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CHAPTER 5

Roll-to-Roll Coating Simulator for Web Tension and Coat Weight During Speed Changes

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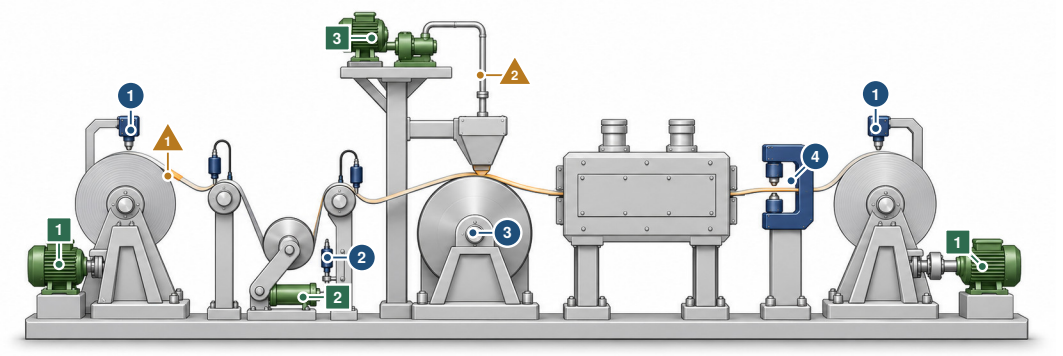
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CHAPTER 5

Roll-to-Roll Coating Simulator for Web Tension and Coat Weight During Speed Changes



The controller moves 1 unwind and rewind motors 2 dancer air load 3 coating pump

The controller reads 1 roll diameter sensors 2 dancer position 3 line speed at the coating roll 4 coat-weight gauge

What disturbs it ▲1 splice to a web of another stiffness ▲2 coating batch of another viscosity

Notice that the die sits on the coating roll far upstream of the gauge, so a thinner coat is made long before it is weighed. Illustration, not to scale.

IN PLAIN TERMS One Speed Change Spoils Two Things at Once

The main idea. A coating line pulls a thin sheet of film or foil between two rolls and spreads a wet layer on it. The sheet must be pulled just tight enough, and the layer must weigh the right amount.

The challenge. A faster line spreads the same coating over more sheet, so the layer thins at once, while the scale that weighs it sits far downstream. The rolls at each end must spin faster, and they change size every turn.

Why it matters. Making the pump and the roll motors follow the speed, not the late readings, saves most of the sheet a speed change would waste.

THREE WAYS TO READ THIS CHAPTER

Explore	13 min	the first page, the two histories in Section 5.2, the try-its and the facts of Section 5.6 and the key points
Study	60 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	20 min	the first page, the results (Section 5.6), Technology in Practice (Section 5.7), Limitations (Section 5.8) and the two open challenges

The control question A coating line sells the tension a web was wound at and its coat weight, and one change of line speed upsets both: the slot die thins the coating at once, and the winders must spin up rolls whose radius and inertia change every turn. Which part of the remedy belongs to feedforward and compensation, and which part can a trim on a late gauge still do?

Learning objectives

- Derive the coat weight, the pump capacity and the gauge delay of a pre-metered die from the flow, the width and the line speed.
- Compute the inertia of a winding roll and the torque, or dancer offset, that a speed ramp demands of it.
- Explain with a mass-on-a-spring model why a softer spliced web, not a stiffer one, destabilizes a hot tension trim.
- Show on the app what pump feedforward and inertia compensation each remove from the scrap of an order change.
- Judge which part of a predictive controller's advantage comes from its model of the pump lags and of a delay counted in meters.

Prerequisites Sections 1.4.3 (line speed as the throughput handle), 1.4.8 (disturbances passed along a line), 1.6.2 (velocity-form PID) and 1.6.4 (scenarios and data). Section 1.6.3 is needed only for the predictive controller.

The app https://apmonitor.com/apps/web-coating/

See also Volume 3, Chapter 6 for a feedforward from the cause with the feedback demoted to a slow trim, and Volume 3, Chapter 12 for the feedforward of a known, fading load. Volume 5, Chapter 5 for a product quality fixed on a moving ribbon long before its gauge reads it, and Volume 5, Chapter 6 for material tracked past a blind instrument.



5.1 Introduction

Paper, plastic film, metal foil and textiles are made and processed as webs, sheets so much longer than they are wide that they travel from one roll to another through the machinery that works on them. The tension in each span between driven rolls is held by the drives at its two ends, and tension control on paper-making and converting machinery, models of tension variation in pliable material and the decentralized control of whole processing lines each have a literature of their own [1–3]. Coating adds a liquid layer to the moving web. A slot die is a pre-metered coater, which lays down everything its pump delivers, so the wet film is the flow per unit width divided by the web speed [4, 5]. The same machine makes adhesive films and labels, and it makes the cathodes and anodes of lithium-ion cells [6, 7], where the dry coat weight sets the capacity per unit area.

Both properties of the coated roll are ratios with the line speed in them, which is exactly what a block diagram with constant gains hides. At steady speed a winder's tension is its torque divided by its radius, the radius of the simulated unwind falls from 300 mm toward a 76 mm core, and any torque that accelerates the roll must also spin up an inertia that grows with the fourth power of that radius. The coat weight made at the die is the pump's flow divided by the width and the speed. On the simulated film line, raising the speed from 120 to 180 m/min with the pump flow held makes the coating 33 % thin at once, and the gauge 19 m downstream first sees it 7.07 s later. The same ramp swings the tension in the first span by +12.1 and −16.6 %, because the web itself has to accelerate a full unwind roll that behaves like 201 kg at its surface. The simulator corrects the belief that tension is a torque setting and coat weight a pump setting, each to be held by its own feedback loop. Both follow the speed through a known law, so the lasting remedies are feedforward and compensation, and feedback is left to trim what they miss. The coagulant dosing of Volume 3, Chapter 6 divides the work between a feedforward and a slow trim in the same way.

The class of problem reaches past coating. A winder is a plant whose gain and inertia change continuously and predictably while it runs. Models that carry the varying radius and inertia underlie the robust, parameter-varying and decentralized designs proposed for web lines [3, 8], and adaptive

proportional-integral (PI) tension control has been implemented on roll-to-roll lines [9]. A quality variable that is set upstream as a flow divided by a throughput and measured downstream inherits a transport delay equal to a distance divided by a speed, so its feedback loop changes character whenever the line changes speed. The control and optimization of coating lines are treated as a subject of their own in the coating literature [10], and even the choice of instrument that closes the tension loop, a dancer roll or a load cell, has been argued out on coating machinery [11].

However, the two halves of the problem are usually taught apart. Tension appears, if at all, as a mass on a spring, and coat weight as a first-order loop with a dead time of a given number of seconds. Neither view shows that one speed ramp disturbs both, that the same gauge is 9.49 s late at 120 m/min and 38.0 s late at 30 m/min, or that a torque-driven tension loop is easier to hold on a stiff web than on a soft one. This chapter traces one speed change along the two physical paths by which it reaches a coated roll, on a simulated line where feedforward from the speed, compensation of the changing radius and inertia, and feedback on a late gauge can each be switched off and priced in meters of scrap. The line speed is the throughput handle of the line in the sense of Section 1.4.3, and the pump and both winders follow it. The tension transport model, radius and inertia compensation, dancers, load cells and speed feedforward are all established practice.

Section 5.2 traces how tension and coat weight came to be controlled on converting lines. Section 5.3 states the model, a line with 24 states and a web map that carries every 5 cm of product to the rewind, in enough detail to rebuild it. Section 5.4 gives the speed master, the winder torques and the pump with their feedback trims, and an optional model predictive controller of the rewind torque and the pump [12]. Section 5.5 derives three reduced models and checks them against the full nonlinear engine: a third-order dancer loop that reproduces the dancer travel and the span tension through a ramp to within 0.7 mm and 0.1 N, a mass-on-a-spring model of the rewind that places the stability limit of the hot load-cell trim of case 4 at 0.80 times the stiffness of the film once the 5 ms control interval is counted, and a delay loop whose critical integral time of 6.4 s at 30 m/min the engine reproduces. Section 5.6 measures nine scenarios and a graded challenge, and sets the predictive controller against the loops case by case. Section 5.7 describes the real sensors, drives and controllers, Section 5.8 states the limitations and Section 5.9 concludes.

5.2 Tension and Coat Weight on Converting Lines

A web line is built from driven sections, and the draw between two of them, the difference of their surface speeds, is what stretches the web in between. An unwind held back by a brake needs a braking torque that falls as the roll runs down, because the torque that gives a fixed tension is proportional to the radius. Tension control on paper-making and converting machinery was being treated as an engineering subject in its own right by 1964 [1], and models of the tension variations in pliable material passing through production machinery followed [2].

Two instruments came to close the loop. A dancer roll rides in a loop of web on a weighted or air-loaded arm, so that its load sets the tension and its position reports the mismatch between the speeds on either side, while a load cell under an idler reads the tension directly. The first history segment follows the choice between them and the estimators that replace both.

> ⧖ HISTORY **1993: Dancer Roll or Load Cell**
>
> Whether paper machinery should close its tension loop on a dancer roll or on load cells was still a question in 1993. A study of that year answered it with a computer model of an existing off-machine coater that carried both systems, analyzed each for stability and dynamic response, and set the results beside measurements made on site [11]. A later answer drops the sensor. For a two-drum paper winder, two tension estimators were built from the unwinding and the rewinding variables, with the dynamics, the friction and the changing inertia taken into account, because load cells are expensive and need frequent maintenance and calibration. Through typical winder cycles the estimators gave stable and precise tension control without a load-cell loop [13].

The winders make the problem hard, because the radius and inertia of the rolls vary widely during winding and unwinding, which changes the plant within every roll [8]. The second history segment traces the designs that decouple tension from speed on such a plant, beyond the decentralized proportional-integral-derivative (PID) loops common in industry, and adaptive PI schemes were implemented for roll-to-roll manufacturing [9]. The structure simulated here, a speed master with torque-driven winders under decentralized PI trims, is the kind of industrial baseline those studies compare against.

> ⧖ HISTORY **2002 and 2007: Decoupling Tension From Speed**
>
> On a winding line, a web break or a fold is prevented by decoupling the web tension from the web velocity, and the wide variation of the rolls' radius and inertia changes the dynamics considerably while they wind. A 2002 study compared a robust controller that reduced the coupling between tension and velocity with the decentralized PID loops common in industry, gave it gains that vary with the radius, and combined it with smoothly scheduled controllers on an experimental winding system [8]. A 2007 design divided a whole processing line into tension zones, each set from its reference tension and from a master speed roller that fixes the transport speed, and tested its decentralized controller against an often-used industrial PI controller on a large experimental platform [3]. In a study of 2023, decentralized PID controllers were still the mainstream in the roll-to-roll industry [14].

Coating science followed a parallel path. A pre-metered coater applies everything it is fed, so its wet thickness is fixed by the flow and the speed, and what the flow in the bead must do is stay stable. The limiting flow of a pre-metered coating device was analyzed in 1976 [4], and the operating limits of slot die coating, from the low-flow limit to dynamic wetting failure and the highest coating speed for a given flow, have since been reviewed as a body of work [5]. Control and optimization of coating processes have a chapter of their own in an edited reference work on liquid film coating [10].

Battery electrodes gave the same machinery a new product. The web is an aluminum or copper current collector, the coating is a thick slurry of active material, and the coating window of such slurries in a slot die has been characterized [6]. Metrology for electrode slurry coating, including its integration into the line, has been reviewed [15], and electrode processing has been costed in enough detail to show that three processing changes, among them replacing the N-methylpyrrolidone solvent, could together lower the pack cost by 26.4 % [16]. Automotive cell production has turned these lines into a manufacturing concern at scale [7]. On an electrode line a coat weight a few percent light is capacity lost, and a torn foil stops the line for a rethread.

5.3 Model of the Coating Line

The simulated line carries a web 1.0 m wide from an unwind to a rewind through two spans. Span 1 runs 4 m from the unwind over a dancer to the coating roll, which is the speed master of the line and carries the slot die. Span 2 runs 24 m from the coating roll through a 15 m dryer that starts 2 m after the die, past the coat-weight gauge 19 m after the die, to the rewind. Two products run on it, a packaging film of polyethylene terephthalate (PET) 50 µm thick carrying a water-based adhesive, and a battery electrode of aluminum foil 15 µm thick carrying a cathode slurry of nickel manganese cobalt oxide (NMC) in N-methylpyrrolidone. The arrangement and every symbol used below are shown in Figure 5.1. The controlled (CV), manipulated (MV) and disturbance (DV) variables and the states are classified in Table 5.1.

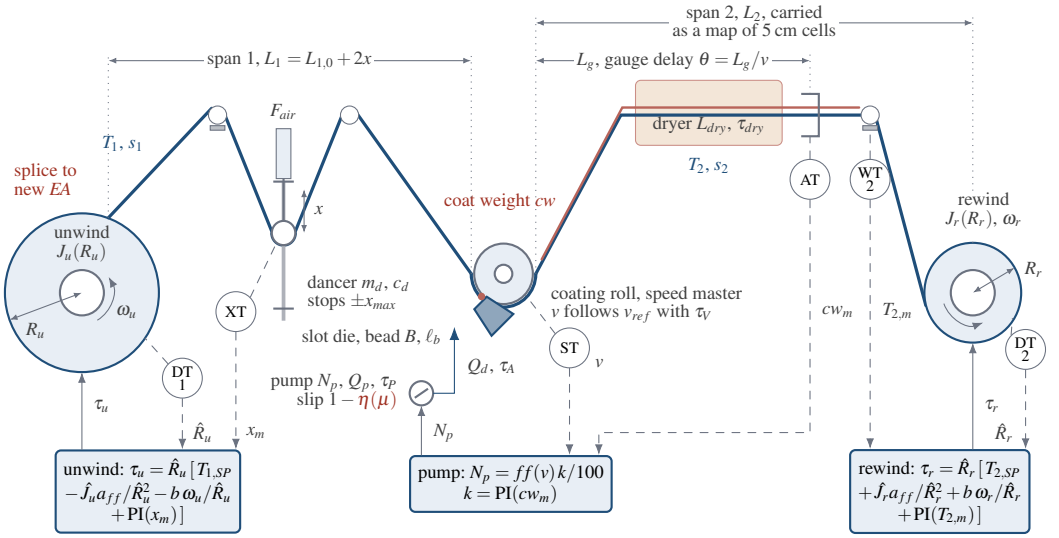


Figure 5.1 Roll-to-roll coating line as modeled. The unwind (R_u, J_u, ω_u) is held back by τ_u and can be spliced to a web of another EA. Span 1 (s_1, T_1) wraps a dancer of mass m_d and damping c_d under the air load F_{air}, whose travel x between stops at $\pm x_{max}$ makes the span $L_{1,0} + 2x$ long. The coating roll is the speed master at v, and its slot die, fed by a gear pump at speed N_p whose slip grows as the viscosity μ falls, holds a bead B of length ℓ_b on the web. Span 2 (s_2, T_2) carries the coat weight cw through the dryer to the gauge AT at L_g and the load cell WT2 and winds onto the rewind (R_r, J_r, ω_r) under τ_r. DT1 and DT2 are ultrasonic diameter sensors, XT the dancer sensor and ST the speed encoder, and the three controllers set τ_u, N_p and τ_r.

Table 5.1 Variables of the Film Line at Its Reset State

Symbol	Role	Nominal	Range
T_1	CV, span 1 tension, set by the dancer	200 N	SP 20–600
T_2	CV, span 2 tension, load cell	150 N	SP 20–600
cw_g	CV, dry coat weight at the gauge	12.0 g/m^2	SP 2–400
x	CV of the dancer loop, position	0 mm	±150
τ_u	MV, unwind holdback torque	59.87 N m	±120
τ_r	MV, rewind torque	18.33 N m	±120
N_p	MV, coating pump speed	52.91 %	0–100
v_{SP}	MV, line speed order	120 m/min	0–300
μ	DV, coating viscosity, % of recipe	100	25–300
f_{EA}	DV, next roll stiffness, $\times EA$	1.00	0.2–3
σ_g	DV, gauge noise (1σ), % of target	0.5	0–3
σ_{lc}	DV, load-cell noise (1σ)	1 N	0–10
—	DV, order, stop, restart, splice, batch	—	events
ω_u, R_u	states, unwind	6.661 rad/s, 300 mm	—
ω_r, R_r	states, rewind	16.663 rad/s, 120 mm	—
x, $\dot{x}$, F_{air}	states, dancer	0, 0, 400 N	—
s_1, s_2	states, span stretch	3.552, 15.989 mm	—
v, ξ	states, line speed, web coordinate	2 m/s, 0	—
Q_p, Q_d	states, pump and die flow	3.175, 3.048 L/min	—
B	state, bead per unit width	0.127 mm^2	—
—	states, three flags, six balances, drive energy	—	—

5.3.1 Rolls That Change Size

Each winder loses or gains one layer of web per turn, and its inertia grows with the fourth power of its radius, as shown in Equations (5.1) and (5.2).

$$\frac{\mathrm{d}R_u}{\mathrm{d}t} = -\frac{h\,\omega_u}{2\pi}, \qquad \frac{\mathrm{d}R_r}{\mathrm{d}t} = \frac{h_c\,\omega_r}{2\pi} \tag{5.1}$$

$$J(R) = J_{core} + \frac{\pi}{2}\,\rho\,W\left(R^4 - R_{core}^4\right) \tag{5.2}$$

where h is the web thickness, W the width, ρ the web density, J_{core} the inertia of the core, shaft and motor, and R_{core} the core radius. The rewind builds with the coated web, of thickness $h_c = h + cw_{SP}/\rho_{dry}$ and density $\rho_c = (\rho h + cw_{SP})/h_c$, which is 60.0 µm and 1358 kg/m^3 for the film. A full 300 mm film roll carries 18.11 kg m^2 against 0.50 kg m^2 for the empty core, and it behaves like $J/R^2 = 201$ kg at its surface, although the film on it weighs 368 kg. A full coil of foil carries 34.71 kg m^2, or 386 kg at its surface, and weighs 714 kg. The web leaves or arrives at the surface speed, so the angular momentum it carries is exactly $\omega\,\mathrm{d}J/\mathrm{d}t$ and the torque balances are written for $J\dot{\omega}$ rather than for $\mathrm{d}(J\omega)/\mathrm{d}t$, as shown in Equation (5.3).

$$J_u\dot{\omega}_u = T_1 R_u - \tau_u - b\,\omega_u, \qquad J_r\dot{\omega}_r = \tau_r - T_2 R_r - b\,\omega_r \tag{5.3}$$

where b is the bearing friction. At the unwind the web pulls the roll round and the motor holds it back, while at the rewind the motor drives and the web resists. At steady speed the holdback torque is $T_1 R_u - b\,\omega_u$, which is 59.87 N m for 200 N on the full film roll.

5.3.2 Spans and the Dancer

The state of each span is its stretch s_i, the path length minus the unstretched length of web in it. Conservation of the unstretched web gives Equation (5.4).

$$\begin{aligned} \dot{s}_1 &= 2\dot{x} + \frac{v}{1+\varepsilon_1} - v_0, \qquad \dot{s}_2 = \frac{v_2}{1+\varepsilon_2} - \frac{v}{1+\varepsilon_1} \\ T_i &= \begin{cases} \max[0,\ (s_i + \tau_w \dot{s}_i)/C_i] & s_i > 0 \\ 0 & s_i \le 0 \end{cases} \end{aligned} \tag{5.4}$$

where $v_0 = \omega_u R_u$ and $v_2 = \omega_r R_r$ are the surface speeds of the winders, v is the speed of the coating roll, C_i is the compliance of the span, the integral of $1/EA$ over the unstretched web in it, τ_w is a retardation time that lumps web, air and idler damping, and $\varepsilon_i = s_i/(C_i EA)$ is the strain of the web leaving span i, evaluated with the EA of the web at that roller. For one web, $C_i = (L_i - s_i)/EA$, and linearizing gives the standard transport equation $\dot{T}_i = (EA/L_i)(v_i - v_{i-1}) + (T_{i-1}v_{i-1} - T_i v_i)/L_i$. A negative stretch is slack web, which carries no tension and must be taken up before tension can build again. After a splice a span holds two webs, and the controller's record of the web supplies C_i as the sum of the two parts. The film has $EA = 225$ kN, so span 2 is a spring of $EA/L_2 = 9.4$ kN/m, and the foil has 1050 kN.

The web wraps the dancer twice, so the dancer lengthens span 1 by $2x$ and its air load balances twice the tension, as shown in Equation (5.5).

$$\begin{aligned} m_d\ddot{x} &= F_{air} - 2T_1 - c_d\dot{x}, \qquad |x| \le x_{max} \\ \tau_{air}\dot{F}_{air} &= 2T_{1,SP} - F_{air} \end{aligned} \tag{5.5}$$

At a stop the dancer lands inelastically. Its velocity is set to zero and held there while it is pushed into the stop, and any travel past the stop within one step is taken from the path, so the stretch loses twice the overshoot. On a stop, span 1 is a fixed length of web between two rolls turning at different speeds.

5.3.3 Coating Roll, Pump, Die and Bead

The coating roll is a stiff speed-regulated drive, and the web coordinate at the die, ξ, counts the unstretched web that has passed it, as shown in Equation (5.6).

$$\tau_V \dot{v} = v_{ref} - v, \qquad \dot{\xi} = \frac{v}{1+\varepsilon_1} \tag{5.6}$$

A gear pump follows its speed command through a lag, loses part of what it displaces to leakage past its gears, and feeds the die through a hose and manifold that act as a second lag, as shown in Equation (5.7).

$$\begin{gathered} \tau_P \dot{Q}_p = \frac{N_p}{100} Q_{max} - Q_p, \qquad \tau_A \dot{Q}_d = \eta\, Q_p - Q_d \\ \eta = 1 - \beta \frac{100}{\max(10,\ \mu)} \end{gathered} \tag{5.7}$$

where Q_p is the displaced flow, Q_d the flow leaving the die, β the slip at the recipe viscosity and μ the viscosity in percent of the recipe. A batch at half the viscosity therefore doubles the slip from 4 to 8 %. The die feeds a small bead between its lips and the web, and the moving web drags the bead away, as shown in Equation (5.8).

$$\frac{\mathrm{d}B}{\mathrm{d}t} = \frac{Q_d}{W} - \frac{v B}{\ell_b}, \qquad h_w = \frac{B}{\ell_b}, \qquad cw_{die} = \varphi\, \rho_{wet}\, h_w \tag{5.8}$$

where B is the bead volume per unit width, ℓ_b its length, h_w the wet film laid down, φ the solids fraction and ρ_{wet} the density of the wet coating. At steady state $h_w = Q_d/(Wv)$, the pre-metered law, which is 25.4 µm wet for 12 g/m^2 of adhesive and 124.2 µm for 200 g/m^2 of cathode. At a standstill the bead grows instead of dividing by zero, and above $h_{bead}\,\ell_b$ it spills. When the interlock lifts the die, its flow and the bead go to the drip tray. The bead time constant ℓ_b/v is 2.5 ms at 120 m/min, so the bead matters only near a standstill.

5.3.4 The Web Map and the Gauge

The controller keeps a record of the web in 5 cm cells indexed by ξ. Each cell carries the dry coat weight it received at the die, averaged over its length, the target it was coated to, the time it has spent in the dryer and a set of defect flags, and it keeps all of them until it is wound. The gauge reads the cell now under it, as shown in Equation (5.9).

$$\begin{gathered} cw_g(t) = cw_{die}\left(\xi(t) - L_g \frac{L_{u2}}{L_2}\right) \\ \theta = \frac{L_g\, L_{u2}}{L_2\, v} \approx \frac{L_g}{v} \end{gathered} \tag{5.9}$$

where $L_{u2} = L_2 - s_2$ is the unstretched web in span 2 and the argument is the coordinate of the cell at the gauge. The delay is 9.49 s at 120 m/min, 38.0 s at 30 m/min and 47.5 s for the foil at 24 m/min. It is fixed in meters, so a change of speed changes it at once, and during a ramp the gauge reads web that was coated at whatever speed it had when it passed the die. The coating-weight gauge of Volume 16, Chapter 10 stands far downstream of its air knives, and its delay moves with the line speed in the same way.

A cell is scrapped at the rewind if it carries a flag, if its coat weight is more than 3 % from the target it was coated to, or if its residual solvent $[(1-\varphi)/\varphi]\exp(-t_{dry}/\tau_{dry})$ exceeds 1 % of the dry coat. A tension excursion beyond ±10 % of its setpoint flags every cell in that span at that instant, because the tension in a span is uniform and all of that web lived through it. Wrinkles below 40 % of the setpoint, a spill, a break, bare web and the half meter on either side of a splice are flagged the same way. The dryer never limits the scenarios, because a film cell needs 2.88 s and a foil cell 11.27 s in the 15 m dryer, which caps the film at 312 m/min and the foil at 80 m/min.

Table 5.2 Line Parameters. Hidden Constants Are Never Displayed, and All Others Can Be Changed in the Model Panel.

Symbol	Meaning	Value	Class
W	web width	1.0 m	adjustable
E/E_0	web stiffness, times the product's	1.00	adjustable
$L_{1,0}$	span 1 path, dancer centered	4 m	adjustable
L_2	span 2 path, coating roll to rewind	24 m	adjustable
L_g	coating roll to gauge	19 m	adjustable
—	coating roll to dryer entry	2 m	hidden
L_{dry}	dryer length	15 m	adjustable
R_{core}	core radius	76 mm	hidden
J_{core}	core, shaft and motor inertia	0.50 kg m^2	adjustable
—	rewind radius at transfer	350 mm	adjustable
b	bearing friction	0.02 N m s	adjustable
τ_{max}	winder torque limit	120 N m	adjustable
τ_V	coating roll speed response	50 ms	adjustable
—	emergency stop deceleration	60 m/min per s	adjustable
—	coating roll radius, inertia (drive power only)	100 mm, 0.5 kg m^2	hidden
m_d, c_d	dancer mass, damping	8 kg, 1000 N s/m	adjustable
x_{max}	dancer travel to each stop	150 mm	adjustable
τ_{air}	dancer loading regulator lag	0.5 s	adjustable
τ_w	span retardation time	5 ms	adjustable
Q_{max}	pump displacement at full speed	6.0 L/min	adjustable
β	pump slip at recipe viscosity	4 %	adjustable
τ_P, τ_A	pump lag, hose and manifold lag	0.3, 0.5 s	adjustable
ℓ_b	coating bead length	5 mm	adjustable
h_{bead}	bead height before it spills	300 µm	adjustable
v_{min}	coating interlock speed	5 m/min	adjustable
—	tension, coat weight bands	±10, ±3 %	adjustable
—	wrinkle threshold, solvent limit	40, 1 %	adjustable

5.3.5 Breaks, Splices and Instruments

The web breaks when either tension exceeds T_{break}, and the line then stops at 60 m/min per s with the pump off. A splice replaces the unwind with a full roll at the same surface speed, either on command or when the unwind is within 5 mm of its core, and it can bring a web whose EA is the product's times the next-roll factor. The rewind transfers to an empty core at 350 mm. The load cells add first-order-filtered Gaussian noise of σ_{lc} with a 20 ms correlation time, the dancer sensor 0.2 mm with 20 ms, and the ultrasonic diameter sensors 0.3 mm with 0.1 s before a 1 s average. The gauge adds noise of σ_g times the target with a 0.5 s correlation time and averages through a 1 s lag. The line speed and the roll speeds come from encoders without noise.

5.3.6 Initialization and Numerics

Table 5.2 gathers the line's constants and Table 5.3 the two recipes. Every scenario opens on the recipe's steady state. The stretch of each span is $s_i = T_{i,SP}L_i/(EA + T_{i,SP})$, the winders turn at $v_0 = v/(1+\varepsilon_1)$ and $v_2 = v(1+\varepsilon_2)/(1+\varepsilon_1)$, the die flow is Wvh_w, the pump flow Wvh_w/η and the bead $h_w\ell_b$, and the unwind is full at 300 mm while the rewind holds 120 mm unless the scenario sets either. The web map is filled with coated web at the target from the rewind to the die and with bare web from the die to the unwind. The application checks that the derivatives of the eleven winder, dancer, span, drive and coating states are below 10^{-9} there, leaving only the two radii, the web coordinate and the running balances in motion. The equations advance in fixed 1 ms steps of fourth-order Runge-Kutta integration, the loops act on a 5 ms cycle, and a historian samples the line at 20 Hz. Halving the physics step while retaining the control interval gives the same splice break

Table 5.3 The Two Products. A Product Is Loaded With Its Recipe on a Freshly Threaded Line.

Quantity	Packaging film	Battery electrode
web, coating	50 µm PET, adhesive	15 µm Al, NMC cathode
E, ρ	4.5 GPa, 1390 kg/m^3	70 GPa, 2700 kg/m^3
full roll radius	300 mm	300 mm
$T_{1,SP}$, $T_{2,SP}$	200, 150 N	120, 100 N
T_{break}	800 N	360 N
cw_{SP}	12 g/m^2	200 g/m^2
φ, ρ_{wet}, ρ_{dry}	0.45, 1050, 1200 kg/m^3	0.70, 2300, 2400 kg/m^3
τ_{dry}	0.6 s	3.0 s
line speed	120 m/min	24 m/min
trim integral time	6 s	30 s

time of 37.848 s to 1 ms precision. Seeding, replay and the playback speed, here 0.5× to 20×, work as Section 1.6.1 describes.

5.3.7 Assumptions

Each span is one spring with uniform tension. A tension wave crosses the 24 m span in 13 ms in the PET and 5 ms in the foil, at wave speeds $\sqrt{E/\rho}$ of 1.8 and 5.1 km/s, which is far faster than anything the controllers do. The idealization leaves out the drag and inertia of the idlers in a long dryer.

Span damping is a retardation time. Writing it as $\tau_w \dot{s}_i / C_i$ makes the damping proportional to the stiffness, and Section 5.5 shows that this proportionality sets the stability limit of the load-cell trim. Damping from air and idler bearings need not scale with the web.

The web never slips, the drives are ideal and the rolls are rigid. The web leaves each roller with the strain it had in the span before it, although a driven roller slips once the tension ratio across it exceeds its capstan limit. The winders are torque drives with ultrasonic diameter sensors and the coating roll a stiff speed master. Wound-in tension, telescoping, crushed cores and taper tension are absent, and the rewind builds one coated thickness per turn.

The coating is pre-metered through one bead. The coat weight follows $Q/(Wv)$ at every speed, so ribbing, air entrainment, bead break-up and the low-flow limit that bound a real slot die never occur [4–6].

Viscosity acts only through pump slip. In a real die circuit the discharge pressure also scales with viscosity, so the viscosity slider stands for any unmeasured change in the delivered flow.

The dryer is one time constant and the gauge sees dry solids only. Residual solvent is scored at the rewind but never reaches the gauge reading.

The break and wrinkle limits are illustrative. They are four and three times the span 1 setpoint for the film and the foil, and 40 % of setpoint, because real webs let go at edge nicks, pinholes and weak splices far below their intact strength.

5.4 Implemented Controllers

Every loop reads a measurement rather than the true state, runs every 5 ms, and is configured as listed in Table 5.4.

5.4.1 Discrete Algorithm

All three loops run the shared velocity-form PID routine of Section 1.6.2, Equations (1.11) to (1.14), with the tracking time $T_t = \tau_I$. Two details are particular to this line. In the winder loops the output bias u_b is not a constant. It carries the feedforward of Equation (5.11) below and is updated at every execution, so the trims add to a feedforward that moves with the radius and the acceleration. The coat-weight trim instead multiplies the pump feedforward of Equation (5.12). The derivative time is zero in all three loops and none has a rate limit, because the drives, the pump and the hose already

Table 5.4 The Three Feedback Loops. Each PI Works in the Units of Its Feedforward, and Each Executes Every 5 ms.

Loop	CV	MV	K_c	τ_I
dancer	x_m, SP 0	$\tau_u/\hat{R}_u$	0.4 N/mm	5 s
load cell	$T_{2,m}$	$\tau_r/\hat{R}_r$	0.5 N/N	2 s
coat weight	$100\,cw_m/cw_{SP}$	trim k	0.3 %/%	6 or 30 s

A long span raises the holdback, a low tension raises the winding torque and a light coat raises the trim. The winder outputs are limited to $\pm\tau_{max}/\hat{R}$, which is ±120 N m of torque. The trim is limited to 50 to 150 %, with its upper limit lowered to $10^4/ff$ whenever that keeps N_p at or below 100 %.

supply the lags. In manual all three PIs track the operator's output, so the return to automatic is bumpless.

5.4.2 Speed Master

The line speed follows a ramped reference, and the acceleration handed to the winders is that ramp passed through the drive's own response, as shown in Equation (5.10).

$$\begin{aligned} v_{ref,k} &= v_{ref,k-1} + \mathrm{clamp}\left(v_{tgt} - v_{ref,k-1},\ \pm a\Delta t\right) \\ a_{ref,k} &= \left(v_{ref,k} - v_{ref,k-1}\right)/\Delta t \\ a_{ff,k} &= a_{ref,k}\left(1 - \mathrm{e}^{-\Delta t/\tau_V}\right) + a_{ff,k-1}\,\mathrm{e}^{-\Delta t/\tau_V} \end{aligned} \tag{5.10}$$

where the ramp rate a defaults to 6 m/min per s and the target v_{tgt} is the order v_{SP}. With the capacity limit on, $v_{tgt} = \min(v_{SP},\ 0.95\,\eta_{nom}Q_{max}/(Wh_{w,SP}))$, which is 215.5 m/min for the film and 44.1 m/min for the foil at the nominal slip. The filter matters. Fed the raw ramp acceleration instead, in a test made for this chapter with a wrapper around the unchanged controller, the suggested configuration of the challenge swings span 2 from −27.5 to +22.1 % and scraps 26.50 m instead of 2.55 m, because the feedforward torque then arrives about 50 ms before the line accelerates and excites the lightly damped rewind on its span.

5.4.3 Winder Torques

Both winders apply a feedforward torque from the tension setpoint, the estimated radius and the planned acceleration, trimmed by a PI in tension units, as shown in Equation (5.11).

$$\begin{aligned} \tau_u &= \hat{R}_u\left[T_{1,SP} - \frac{\hat{J}_u a_{ff}}{\hat{R}_u^2} - \frac{b\,\omega_u}{\hat{R}_u} + \mathrm{PI}_u(x_m)\right] \\ \tau_r &= \hat{R}_r\left[T_{2,SP} + \frac{\hat{J}_r a_{ff}}{\hat{R}_r^2} + \frac{b\,\omega_r}{\hat{R}_r} + \mathrm{PI}_r(e_r)\right] \end{aligned} \tag{5.11}$$

where $\hat{J} = J(\hat{R})$ from Equation (5.2), $e_r = T_{2,SP} - T_{2,m}$, and the bracketed feedforward enters each PI as its bias. Because the trims work in newtons and are multiplied by the radius, their gains need no rescaling as a roll grows or empties. The unwind's PI keeps the dancer mid-stroke, since the air load already sets the tension, and the rewind's PI corrects the tension read by its load cell. Multiplying by $\hat{R}$ is radius compensation. The *fixed torque* option replaces $\hat{R}$ by the radius at the moment it is selected, and the load-cell trim can be switched off, leaving the rewind on its feedforward alone. Inertia compensation is the $\hat{J}a_{ff}$ term and can also be switched off.

The radius comes from an ultrasonic diameter sensor on each winder, preset from the new roll at a splice or a transfer. A radius estimated instead from the ratio of line speed to unwind speed would read $R_u(1 - 2\dot{x}/v_0)$ on this line, because the web leaving the unwind moves at $v + 2\dot{x}$ while the dancer travels. Section 5.5 shows that this error feeds the dancer's motion back into the holdback torque with a destabilizing sign.

5.4.4 Coat Weight

The pump speed is a feedforward from the measured line speed times a trim, a ratio of pump to line speed, as shown in Equation (5.12).

$$\begin{aligned} N_p &= \frac{ff\,k}{100}, \qquad k = \mathrm{PI}_{cw}\left(\frac{100\,cw_m}{cw_{SP}}\right) \\ ff &= \frac{100\,W\,v\,h_{w,SP}}{\eta_{nom}\,Q_{max}} \end{aligned} \tag{5.12}$$

where $h_{w,SP} = cw_{SP}/(\varphi\rho_{wet})$ and $\eta_{nom} = 0.96$ is the efficiency at the recipe viscosity. The feedforward knows the recipe and nothing about the coating actually in the pump. With the speed feedforward switched off, ff is held at its last value. The trim's upper limit moves with the feedforward so that N_p never asks for more than 100 %, which keeps the integral from winding up while the pump is saturated.

Below $v_{min} = 5\,\mathrm{m/min}$ the coating interlock lifts the die, stops the pump and makes the trim track its held value, and on the restart it holds the trim until web coated 2 m after the die re-engaged reaches the gauge. With the interlock off, the die stays on the web whatever the speed. After a break the winders brake their rolls to rest in about 0.5 s and the pump stops. In manual the operator sets τ_u, τ_r and N_p and all three PIs track.

5.4.5 Simulation, Control and Controller Models

Equations (5.1) to (5.9), evaluated with the true radii, strains, splices and viscosity, form the simulation model. The loops' internal model is the feedforward of Equations (5.10) to (5.12), which uses the sensed radii, the recipe density and slip, and the drive's 50 ms response, and never the true viscosity or the true EA of a spliced web. The control models of Section 5.5 are linearizations made for analysis, and the application does not identify or use them. The predictive controller of Section 5.4.6 carries a model of its own.

5.4.6 Model Predictive Control of the Rewind and the Pump

A structure switch hands the rewind torque and the coating pump either to the loops above or to a model predictive controller (MPC), set up in the general form of Section 1.6.3. The loops stay the default everywhere except in case 9. In automatic the MPC decides the force the rewind torque puts on the web, $F = \tau_r/\hat{R}_r$, and the pump speed N_p together every $T_s = 0.05\,\mathrm{s}$, which is ten control intervals. Its horizon of $N = 60$ steps (3 s) is cut into eight move blocks of 1, 1, 2, 3, 5, 8, 13 and 27 steps, so each quadratic program carries 16 moves and one slack, and each plan's opening move stands until the next plan [12]. The unwind, the dancer and the speed master keep their loops. Horizons of 1.5 and 6 s leave the scrap of case 9, case 2 and the challenge unchanged, and so does 5 s ($N = 100$), at a mean of 228 µs a plan in Node against 148 µs for 3 s in the same run on a shared host.

The controller's model is written from Equations (5.3) to (5.8) with the declared parameter defaults and the recipe, frozen when the application loads, and never with the run's parameters. Its states are the coating roll speed v_1, the rewind surface speed relative to that roll z, the span 2 stretch s_2, and the pump and die flows q_p and q_d in percent of Q_{max}, as shown in Equation (5.13).

$$\begin{aligned} \tau_V\dot{v}_1 &= v_{ref} - v_1, \qquad \hat{T}_2 = ks_2 + cz \\ \hat{m}\dot{z} &= F + d - \hat{T}_2 - \frac{b}{\hat{R}_r^2}(v_1 + z) - \delta_J\hat{m}\dot{v}_1 \\ \dot{s}_2 &= \left(1 - \frac{T_{2,SP}}{EA}\right)z - \frac{\bar{v}}{L_2}s_2 \\ &\quad + \frac{T_{1,SP} - T_{2,SP}}{EA}v_1 + \frac{\bar{v}\,T_{2,SP}}{EA} \\ \tau_P\dot{q}_p &= N_p - q_p, \qquad \tau_A\dot{q}_d = q_p - q_d \end{aligned} \tag{5.13}$$

where $\hat{m} = J(\hat{R}_r)/\hat{R}_r^2$ from Equation (5.2) with the coated density, $k = EA/L_2$, $c = \tau_w k$, $\bar{v}$ is the measured speed at which the transport term is linearized, d is an estimated force on the rewind, and δ_J is 0 with inertia compensation on and 1 with it off. On the film $\hat{m}$ is 60.5 kg at 120 mm, k is 9375 N/m and c is 46.9 N s/m, so the rewind rings at 1.98 Hz with a damping ratio of 0.035 at 120 m/min, while on the foil $\hat{m}$ is 81.1 kg and k is 43 750 N/m. The model is discretized exactly with a zero-order hold at T_s and rebuilt when the measured radius has moved 1 % or the speed 10 %. Against steps of ± 1 N m and ± 5 % of pump on the engine, with the noise off, on the film at 120 and 30 m/min and the foil at 24 m/min, it leaves 1.5 to 8.7 % of the rms span 2 response and 0.12 to 0.58 % of the die's unexplained. The preview $v_{ref,i}$ at step i is the speed master's own ramp from its present reference to its target at the ordered rate, taken at the middle of each step. With the preview off the present reference is held.

Two estimators run every 5 ms under either structure, so a switch to the MPC starts warm. A steady-state Kalman filter on $[z, s_2, d]$ reads the load cell with a design variance of 1 N^2 and lets d drift as a random walk of 1×10^{-5} N^2 per scan, the integrating disturbance that removes offset under a mismatched model [17]. It estimates 63 % of an unmodeled 1 N force in 1.635 s on the film and 1.620 s on the foil. That variance is the fastest of the four tried, 4×10^{-4} to 4×10^{-6}, that held a splice to every next-roll stiffness from 0.2 to 3 times the product's, while 4×10^{-5} let span 2 swing from -67 to +71 % on the softest web and 4×10^{-4} broke it. Kalman filtering of the tension sensor, combined with a disturbance observer, has improved tension control on an industrial roll-to-roll system [18]. With the load-cell trim switched off the load cell counts as out of service and the filter runs on its model alone.

The coat weight is estimated across the delay. The controller integrates the encoder speed into a web odometer $\hat{\xi}$, records the coat weight its model laid at the die on every 2 cm of web, and reads that record $L_g = 19$ m back through the gauge's 1 s average. The ratio of the gauge reading to this model estimates the gain $g = \eta/\eta_{nom}$ of Equation (5.20), the pump efficiency relative to the recipe's, as shown in Equation (5.14).

$$\tau_g \dot{\widehat{cw}}_g = \widehat{cw}_{die}(\hat{\xi} - L_g) - \widehat{cw}_g, \qquad \tau_{est}\dot{\hat{g}} = \frac{cw_m}{\widehat{cw}_g} - \hat{g} \tag{5.14}$$

where $\widehat{cw}_{die} = \varphi \rho_{wet} \eta_{nom} Q_{max} q_d/(100 W v_1)$ is the model's coat weight at the die, cw_m the gauge reading and $\tau_{est} = 10$ s. The estimate $\hat{g}$ is clamped to 0.5 to 2 and held while the interlock holds the trim, while the line runs below v_{min} or the web under the gauge was coated with the die lifted or below it, and after a break. Because the delay is counted in meters it follows the speed at every speed and stops with the line. Through pump steps the model knows, $\hat{g}$ stays within 0.07 % of 1 at 10, 30 and 120 m/min, where the gauge read against what the die lays at the same instant would be up to 15.8 % off, and within 0.0101 % through the stop and restart of case 8, during which the odometer does not move. Delays defined implicitly by an integral of a transport rate, as this one is, have been treated with prediction-based feedback where the rate is itself the control input [19]. The plan predicts the die, because the web between the die and the gauge is already coated, and needs no chain of delay states, which at T_s would number 760 at 30 m/min.

The plan minimizes the objective of Equation (5.15).

$$\begin{aligned} J = &\sum_{i=1}^{N} \left[w_T\, e_{T,i}^2 + w_C\, e_{C,i}^2 \right] + \gamma_2\, \nu^2 + \gamma_1\, \nu \\ &+ \sum_j \left[\kappa_F \lambda_T\, \Delta F_j^2 + \kappa_P \lambda_P\, \Delta N_{p,j}^2 \right] \end{aligned} \tag{5.15}$$

where $e_{T,i} = 100(\hat{T}_{2,i} - T_{2,SP})/T_{2,SP}$ and $e_{C,i} = 100(q_{d,i} - q_i^*)/q_i^*$ are the tension and die-flow errors in percent at step i, $w_T = 1$ and $w_C = 4$ their weights, $\kappa_F = 0.2$ N^{-2} and $\kappa_P = 0.5$ per percent squared the prices of the moves at each block boundary j, $\lambda_T = \lambda_P = 1$ two price multipliers set on the app, and ν the slack of the soft tension limit. The die-flow target q_i^* is the pump feedforward of

Equation (5.12) at the predicted speed $v_{1,i}$ divided by $\hat{g}$ and capped at 100 %, with the weight's denominator floored at its value for v_{min}. The bounds $|F| \le \tau_{max}/\hat{R}_r$, the shipped trim's clamp, and $0 \le N_p \le 100\,\%$ are hard. The tension band of $\pm 10\,\%$ is soft, judged every third step with one slack over the whole horizon priced at $\gamma_2 = 10^3$ per percent squared and $\gamma_1 = 10^2$ per percent, and with a 0.5 s funnel where the free response already lies outside it. The weights were chosen once, on case 9, and are never retuned per case. With inertia compensation on, the shipped compensation stays beneath the plan at every 5 ms scan, so the applied torque is $\tau_r = \hat{R}_r F + \hat{J}_r a_{ff}/\hat{R}_r$ within $\pm\tau_{max}$. The coating interlock, the braking after a break and the dancer's stops act above the plan unchanged.

A plan is used only when its solver status reads optimal, every planned command lies inside its bounds with the first equal to the applied move, and the cost, the slack and every prediction converted to newtons and grams per square meter are finite. Otherwise the shipped trims take over, which under the MPC track the applied torque and the applied ratio of pump speed to feedforward at every scan. With the noise off a forced rejection moves the torque by at most 0.0007 N m and the pump by at most 0.06 % on the hand-over scan, except in the challenge as loaded, where the trim's 150 % limit on a feedforward frozen at the old speed moves the pump by 21.0 %. At ten captured decisions an independent condensation reproduces the solver's objective to a relative 2.4×10^{-12} with the optimality conditions met. In Chrome a plan costs 104 µs, from the difference in wall time between 300 s of case 9 under the MPC and under the loops, which is 0.21 % of one core in real time and 4.1 % at the 20× playback speed.

The simulation model, the instruments and the controller's model stay apart. The plant integrates Equations (5.1) to (5.9) with the true radii, strains, splices and viscosity. The MPC reads only the encoder, the rewind's diameter sensor, the noisy load cell, the noisy averaged gauge, its own applied commands, the interlock and break signals, the setpoints and the declared constants. A replay of the same measurements over a different hidden plant reproduces its commands bit for bit, and the application's tests catch each of 25 copies of the controller doctored to read one true quantity or run parameter or to keep its state outside the engine.

5.5 Three Reduced Models

5.5.1 The Dancer Through a Ramp

With $F_{air} = 2T_{1,SP}$, Equation (5.5) says exactly what span 1 tension does while the dancer moves, as shown in Equation (5.16).

$$T_1 - T_{1,SP} = -\tfrac{1}{2}\left(c_d \dot{x} + m_d \ddot{x}\right) \tag{5.16}$$

The dancer holds the tension only while it is still. In the ramp of case 2 the identity holds in the engine to 0.004 N. Span 1 is so stiff, 56 kN/m for the film, that its strain barely changes, so the unwind surface moves at $v_0 = v + 2\dot{x}$. Substituting into the unwind balance of Equation (5.3) with the torque of Equation (5.11), the sensed radius equal to the true one and the friction canceled by its feedforward, gives a third-order loop driven by the line acceleration, as shown in Equation (5.17).

$$\begin{aligned} &\left(2m_u + \tfrac{1}{2}m_d\right)\ddot{x} + \tfrac{1}{2}c_d\dot{x} + K_c x \\ &\qquad + \frac{K_c}{\tau_I}\int x\,dt = -m_u\left(\dot{v} - \hat{a}\right) \end{aligned} \tag{5.17}$$

where $m_u = J_u/R_u^2$ is the roll's equivalent mass at its surface and $\hat{a}$ the compensated acceleration, a_{ff} with inertia compensation and zero without it. For the full film roll, $m_u = 201$ kg and the roots are $-0.272\ \mathrm{s}^{-1}$ and $-0.479 \pm 0.703\,j\ \mathrm{s}^{-1}$, a damped oscillation of 8.9 s period. Without compensation the proportional term alone would need a dancer offset of $m_u a/K_c$ to supply the accelerating torque, 101 mm for the film at 12 m/min per s against stops at 150 mm, and the integral removes it only over several seconds. Driven by the case 2 ramp, Equation (5.17) gives a dancer swing from −93.1 to +76.2 mm and a span 1 tension from 224.1 down to 166.7 N at 11.16 s and 16.06 s, while the engine with its noise switched off gives −92.8 to +75.5 mm and 224.1 to 166.8 N at the same instants. For

the full coil of foil, $m_u = 386\,\text{kg}$, and the challenge ramp gives -115.0 to $+85.5\,\text{mm}$ and 86.0 to 177.6 N against the engine's -115.1 to $+85.7\,\text{mm}$ and 85.9 to 177.7 N.

The same model prices the speed-ratio radius estimate. With $\hat{R}_u = R_u(1 - 2\dot{x}/v_0)$ the holdback, in tension units, changes by $-2T_{1,SP}\dot{x}/v_0$, and the damping of Equation (5.17) becomes $c_d/2 - 2T_{1,SP}/v_0$. That is +300 N s/m for the film at 120 m/min, but −100 N s/m for the foil at 24 m/min and −300 N s/m for the film at 30 m/min, where the model's roots move to $0.155 \pm 0.740\,j$ and $0.455 \pm 0.966\,j\ \text{s}^{-1}$. In a test made for this chapter with a wrapper that replaces the unwind radius estimate by the ratio and leaves the controller otherwise unchanged, the foil line running steadily at 24 m/min loses its dancer, whose swing roughly doubles every 5 s until the foil breaks at 56.9 s, and the film line at 30 m/min breaks at 14.45 s. The error grows as the speed falls, which is why the application measures the diameter.

5.5.2 The Rewind on Its Span

Span 2 is a spring between the coating roll, which holds its speed, and the rewind, which has an equivalent mass $m_r = J_r/R_r^2$ of 61 kg at 128 mm. The load-cell trim acts on the tension that the spring itself applies to that mass. Linearized with the feedback delayed by T_d, Equations (5.3), (5.4) and (5.11) give the characteristic equation of Equation (5.18).

$$m_r s^2(s+\alpha) + (k+cs)\left[s + K_c\left(s + \frac{1}{\tau_I}\right)\mathrm{e}^{-sT_d}\right] = 0 \tag{5.18}$$

where $k = EA/L_2$, $c = \tau_w k$ and $\alpha = v/L_2$ is the transport term. The first term in the bracket is the tension acting on the roll directly, and the proportional trim adds K_c times as much again, so the oscillation has a period near $2\pi\sqrt{m_r/[(1+K_c)k]}$. With $T_d = 0$ and a small α, the Routh criterion gives Equation (5.19).

$$\tau_I > \frac{m_r K_c}{(1+K_c)^2\,\tau_w k} \tag{5.19}$$

The span's damping is itself proportional to its stiffness, so the stabilizing side of the Routh condition grows with the square of the stiffness and the destabilizing side only with the stiffness, and the shortest usable integral time is inversely proportional to the stiffness of the web. For the hot trim of case 4, $K_c = 1$ and $\tau_I = 0.5\,\text{s}$, Equation (5.19) with the transport term restored gives a critical integral time of 0.30 s on the PET and 0.91 s on the web of 0.3 times its stiffness. The PET is held and the softer web is not, and a splice to a stiffer web moves the loop away from instability rather than toward it.

🕮 **Pause.** Try Exercise 5.2 before reading on.

The 5 ms control interval is not negligible here. The oscillation is so lightly damped, at a damping ratio of 0.018 on the PET without delay, that the half-sample delay of the zero-order hold, $T_d = 2.5\,\text{ms}$, removes a large share of the margin. The growth rates measured on the engine after a 10 N setpoint step, with the load-cell noise off, fall on the delayed model and not on the continuous one, as shown in Figure 5.2. At 0.3 times the PET stiffness the oscillation grows at $0.285\ \text{s}^{-1}$ with a 0.651 s period against $0.282\ \text{s}^{-1}$ and 0.652 s predicted, and on the PET it decays at $0.114\ \text{s}^{-1}$ against $0.117\ \text{s}^{-1}$. The stability limit of the hot trim is 0.80 times the PET stiffness with the delay and 0.59 without it.

5.5.3 The Coat-Weight Trim and Its Delay

From the trim k to the gauge reading in percent of target the plant is a gain $g = \eta/\eta_{nom}$ behind the transport delay and four small lags, as shown in Equation (5.20).

$$G(s) = \frac{g\,\mathrm{e}^{-\theta s}}{(\tau_P s+1)(\tau_A s+1)(\tau_g s+1)(\ell_b s/v+1)} \tag{5.20}$$

where $\tau_g = 1\,\text{s}$ is the gauge average and $g = 0.958$ after a thin batch. With that gain and the film recipe trim, $K_c = 0.3$ and $\tau_I = 6\,\text{s}$, the loop has a gain margin of 2.87 at 120 m/min, where $\theta = 9.49\,\text{s}$,

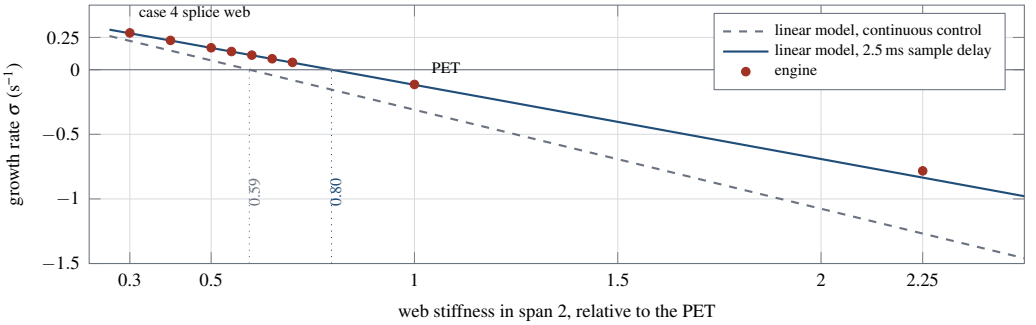


Figure 5.2 Growth rate of the rewind tension oscillation under the hot load-cell trim ($K_c = 1$, $\tau_I = 0.5$ s) against the stiffness of the web in span 2. The lines are Equation (5.18) at $R_r = 128$ mm without the half-sample delay (dashed) and with it (solid), and the dots are the engine's envelope after a 10 N setpoint step at 27 s of case 4. The dotted verticals mark the two stability limits, 0.59 and 0.80.

and of 0.93 at 30 m/min, where $\theta = 37.97$ s, with a crossover period of 135.7 s. The critical integral time at 30 m/min is 6.40 s. The engine agrees. Swept with the gauge noise off, its oscillation after the thin batch grows at 1.56×10^{-3} s^{-1} for $\tau_I = 6$ s against 1.52×10^{-3} s^{-1} predicted, is neutral at 6.4 s, and decays at 2.12×10^{-3} s^{-1} for 7 s against 2.17×10^{-3} s^{-1}. The rule of thumb for integral action on a pure delay, $K_c\theta/\tau_I < \pi/2$, gives 1.90 at 30 m/min and 0.47 at 120 m/min, which is on the conservative side of the same limit.

The recipe trims follow a standard rule. For a pure delay the simple internal model control (SIMC) rule asks for integral action with $K_i = 1/[g(\tau_c + \theta)]$, and with $\tau_c = \theta$ and $K_c = 0.3$ that is an integral time of $0.6\,g\,\theta$ [20]. With $g = 1$ this gives 5.7 s for the film at 120 m/min, against the recipe's 6 s, and 28.5 s for the foil at 24 m/min, against 30 s. At 30 m/min the same rule asks for 22.8 s, close to the 25 s that case 6 offers as its fix. Each recipe trim is right at one speed only, because the delay it faces is a distance. The SIMC integral time is proportional to $\theta \approx L_g/v$, so an integral time scheduled on the line speed would keep about the same margin at every speed. The basis weight loops of Chapter 3 face the same accounting, with a scanning gauge whose averaging adds to the transport delay.

5.6 Scenarios and Measured Results

The ten cases of Table 5.5 were run on the engine at the default seed 20261023. Settings for each comparison were made before Run, as a reader makes them on the app (Section 1.6.4), with scheduled events applied at their nominal boundary. The case 1 order was fired at 60 s. Deviations are those of the true tensions and of the true coat weight under the gauge, as the scorecard reports them, and scrap is counted in 5 cm cells and quoted to 0.05 m. Table 5.6 collects the results of cases 1 to 8 and Table 5.7 the challenge. Section 5.6.7 compares the predictive controller with the loops on case 9 and the others.

5.6.1 A Steady Line and a Ramp With Feedforward

Over 120 s of case 1 the span 1 tension holds 200 N to 0.047 N rms, because the dancer's air load sets it, while span 2 holds 150 N to 0.78 N rms as its trim answers load-cell noise of 1 N. The true coat weight at the gauge stays within 0.30 % of target and the line makes 7195 m^2 of good product an hour. An order of +50 % placed after a minute moves span 1 by less than 0.2 N and the dancer by less than 0.5 mm with both feedforwards on. The coating still dips 3.60 % at the die during the 10 s ramp at 6 m/min per s, because the pump and hose lag the speed by their $\tau_P + \tau_A = 0.8$ s, and that scraps 10.65 m. At 60 m/min per s the dip is 21.5 % deep but lasts about a second, and it scraps 10.30 m. The shallow dip sits only a few tenths of a percent past the band, so its scrap depends on

Table 5.5 The Ten Cases, in Teaching Order

#	Scenario	Teaching point
1	Steady coating, film at 120 m/min	the reference line
2	Speed ramp, both feedforwards off, to 180 m/min at 10 s	one speed, two paths
3	Rewind from 80 mm at 210 m/min on fixed torque, trim off	$T = \tau/R$
4	Splice at 10 s to a web of 0.3 times the stiffness, hot trim	the span is a spring
5	Electrode at 24 m/min, half viscosity at 20 s	a change behind a delay
6	Film at 30 m/min, thinner batch at 10 s	a delay fixed in meters
7	Order of 240 m/min at 10 s	a capacity limit
8	Stop at 15 s, restart at 45 s	standstill logic
9	Film at 30 m/min, thinner batch at 10 s, order of 120 m/min at 150 s, MPC	a plan against the loops
10	Challenge, foil order 24 to 42 m/min at 20 s	the whole design

Table 5.6 Measured Results, Cases 1 to 8. Ramp Rates in m/min per s

Case and condition	Result
1, over 120 s	T_1 0.047, T_2 0.78 N rms, *cw* within 0.30 %
1, order +50 %, ramp 6 / 60	die dip 3.60 / 21.5 %, 10.65 / 10.30 m
2, as shipped	die 8.02 g/m^2, gauge 7.07 s later, 208.90 m
2, span 1 / span 2	+12.1, −16.6 / −9.6, +6.9 %
2, dancer	−93.0 to +75.7 mm
2, pump feedforward / both	22.30 / 12.80 m, span 1 within 0.2 N
3, fixed torque	122.0, 73.9, 60.3 N at 99, 163, 200 mm
3, fixed torque, 700 s	wrinkles 508.5 s, 2362.9 of 2447.8 m
3, $T \times R$ / fixed with trim	149.7–152.7 / 145.4–151.7 N
4, hot trim, soft web	breaks at 37.85 s
4, τ_I 2 s / default, soft	within 2.44 / 1.44 %
4, hot trim, 2.25 times as stiff	within 2.94 %
5, half viscosity	die 191.39 g/m^2, gauge 47.63 s later, 20.25 m
5, τ_I 15 / 60 s	20.15 / 20.35 m, peak 202.07 g/m^2
6, recipe trim	peaks at 13.11, reaches 10.81 g/m^2 at 600 s, 188.15 m
6, τ_I 25 s / K_c 0.1 / at 120	20.55 / 25.40 / 23.85 m
7, order 240 m/min	pump full at 223.1 m/min, 11.34 g/m^2, 644.5 m
7, capacity limit	held at 215.5 m/min, 22.05 m
8, interlock	die off 24.64 to 45.47 s, 4.52 mL, 20.60 m
8, no interlock	1.891 mL spilled, 141.75 g/m^2, 27.65 m

where the noise-driven trim happens to be when the order arrives. Placed at 0 s, 10 s or 30 s instead, the same order scraps 10.00, 9.20 and 17.45 m.

5.6.2 One Speed Change, Two Paths

Case 2 repeats the order at 12 m/min per s with the pump feedforward and inertia compensation off. The coating at the die falls 33.2 %, from 12.0 to 8.02 g/m^2, as soon as the ramp begins, because the fixed flow is spread over half as much web again. The gauge first sees it 7.07 s later, less than the 9.49 s of the steady line because the web accelerates on its way, and the slow trim is not back inside the band until 87.1 s. The order costs 208.90 m of scrap. At the same moment the full unwind has to be spun up through the web. Span 1 rises 12.1 % as the ramp starts and falls 16.6 % as it ends, the dancer travels from −93.0 to +75.7 mm, and span 2 swings from −9.6 to +6.9 % as the rewind lags and catches up. The screen 4 s into the ramp is shown in Figure 5.3. The pump feedforward alone cuts the scrap to 22.30 m, of which 16.35 m is web that lived through the span 1 excursion, and adding inertia compensation holds span 1 within 0.2 N and the dancer within 0.5 mm and leaves 12.80 m,

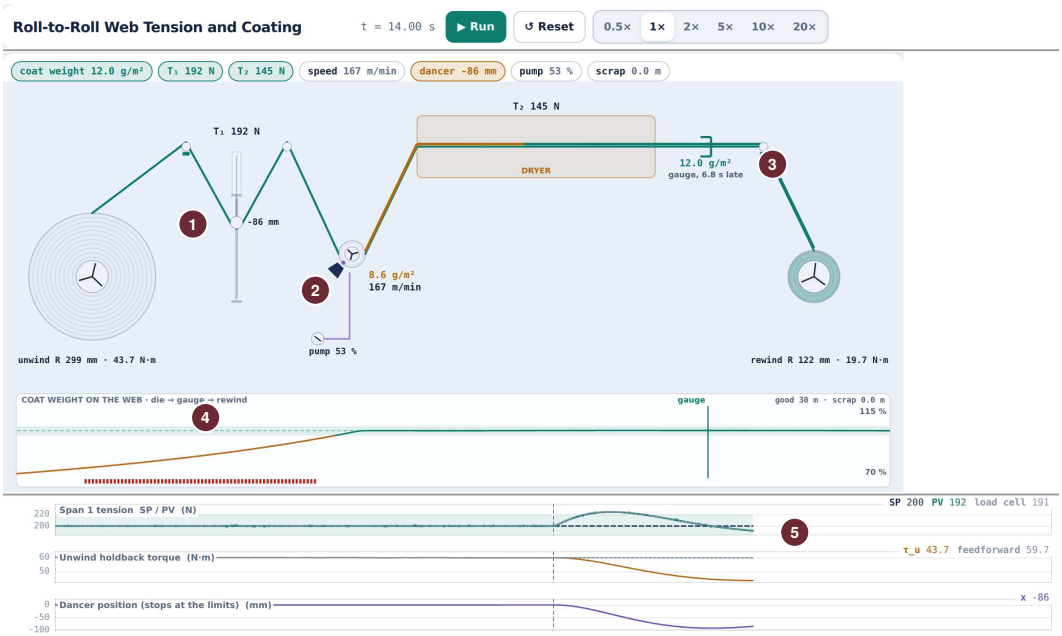


Figure 5.3 Case 2, "Speed ramp, feedforward off", paused at $t = 14.00$ s, 4 s into the ramp from 120 to 180 m/min at 12 m/min per s with the pump feedforward and inertia compensation off. The picture is a composite of the app's header, its plant view with the web map, and the first three of its trend strips. The side view shows the unwind at 299 mm and 43.7 N m, the dancer (1) 86 mm toward its short-span stop with a warning badge, span 1 at 192 N, span 2 at 145 N, the die (2) laying 8.6 g/m^2 in the warning color with the pump at 53 %, and the gauge (3) still reading 12.0 g/m^2, 6.8 s late. On the web map below (4), the thin section rises from the die toward the ±3 % band short of the gauge, and marks flag web that was in span 1 while its tension was outside ±10 %. The trends (5) show span 1 rising above 220 N and falling back through its setpoint, the holdback torque 16 N m below its 59.7 N m feedforward and the dancer at −86 mm. No scrap is yet wound, and the worst tension deviation of the run, 12.1 %, is the span 1 peak of Table 5.6.

all of it the pump's lag during the ramp. Inertia compensation alone removes the tension scrap and leaves all 208.90 m of coat-weight scrap.

> **TRY IT IN THE APP** **2 · Speed Ramp, Feedforward Off**
>
> Load the scenario, press Run and watch the coat weight printed beside the die. When the order of 180 m/min starts the ramp at 10 s, the coating falls from 12.0 to 8.02 g/m^2 at once, while the gauge downstream keeps reading the target for another 7.07 s.

5.6.3 The Radius and the Splice

Case 3 builds the rewind from 80 mm at 210 m/min on the torque that gave 150 N at the start, with its load cell out of service. The tension follows $T = \tau/R$, reading 122.0 N at 99 mm, 73.9 N at 163 mm and 60.3 N at 200 mm, slightly above $150 \times 80/R$ because the rewind decelerates as it grows and returns a little torque. The tension leaves its band at 24.3 s and the web wrinkles at 508.5 s, so 2362.9 m of the 2447.8 m wound in 700 s is scrap. Multiplying the setpoint by the measured radius holds 149.7 to 152.7 N over the whole build, and the load-cell trim on fixed torque holds 145.4 to 151.7 N, removing by feedback an error that radius compensation prevents outright.

DID YOU KNOW? A Fixed Torque Loses Tension as the Roll Grows

From the simulator: a rewind built from 80 mm on the torque that gave 150 N at the start reads 60.3 N at 200 mm, and the web wrinkles at 508.5 s, so 2362.9 of the 2447.8 m wound is scrap. Multiplying the setpoint by the measured radius holds 149.7 to 152.7 N (Table 5.6).

Case 4 splices an almost empty roll to a web with 0.3 times the stiffness of the PET, under a trim tuned hot on the PET that holds it within 2.94 % before the splice. The soft web reaches the coating roll at 12.00 s and fills span 2 at 24.01 s. The oscillation grows as the soft web fills the span and afterward at about the rate of Figure 5.2 until the web breaks at 37.85 s. The same hot trim holds a web 2.25 times as stiff within 2.94 %, the hot gain with a 2 s integral time holds the soft web within 2.44 %, and the default trim of 0.5 and 2 s holds it within 1.44 % through 40 s.

TRY IT IN THE APP 4 · Splice to a Softer Web

Load the scenario, press Run and watch span 2 after the splice at 10 s. The oscillation grows as the softer web fills the span until the web breaks at 37.85 s. Press Reset, set Load-cell trim integral time to 2 s, keep the gain at 1 and run again: span 2 now stays within 2.44 %.

5.6.4 An Unmeasured Change and a Late Gauge

Case 5 runs the electrode recipe, and at 20 s a batch at half the viscosity doubles the pump slip. The die makes 191.39 g/m^2, 4.30 % light, and the gauge first sees it 47.63 s after the batch arrives. The trim restores the target and the gauge is back in band at 118.8 s, after 20.25 m of scrap. With integral times of 15 and 60 s the scrap is 20.15 and 20.35 m, and the faster trim overshoots at the die, to 202.07 g/m^2. The 19 m already coated between the die and the gauge when the gauge first sees the change is most of that scrap, so the delay rather than the tuning sets what an unmeasured disturbance costs.

Pause. Try Exercise 5.1 before reading on.

Case 6 runs the film at 30 m/min with the trim tuned for 120 m/min and a thinner batch at 10 s. The gauge is 37.97 s late and the loop sits just past its limit, so the gauge rings with a period of about 133 s and growing swings, peaking at 12.59, 12.74, 12.85 and 13.11 g/m^2 and falling to 11.34, 11.24 and 11.05 g/m^2, and it reaches 10.81 g/m^2 at 600 s, the bottom of the next swing. In those ten minutes 188.15 m of the 299.8 m wound is scrap. A 25 s integral time recovers without overshoot and scraps 20.55 m, a gain of 0.1 scraps 25.40 m, and on a line started at 120 m/min the recipe trim meets the same batch with 23.85 m. Reloading case 6 and setting the order to 120 m/min before Run starts at that speed, with the same 23.85 m of scrap, while an order given after Run ramps from the current line speed instead. Because Reset keeps the reader's settings (Section 1.6.1), the recipe integral time comes back only when the scenario is reloaded.

5.6.5 The Pump's Capacity and a Stop

Case 7 orders 240 m/min at 12 g/m^2, more than the 226.8 m/min that the pump can coat at full speed. The pump reaches 100 % at 223.1 m/min during the ramp, and at 240 m/min the coating is 11.34 g/m^2, 5.50 % light, so 644.5 m of the 689.3 m made in 180 s is scrap. The trim sits at its moving limit of 94.5 % without winding up. Holding the speed within the pump's capacity stops the ramp at 215.5 m/min, where the coat weight holds and the scrap is the 22.05 m of the ramp itself. The capacity limit is an override, because the speed the customer ordered gives way to the speed at which the product can still be made. Volume 16, Chapter 9 likewise caps its process speed, there just below the rate at which its entry can supply strip.

Case 8 stops the film line at 15 s and restarts it at 45 s. The pump follows the speed down through its lag, so the last meters are coated heavy, up to 32.9 g/m^2 at the die just before it lifts. The interlock lifts the die at 24.64 s, sends 4.52 mL of coating to the drip tray, re-engages at 45.47 s and holds the

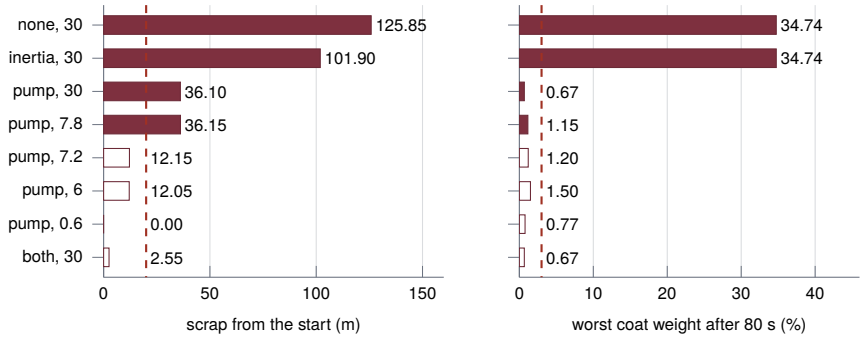


Figure 5.4 The challenge configurations of Table 5.7, labeled by feedforward and ramp rate in m/min per s. Dark bars fail the challenge and white bars meet it. The dashed lines are its 20 m scrap limit and its ±3 % coat-weight band. Notice that the pump feedforward alone brings the coat weight inside the band, and that what remains, the tension scrap of a steep ramp, goes either to inertia compensation or to a gentler ramp.

trim until fresh web reaches the gauge, and the stop costs 20.60 m. Without it the bead grows on the stationary web and 1.891 mL spills from 25.22 s, the restart lays down a stripe of 141.75 g/m^2, which is the full bead, and the trim chases the defect past the gauge, for 27.65 m of scrap.

5.6.6 The Graded Challenge

The challenge changes the electrode order from 24 to 42 m/min at 20 s with a 30 m/min per s ramp and both feedforwards off. It is met with no break, both tensions within ±10 % and the coat weight at the gauge within ±3 % from 80 s to the end of the 200 s run, and no more than 20 m of scrap in total, with the model parameters and disturbance settings left as supplied. The configurations measured are listed in Table 5.7. As shipped the foil survives, peaking at 177.6 N in span 1 against its 360 N limit, but the coat weight is 34.74 % off after 80 s and 125.85 m is scrap. Only the pump feedforward is indispensable, because without it the trim, capped at 150 % of a feedforward frozen at the old speed, cannot supply the 75 % more flow the new speed needs. With inertia compensation on and no pump feedforward it reaches 148.6 % while the gauge still reads 164.8 g/m^2 at 200 s. With the pump feedforward alone the steep ramp scraps 36.10 m, of which 34.95 m carries tension defects, adding inertia compensation leaves 2.55 m, and leaving the compensation off but ramping at 7.2 m/min per s or less also passes, with scrap falling from 12.15 m at that rate to none at 0.6 m/min per s. At 7.8 m/min per s span 2 dips to 89.5 N, 10.5 % low, which flags all 24 m of web in the span at once and lifts the scrap to 36.15 m. The 2.78 % in span 2 after 80 s is the same in every configuration, because it is load-cell noise at 106.7 s that the fixed seed repeats, and it falls to 0.15 % with that noise off. Figure 5.4 sets the scrap and the coat weight of each configuration against the two limits of the challenge.

5.6.7 Model Predictive Control Against the Loops With Feedforward

The MPC is set against the loops in Table 5.8, every case at its own seed, duration, instruments, noise and events. The loops run with both feedforwards on, case 3 with radius compensation and its load cell out of service, case 4 with its hot trim and the challenge with its suggested settings, while the MPC carries case 9's settings into every case unchanged. The measures accumulate at the 1 ms step: the scorecard's scrap, the time and depth of the true coat weight under the gauge outside ±3 %, the rms span 2 tension about its setpoint, and the pump travel summed over every 5 ms scan. Three loop variants, none of them a setting in the application, hand the loops what the plan carries. Lead evaluates the pump feedforward at the speed master's reference 0.75 s ahead, the preview the MPC receives, accel evaluates it at $v + (\tau_P + \tau_A)\, a_{ff}$, the measured speed advanced by the two lags with no

Table 5.7 The Challenge. Worst Deviations Count From 80 s and Scrap From the Start

Feedforward, ramp	T_1 max (N)	Dancer (mm)	*cw* worst (%)	Scrap (m)	Met
none, 30	177.6	−115/+86	34.74	125.85	no
inertia, 30	120.1	−0.2/+0.3	34.74	101.90	no
pump, 30	177.6	−115/+86	0.67	36.10	no
pump, 7.8	145.2	−101/+80	1.15	36.15	no
pump, 7.2	143.2	−98/+79	1.20	12.15	yes
pump, 6	139.4	−91/+76	1.50	12.05	yes
pump, 0.6	121.9	−10/+10	0.77	0.00	yes
both, 30	120.1	−0.2/+0.3	0.67	2.55	yes

Ramp rates in m/min per s. "Pump" is the speed feedforward to the pump, "inertia" the inertia compensation and "both" the suggested configuration. The worst span deviations after 80 s are 0.09 and 2.78 % in every row.

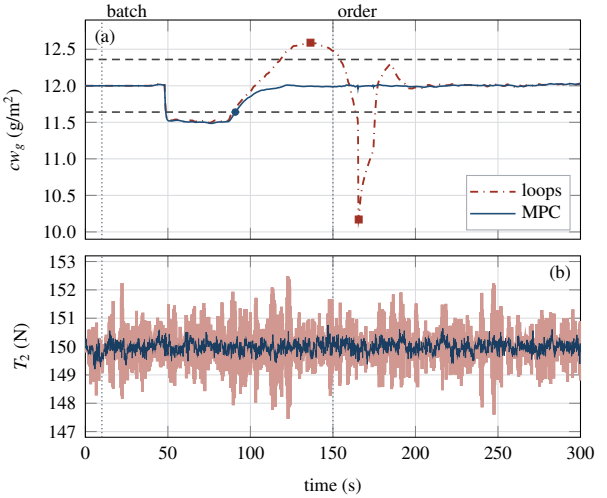


Figure 5.5 Case 9 under the MPC and under the loops with both feedforwards at the case's own seed. (a) True dry coat weight of the web under the gauge against the ±3 % band (densely dashed). (b) True span 2 tension. The MPC is the solid line in (a) and the thin dark trace in (b), the loops the dash-dotted line in (a) and the wide light trace in (b). The thinner batch arrives at 10 s and the order of 120 m/min at 150 s (dotted verticals). The square marks show the loops' overshoot to 12.59 g/m^2 and their dip to 10.17 g/m^2 after the ramp, and the round mark the MPC's return into the band for good at 90.9 s.

preview at all, and aligned replaces the coat-weight trim by the MPC's own $\hat{g}$. Hindsight is the best of 20 coat-weight trims, K_c from 0.1 to 0.5 and τ_I from 3 to 50 s, found on case 9 after the fact.

Case 9 runs the film at 30 m/min with both feedforwards and the recipe trim. A batch at half the viscosity arrives at 10 s, the die lays 11.50 g/m^2, 4.2 % light, and the gauge 38.0 s downstream first reads the thin web 1.5 % light at 48.2 s. The MPC compares the gauge with what its model laid on the same web, so $\hat{g}$ has moved 0.5 % by 50.4 s, settles at 95.83 %, and the coat weight returns inside the band for good at 90.9 s, as shown in Figure 5.5. Its 21.05 m of scrap is the web coated light before the gauge could see it. The recipe trim, tuned for 120 m/min, overshoots to 12.59 g/m^2 at 136.4 s and still reads 12.48 g/m^2 when the order of 120 m/min arrives at 150 s, for 30.90 m of scrap. Through the 15 s ramp the loops' pump follows the measured speed through the 0.8 s of pump and hose lag and the die dips to 10.17 g/m^2, for 32.10 m more, while the plan drives the pump ahead of the flow and holds the die between 11.94 and 12.01 g/m^2. Span 2 holds 150 N to 0.212 N rms against the loops' 0.760 N.

Removing one part of the plan at a time locates the gain. Without the pump and hose lags in its

Table 5.8 The MPC Against the Loops With Both Feedforwards, and the Loops Handed What the Plan Carries

Case	Structure	Scrap (m)	*cw* off band s (% s)	T_2 rms (N)	Pump (%)
9	loops	63.00	88.4 (158.3)	0.760	54.4
	MPC	21.05	42.1 (44.1)	0.212	51.7
	MPC, preview off	21.05	42.1 (44.1)	0.212	50.7
	MPC, no pump lags	40.40	52.3 (72.6)	0.212	43.9
	MPC, delay in time	71.00	94.0 (122.6)	0.212	52.8
	loops, τ_I 25 s	39.95	50.8 (79.1)	0.760	52.8
	loops, lead, τ_I 25 s	20.55	41.1 (43.5)	0.760	50.6
	loops, accel, τ_I 25 s	20.80	41.3 (43.5)	0.760	54.6
	loops, lead, aligned	21.40	42.8 (44.8)	0.760	43.9
	hindsight	39.35	— (72.4)	—	—
	hindsight, lead	19.70	— (41.8)	—	—
	hindsight, accel	19.80	— (41.8)	—	—
	loops, load cell 0.1, 5 s	63.00	88.4 (158.3)	0.218	54.4
2	loops	12.80	4.3 (10.9)	0.742	43.1
	MPC	0.00	0	0.215	38.3
	MPC, no pump lags	12.75	4.3 (10.3)	0.215	29.4
	loops, accel	0.00	0	0.742	48.6
3	loops	0.00	0	0.233	56.3
	MPC	0.00	0	0.274	16.7
4	loops, hot trim	29.45[a]	0	—	54.9
	loops, default trim	1.05	0	0.814	5.0
	MPC	1.05	0	0.263	1.6
5	loops	20.25	50.6 (55.0)	0.670	31.7
	MPC	20.70	51.8 (55.7)	0.297	11.8
	loops, K_c 0.3, τ_I 12 s	20.10	50.3 (52.7)	0.670	32.7
6	loops	188.15	386.6 (950.8)	0.767	18.3
	MPC	21.05	42.1 (44.1)	0.214	3.4
	MPC, delay in time	207.35	418.7 (1723.9)	0.214	21.7
	loops, τ_I 25 s	20.55	41.1 (43.5)	0.767	8.1
7	loops	644.50	162.7 (402.3)	0.734	47.5
	MPC	617.55	155.8 (388.8)	0.213	49.6
	loops, capacity limit	22.05	6.2 (13.3)	0.737	62.1
	MPC, capacity limit	0.00	0	0.214	54.3
8	loops	20.60	10.3 (120.5)	0.773	115.7
	MPC	0.20	0.1 (2.7)	0.216	312.4
	MPC, preview off	4.25	2.1 (4.2)	0.216	226.4
	loops, accel	0.50	0.3 (5.8)	0.773	121.4
10	loops, suggested	2.55	3.6 (28.0)	0.662	65.5
	MPC, suggested	0.60	0.9 (6.6)	0.294	69.5
	MPC, preview off	0.70	1.0 (11.0)	0.294	69.5
	loops, accel	0.80	1.1 (8.7)	0.662	79.2
	loops, as loaded	125.85	152.7 (3897.0)	1.695	28.6
	MPC, as loaded	10.95	0.9 (6.6)	0.322	69.5

Runs last 300, 180, 600, 90, 600, 600, 180, 180 and 200 s for cases 9, 2 to 8 and the challenge 10. The band is ±3 % of the target, the depth in parentheses integrates the excursion beyond it, and pump travel sums the changes of the pump command. The MPC made 20 plans a second, 6000 on case 9, and rejected none, at a mean of 160 µs a plan in Node on a shared host.
[a]The web breaks at 37.85 s.

model the plan scraps 40.40 m on case 9 and 12.75 m on case 2. Reading the record a fixed 9.5 s late, a delay fixed in time rather than in meters, it rings on the slow line and scraps 71.00 m on case 9 and 207.35 m on case 6. The preview leaves every scrap count of cases 2 to 6 and 9 unchanged and matters on the steep stop of case 8 (0.20 against 4.25 m) and a little in the challenge (0.60 against 0.70 m). The soft band never binds, and removing it changes no number. The estimate time moves the result in the expected direction. At 2 and 30 s instead of the shipped 10 s, the plan scraps 19.65 and

24.30 m on case 9, because a faster $\hat{g}$ takes up the thinner batch sooner once the gauge sees it. The loops reach the same result when handed the same knowledge. A trim retuned to 25 s for the slow line scraps 39.95 m, and 20.55 m with a lead on the pump or 20.80 m with accel, against the plan's 21.05 m. With the plan's own $\hat{g}$ in place of the trim and either lead they scrap 21.40 m. The tension gain comes from acting gently on a noisy load cell, which the loops can also do, since the load-cell trim calmed to $K_c = 0.1$ and $\tau_I = 5$ s holds 0.218 N rms on case 9. On case 9, therefore, neither the preview, the soft band nor the optimization adds a measurable share.

🕮 **Pause.** Try Exercise 5.3 before reading on.

Elsewhere the MPC removes the 12.80 m of case 2, holds the softer web of case 4 with only the 1.05 m of the splice zone scrapped, where the hot trim breaks it at 37.85 s, and with the capacity limit on scraps nothing on case 7 against the loops' 22.05 m. The losses are reported as measured. On case 5 the plan scraps 20.70 m against the loops' 20.25 and a retuned trim's 20.10 m, and it loses on each of four noise seeds, because its 10 s estimate is slower than the recipe trim at 24 m/min. A 2 s estimate, not shipped, would scrap 19.70 m. On cases 6 and 9 a trim retuned to 25 s scraps 20.55 m against 21.05 m, a trim of 0.2 and 6 s matches the plan's 21.05 m on case 6 with less depth (41.5 against 44.1 % s), and the hindsight trims with a lead or accel reach 19.70 and 19.80 m on case 9. With the load cell out of service in case 3 the plan runs on its model alone and holds 0.274 N rms against the radius-compensated loops' 0.233 N. On case 8 it moves the pump 312.4 % to the loops' 115.7 %, driving it past its steady value to push the flow through the lags at the stop and the restart. Both structures lose most of case 7 to the pump's capacity. At seeds 11, 12 and 13 case 9 scraps 21.30, 21.00 and 21.45 m under the MPC against 63.00, 62.65 and 64.25 m under the loops, and halving the physics step changes no scrap count of cases 2, 5, 6, 8, 9 and the challenge under either structure.

> ✦ **DID YOU KNOW? The Optimizer Is Not Where the Gain Lies**
>
> From the simulator: on case 9 the predictive controller scraps 21.05 m against the loops' 63.00 m. Loops handed the same knowledge, a 25 s trim and a lead on the pump, scrap 20.55 m, and the plan without its model of the pump lags scraps 40.40 m (Table 5.8).

With its suggested settings the challenge is met by both structures, with 2.55 m under the loops and 0.60 m under the MPC. As loaded, with both feedforward switches off, the loops fail with 125.85 m while the MPC meets the target with 10.95 m, all of it tension scrap. The plan supplies the rewind's inertia torque itself, but the unwind keeps the shipped law without inertia compensation, so span 1 still peaks at 177.6 N, 48 % over its setpoint against a 360 N break, and the dancer swings from −115 to +86 mm before scoring starts at 80 s. The challenge does not score those limits, and they are the same under the loops as loaded.

5.7 Technology in Practice

What Measures It

The line has two ways to read tension, and the chapter uses both: the dancer of span 1, whose position XT reports the mismatch of speeds while its air load sets the tension, and the load cell WT2 under an idler of span 2, which reads the tension directly. The radius that both winder torques are scaled by can be read by reflective laser sensors beside the rollers or, where no sensor is wanted, estimated by integrating the web thickness over the turns of the roll [14]. The chapter's DT1 and DT2 are ultrasonic diameter sensors with 0.3 mm of noise and a 1 s average. For the coat itself, laser caliper sensors mounted and calibrated at the oven inlet of a slot-die coater have monitored the wet thickness of cathodes and anodes with a precision better than ±2 % [21]. The chapter's gauge AT reads the dry coat weight 19 m after the die, through a 1 s average and noise of 0.5 % of the target.

TECHNOLOGY **Sensor: The Tension Load Cell Under an Idler**

A load cell is one or more strain gauges bonded to a metal structure of precisely known elastic properties, which stretches with the applied force like an extremely stiff spring, so the gauges turn force into a change of resistance [22]. Web tension measuring devices usually mount load cells under the bearings of a roller that the web wraps at a fixed angle, and the force on the cells is then proportional to the tension [23]. As tension sensors, load cells are expensive and need frequent maintenance and calibration [13]. An electric current through a load cell, from a ground fault or welding, is read as a change of resistance and so as a false force [22], which a load-cell trim would hold on its setpoint. The chapter's WT2 is ideal apart from noise of 1 N with a 20 ms correlation time.

What Moves It

Three drives move the line. The coating roll is the speed master, a stiff speed-regulated drive with a 50 ms response, and the transport speed of every tension zone is referred to such a roller [3]. The two winders are torque drives, and the gear pump that feeds the die is a third speed-commanded drive whose delivered flow falls short of its displacement by a slip that grows as the viscosity falls. The chapter gives the pump a 0.3 s lag and its hose and manifold a 0.5 s lag, and those 0.8 s are what the pump feedforward cannot remove during a ramp.

TECHNOLOGY **Final Element: The Winder Drive in Torque Mode**

A variable frequency drive achieves precise speed control of an alternating-current motor by varying the frequency of the power it feeds, and precise torque control by varying the voltage and current. An unwind that holds the web back works its motor as a generator. Dynamic braking dissipates that energy in a resistor, while a regenerative drive pumps it back into the supply grid. Every electronic braking method depends on the drive working, and a drive whose braking needs line power has no braking capacity at all when that power is lost [22]. An unwind left without braking can no longer hold its roll back. The chapter's winders are ideal torque drives, commanded as $\hat{R}$ times a force and limited to ± 120 N m.

Where the Controller Runs

In industrial control, loops are often nested or cascaded, with cycle times from milliseconds to minutes, and programmable logic controllers serve as local controllers within a supervisory control scheme [24]. The chapter's structure is of that kind. The speed master hands its filtered acceleration to both winders, each winder loop carries its feedforward torque as the bias of a PI trim in newtons, and the pump runs as a ratio to the measured line speed, all on a 5 ms cycle. The optional predictive controller plans the rewind force and the pump speed every 0.05 s above those loops. Figure 5.6 draws the loops on their devices.

IN PRACTICE **Where the Load-Cell Roller Goes**

A load-cell roller reads tension cleanly where the web wraps it at a fixed angle. Next to a coiler the wrap angle changes as the coil builds, so the usual solution is a second roller, a little farther from the coil, over which the web passes at a fixed wrap. A single roller beside the coil can serve instead if its signal is corrected with the current coil diameter, which most coiler drives already measure or compute [23]. Load cells read every force on their structure, and vibration from nearby machinery puts oscillating forces on them [22]. The chapter's WT2 sits on an idler in span 2 and is read as the tension itself.

What Is Modernizing It

Signal processing and disturbance estimation are one direction. On an industrial roll-to-roll system, a disturbance observer gave robustness to the changing inertia of the web roll and to disturbances from web slip, a feedforward cut the tracking error where the tension setpoint changes, and Kalman filtering of the tension sensor greatly improved the control performance [18]. Constrained predictive control is the second: a design of 2023 wrote the rated motor torque into its constraints and updated

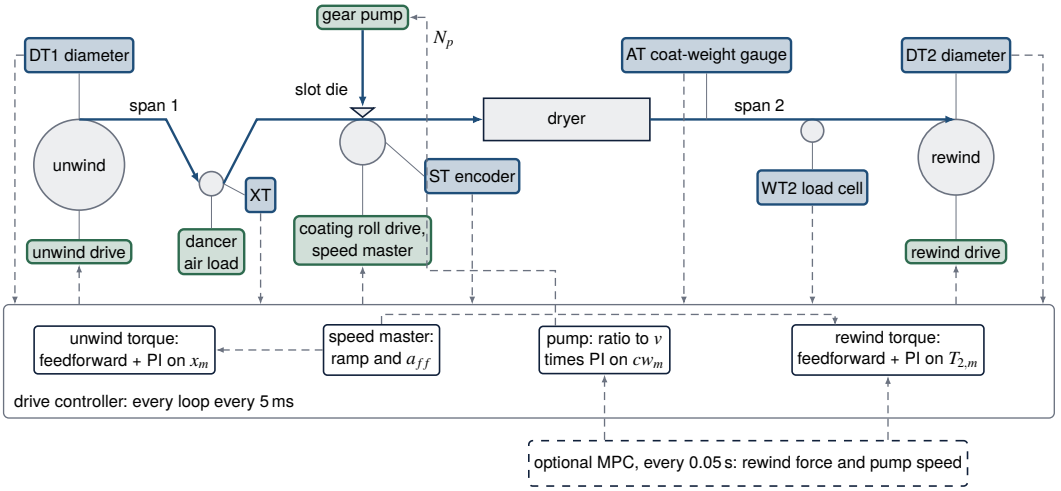


Figure 5.6 The loops on line hardware. Every sensor and drive is one of the chapter's: DT1 and DT2 read the roll diameters, XT the dancer, ST the line speed, AT the dry coat 19 m after the die and WT2 the span 2 tension. One drive controller runs all loops every 5 ms: the speed master hands its ramp and filtered acceleration to the winder feedforwards, and the pump runs as a ratio to the line speed under a slow trim on the late gauge. Notice that only the dancer's air load sets a tension directly, and that the optional MPC replaces the pump and rewind loops but not the unwind.

its model from the measured or estimated roll radius [14]. The chapter's own predictive controller carries both ideas, a Kalman filter with an integrating disturbance on the load cell and the torque limit as a hard bound, and Section 5.6.7 sets it against the loops case by case.

5.8 Limitations

The spans are lumped springs whose damping scales with their stiffness, and the stability limit of the load-cell trim in Section 5.5 rests on that scaling, so a line damped mostly by idler bearings and air would place it elsewhere. Tension waves, roller slip and the capstan limit, backlash, and the mechanics of the wound roll, among them wound-in tension, telescoping and taper tension, are outside the model. The coating obeys the pre-metered law at every speed, with no coating window, edge build-up or cross-web profile, and viscosity reaches the coat weight only through pump slip [5, 6]. The dryer is one time constant and the gauge a point sensor on the dry solids.

> ⚠ **OPEN CHALLENGE** **Seeing What the Electrode Coat Becomes**
>
> The link between the physical processes of electrode manufacture and its outputs is not yet fully understood, partly because so many parameters are involved and complete data sets under different processing conditions are lacking. A 2021 review of metrology for slurry coating found a range of measurements that need little improvement, with in-line particle sizing the exception, but few studies that bring them together, which multiphysics and data-driven models need [15]. The chapter's gauge is one point sensor on the dry solids. Progress would be in-line measurements joined into one picture of the coat as it is made.

Switching the product during a run re-threads the line at the new recipe's steady state instead of splicing the new web in, so a product change cannot be run as a transient. The break limits, the wrinkle threshold and the scrap rules are illustrative design choices of the application, and its scrap counts compare controllers with one another rather than predicting a real line's yield. The three reduced models of Section 5.5 are checked against the simulator and not against a physical line, so they establish what the teaching model does rather than what a given line would do.

The predictive controller's model is the line at its declared constants and recipe, linearized at the measured radius and speed. It does not know the stiffness of a spliced web, which reaches it only through the load cell's force estimate, nor the true viscosity, which reaches it only through $\hat{g}$ one gauge delay later. It leaves out span 1 and the dancer, the bead's 2.5 ms lag at 120 m/min, the growth of the radius within a plan, and the stretch of span 2, which moves the gauge's place on the film web by about 13 mm. It also takes the width, the pump displacement and the other constants at their declared values while the shipped feedforward reads the run's, so a reader's change to those favors the loops. The tension band carries one slack over the whole horizon rather than one per step, and the weights, chosen once on case 9, lose case 5.

OPEN CHALLENGE **Tension Tracking While the Web Changes**

Roll-to-roll lines still make products less consistent than batch processes, and tension-induced distortion is among the root causes. Coating and drying change the elasticity of the substrate, the radius and inertia of the rolls change all the time, and the rated torque of the motors must not be exceeded. A study of 2023 met these with a robust predictive controller whose parameters are scheduled, shown in simulation of an actual line [14]. Progress would be tension tracking that stays precise as the web's elasticity changes, shown on a running line.

5.9 Conclusion

This chapter put a torque-driven winder pair, a dancer, a pre-metered slot die and a late gauge on one speed, so that each remedy for a speed change could be priced separately. A ramp from 120 to 180 m/min with the pump flow held makes the coating 33.2 % thin at the die and costs 208.90 m of film, and the pump feedforward and inertia compensation together cut that to 12.80 m. A reduced third-order model of the dancer loop reproduces the dancer travel and span tension through that ramp and shows why a speed-ratio radius estimate destabilizes the foil line at 24 m/min. A mass-on-a-spring model of the rewind explains the break of a softer spliced web at 37.85 s and places the hot trim's stability limit at 0.80 times the PET stiffness once the 5 ms control interval is counted. The coat-weight trim tuned at 120 m/min has a gain margin of 0.93 at 30 m/min after a thin batch, and a batch change behind the 19 m gauge costs the electrode line 20.15 to 20.35 m whatever the integral time.

The optional model predictive controller scraps 21.05 m against the loops' 63.00 m when a thinner batch and a faster order reach the film at 30 m/min, a gain owed to its model of the pump's lag and its delay counted in meters, which loops with a 25 s trim and a lead on the pump match with 20.55 to 20.80 m.

The model omits the coating window, roller slip, the mechanics of the wound roll and any damping not proportional to the web's stiffness. A fuller model would add a taper-tension schedule, a second coating station with register control, an estimator that reads the flow into the die ahead of the gauge, and a speed-scheduled trim. On the app, feedforward, compensation and delayed feedback are learned by running them against one another.

KEY POINTS

- One speed change thins the coating at once and upsets the tension, because the winders must spin up rolls that change every turn.
- The pump feedforward and inertia compensation cut the scrap of a ramp from 120 to 180 m/min from 208.90 to 12.80 m.
- A softer spliced web, not a stiffer one, breaks the hot load-cell trim.
- The predictive controller's gain on case 9 comes from its model of the pump's lag and its delay in meters.

Where else this applies. Volume 16, Chapter 10 weighs its coating through a delay set by the line speed.

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5.10 Exercises

5.1 Concept check · 2 min

In case 5 a batch of cathode paste at half the viscosity reaches the electrode line at 20 s, with the line at 24 m/min. With coat-weight trim integral times of 15, 30 and 60 s the run scraps 20.15, 20.25 and 20.35 m of foil. What sets most of that scrap?

(a) The integral time of the trim, because the fastest trim overshoots at the die

(b) The foil already coated between the die and the gauge before the gauge sees the change

(c) The dryer's time constant, which leaves solvent in the foil while the batch changes

(d) The load-cell noise, which flags tension defects on the foil during the batch change

5.2 Concept check · 1 min

A rewind tension trim tuned hot on the PET film ($K_c = 1$, $\tau_I = 0.5\,\mathrm{s}$) holds span 2 within 2.94 %. The next roll will be spliced in with a different web. According to the mass-on-a-spring model of Section 5.5, which splice is the dangerous one?

(a) A softer web, but only because it stretches further before it breaks

(b) Neither, because the trim works in newtons and is multiplied by the radius

(c) A softer web, because the shortest stable integral time grows as the stiffness falls

(d) A stiffer web, because the tension rises faster for the same speed mismatch

5.3 Concept check · 2 min

On case 9 the predictive controller scraps 21.05 m and the loops with both feedforwards 63.00 m. Which result from Table 5.8 locates the source of the difference?

(a) With the speed preview off the plan scraps far more, so the preview carries the gain

(b) Without the soft tension band the plan scraps more, so the constraint carries the gain

(c) No retuning brings the loops near the plan, so the optimization carries the gain

(d) Without the pump lags, or with the delay counted in time, the plan scraps far more

5.4 Theory and calculation · 6 min

The film recipe coats $12\,\mathrm{g/m^2}$ of dry adhesive with a solids fraction $\varphi = 0.45$ and a wet density $\rho_{wet} = 1050\,\mathrm{kg/m^3}$ on a web $W = 1.0\,\mathrm{m}$ wide. The gear pump displaces $Q_{max} = 6.0\,\mathrm{L/min}$ at full speed and delivers $\eta_{nom} = 0.96$ of it at the recipe viscosity.

(a) Compute the wet film $h_{w,SP}$ the die must lay down. *Checkpoint:* 25.4 µm.

(b) Compute the fastest line speed at which the pump can still coat the target at full speed, and the speed at which the capacity limit of Equation (5.10) holds the line. *Checkpoint:* 226.8 m/min and 215.5 m/min.

(c) Case 7 orders 240 m/min. Compute the coat weight the pump makes there at full speed and how light it is, and say whether the coat-weight trim can restore the target. *Checkpoint:* $11.34\,\mathrm{g/m^2}$, 5.5 % light. It cannot.

5.5 Theory and calculation · 5 min

A full film roll on the unwind has $R_u = 300\,\mathrm{mm}$ on a core of $R_{core} = 76\,\mathrm{mm}$, a web density $\rho = 1390\,\mathrm{kg/m^3}$, a width $W = 1.0\,\mathrm{m}$ and $J_{core} = 0.50\,\mathrm{kg\,m^2}$. The span 1 setpoint is 200 N, the bearing friction $b = 0.02\,\mathrm{N\,m\,s}$, and at 120 m/min the roll turns at 6.661 rad/s.

(a) Compute the roll's inertia from Equation (5.2) and its equivalent mass $m_u = J_u/R_u^2$ at its surface, and compare it with the mass of the film on the roll. *Checkpoint:* $18.11\,\mathrm{kg\,m^2}$, 201 kg, against 368 kg of film.

(b) Compute the holdback torque the unwind motor applies at steady speed. *Checkpoint:* 59.87 N m.

(c) The line ramps at 12 m/min per s with inertia compensation off. From Equation (5.17), find the steady dancer offset the proportional term alone would need to supply the accelerating force, with the dancer loop gain of 0.4 N/mm. *Checkpoint:* 101 mm, against stops at 150 mm.

5.6 Theory and calculation · 8 min

The rewind of case 4 has an equivalent mass $m_r = 61\,\text{kg}$ at 128 mm. Span 2 is $L_2 = 24\,\text{m}$ of PET with $EA = 225\,\text{kN}$ and a retardation time $\tau_w = 5\,\text{ms}$. The hot load-cell trim has $K_c = 1$ and $\tau_I = 0.5\,\text{s}$.

(a) From Equation (5.19), compute the critical integral time on the PET and on a web of 0.3 times its stiffness, and say which of the two the hot trim holds. *Checkpoint:* 0.33 s and 1.08 s. It holds the PET only.

(b) Find the stiffness, as a multiple of the PET's, at which $\tau_I = 0.5\,\text{s}$ is just critical by the same equation, and compare it with the two limits of Figure 5.2. *Checkpoint:* 0.65, between 0.59 and 0.80.

(c) Estimate the period of the tension oscillation on the softer web, and compare it with the 0.651 s measured on the engine. *Checkpoint:* 0.654 s.

5.7 App challenge · 8 min

Load scenario 2, Speed ramp, feedforward off, and change no setting. The order from 120 to 180 m/min arrives at 10 s and ramps at 12 m/min per s. Set the playback speed to 20×, run to 180 s with the default seed and export the CSV file. Read the scrap in the last row of `metric_scrap_m` and the Worst tension deviation tile at 180 s.

(a) Read the lowest coat weight at the die, column `cw_die_gm2`, and compare it with the pre-metered law for a flow held while the speed rises by half. Read the scrap. *Checkpoint:* 8.02 g/m^2 (within 0.02) against 8.0 g/m^2, and 208.90 m (within 0.1 m).

(b) Press Reset, set Line speed feedforward to the pump to On before Run, and run to 180 s. Read the scrap and the Worst tension deviation tile. *Checkpoint:* 22.30 m and 16.6 %.

(c) Press Reset, set Inertia compensation during ramps to On as well, and run to 180 s. Read the same two values and say what the remaining scrap is. *Checkpoint:* 12.80 m and 1.6 %.

5.8 App challenge · 8 min

Load the challenge, Challenge · order change on foil, and change no setting. The electrode order goes from 24 to 42 m/min at 20 s with a ramp of 30 m/min per s, and both feedforward switches are Off. Set the playback speed to 20× and run the full 200 s with the default seed. Read the Worst coat-weight deviation tile and, for two decimals, the last row of `metric_scrap_m` in the exported CSV file.

(a) Read the scrap and the coat-weight deviation as loaded, and explain why the coat-weight trim cannot recover the order. *Checkpoint:* 125.85 m (within 0.1 m) and 34.7 %.

(b) Press Reset, set Line speed feedforward to the pump to On and Speed ramp rate to 6 m/min per s before Run, leave Inertia compensation during ramps Off, and run 200 s. Is the target met? *Checkpoint:* 12.05 m, met.

(c) Press Reset, set the ramp rate back to 30 m/min per s and Inertia compensation during ramps to On, and run 200 s. Compare with the pump feedforward alone at that ramp in Table 5.7. *Checkpoint:* 2.55 m, met, against 36.10 m.

5.9 App challenge · 8 min

Load scenario 9, A slow line, a thinner batch and a faster order: MPC against the loops with feedforward, and change no setting. The predictive controller is selected. Set the playback speed to

20× and run to 300 s with the default seed. Read the scrap in the last row of `metric_scrap_m` of the exported CSV file after each run.

(a) Read the scrap under the MPC. Then press Reset, set Tension and coat weight to Loops before Run, and run to 300 s again. *Checkpoint:* 21.05 m and 63.00 m (within 0.1 m).

(b) Reload the scenario, switch to Advanced mode, set MPC coat-weight estimate time to 2 s before Run and run to 300 s. Reload again and repeat with 30 s. *Checkpoint:* 19.65 m and 24.30 m.

(c) The estimate time moves the scrap by a few meters. Use Table 5.8 to say which parts of the plan carry the remaining 40 m or so, and which two changes to the loops close the gap. *Checkpoint:* The pump-lag model and the delay in meters. A 25 s trim and a lead on the pump.

5.10 Application area · 3 min

An electrode line coats 200 g/m^2 of cathode paste with $\varphi = 0.70$ and $\rho_{wet} = 2300\,\mathrm{kg/m^3}$ on foil 1.0 m wide, through the pump of Table 5.2 and a 15 m dryer. The residual solvent of Section 5.3 must fall below 1 % of the dry coat, with $\tau_{dry} = 3.0\,\mathrm{s}$.

(a) Compute the fastest speed the dryer allows and the fastest speed the pump can coat at full speed. Which one caps the line? *Checkpoint:* 79.8 m/min and 46.4 m/min. The pump.

(b) Production asks for 60 m/min. What pump displacement would coat it at full speed at the recipe slip? *Checkpoint:* 7.76 L/min.

5.11 Application area · 4 min

A drive engineer proposes to remove the ultrasonic diameter sensor from the unwind and estimate the radius from the ratio of the line speed to the unwind speed, a common practice. Section 5.5 shows that the estimate turns the damping of Equation (5.17) into $c_d/2 - 2T_{1,SP}/v_0$, with $c_d = 1000\,\mathrm{N\,s/m}$.

(a) Compute the damping for the film ($T_{1,SP} = 200\,\mathrm{N}$) at 120 and 30 m/min, and for the foil ($T_{1,SP} = 120\,\mathrm{N}$) at 24 m/min. *Checkpoint:* $+300$, -300 and -100 N s/m.

(b) Below what line speed does each product lose its damping, and what do you advise the engineer? *Checkpoint:* 48 m/min for the film, 28.8 m/min for the foil.

5.12 Review the agent · 5 min

An AI assistant is asked how to tune the coat-weight trim of the film line for a heavy order that will run at 30 m/min. It answers: “The recipe trim, gain 0.3 and integral time 6 s, has a gain margin of 2.87 on this line, with the gauge 19 m from the die. The gauge and the loop do not change with the order, so the trim is safe at 30 m/min. To correct a thinner batch faster at the lower speed, raise the gain to 0.5.” Find the flaw, and say how you would check the advice on the app before using it.