
```

The algorithm is written generically and can be used for 2 spindle turrets with 2 intermediate carry over idler rolls. Several constants are measured (i.e. turret radius, surface roll diameter, etc) and entered in. Not shown are the additional compensation terms for spindle precession due to floor mounted spindle motors and the calculation to convert the differential web length change of speed, etc. Often time the feed forward term can be more intuitive and other cases the feed forward term can be quite complicated. The reward though is that in this particular example, a turret index and spindle transfer time of around 10 seconds can be accomplished with almost no appreciable web tension disturbances.

Conclusions

In converting control schemes where predominantly feedback systems are used, there are opportunities to improve control by injecting feed forward terms. In most cases, the understanding of the underlying physical and mechanical systems is needed to properly calculate the feed forward terms. In some cases, the underlying calculations can be quite complex, but the more accurately the mechanical system is modeled, the more effective the feed forward algorithms are, in ensuring system accuracy and stability.

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[i] http://en.wikipedia.org/wiki/Feedforward