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CHAPTER 6

Mold Level Simulator for Telling a Sticking Gate From Bulging and Overtuning

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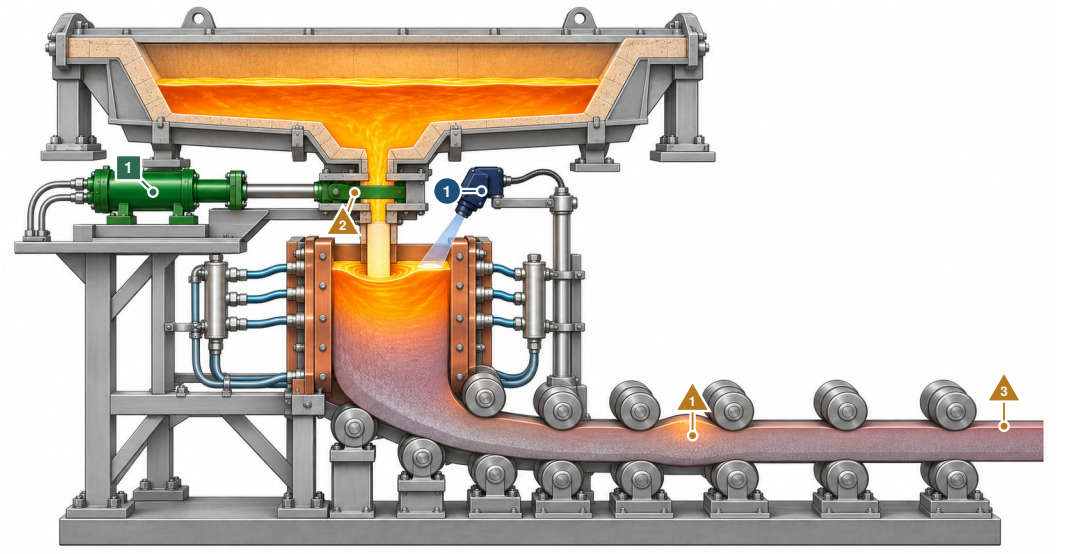
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CHAPTER 6

Mold Level Simulator for Telling a Sticking Gate From Bulging and Overtuning



The controller moves 1 the slide gate, moved by its hydraulic cylinder

The controller reads 1 the level of the steel in the mold

What disturbs it 1 the strand bulging between its rolls 2 gate plates that stick 3 a change in casting speed

Notice that the strand leaves at a rate set by the casting speed, not by the level, so every gap between the flow through the gate and the steel withdrawn makes the level climb or fall until the gate moves. Illustration, not to scale.

IN PLAIN TERMS **Three Reasons a Steel Level Swings**

The main idea. Melted steel pours into a copper box with no bottom. It freezes there into a slab that is pulled out below. A sliding gate above the box sets how fast steel flows in, and a controller moves the gate to keep the level steady.

The challenge. The level can swing because the gate sticks, because the slab bulges between its rollers, or because the controller reacts too hard. All three draw almost the same wavy line, and each fix works only on its own cause.

Why it matters. The steel surface in the box decides the quality of the slab, and the wrong fix wears out the gate and leaves the swing.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	The first page, the fact box of the Introduction, the history box of Section 6.2 and the one of Section 6.4, the fact and try-it boxes of Section 6.5, and the key points
Study	35 min	The whole chapter with its pause points and the twelve exercises
Practice	15 min	The first page, Section 6.5, Section 6.6, Section 6.7 with its two open challenges

The control question The mold of a continuous caster is an integrator fed through a slide gate, and its level can oscillate because the gate plates stick, the strand bulges between its rolls or the controller carries too much gain. On a trend the three look alike. Which tests tell them apart, and what does each remedy cost when it is applied to the wrong cause?

Learning objectives

- Derive the integrating gain of the mold from the gate's lens area and the volume balance, and compute SIMC settings and the ultimate gain from it.
- Explain why a sticking gate on an integrating plant cycles even without integral action.
- Apply the open-loop test, the speed-change test and the signature plot to name the cause of an oscillation.
- Compute the bulging period from the roll pitch and casting speed, and the gate motion a canceller needs.
- Compare the knocker, the canceller and retuning by level variation and gate travel, and choose the order of repairs.

Prerequisites Sections 1.6.2 (velocity form and anti-windup), 1.4.5 (a disturbance frequency set by speed) and 1.6.4 (scenarios, tiles and the CSV file).

The app https://apmonitor.com/apps/continuous-caster/

See also Volume 2, Chapter 5 for an integrating level tuned by SIMC and Volume 2, Chapter 4 for a sticking steam valve. Volume 1, Chapter 13 for loop-performance tests on recorded loops, one of them this caster. Volume 7, Chapter 11 for a disturbance whose frequency the speed sets and Volume 7, Chapter 13 for two limits that look alike but need different remedies.

6.1 Introduction

An oscillating control loop invites retuning, and retuning is often the wrong response. Surveys of industrial loop performance have found that a large share of oscillating loops oscillate because of the final control element or an external periodic disturbance rather than the controller settings, and that the diagnosis has to separate those causes before any remedy is chosen [1, 2]. A sticking valve responds to tuning, just never enough. A periodic disturbance responds to tuning in either direction depending on where its frequency sits against the loop bandwidth. Only a genuinely overtuned loop is cured by less gain.

The steel continuous caster is an unusually clean home for that problem. The mold is an integrator, because the strand withdraws steel at a rate set by the casting speed and not by the level, and on an integrating plant a sticking valve produces a limit cycle at any nonzero gain, even without integral action [3]. The strand bulges between its support rolls and pumps the liquid core into and out of the mold at a frequency that is known exactly from the casting speed and the roll pitch [4]. The measurement delay and the hydraulic actuator put a hard ceiling on the gain. All three occur on real casters, often at once, and all three produce a level trend that looks roughly the same.

> **DID YOU KNOW? Nearly All Steel Is Cast Continuously**
>
> By 2000, barring specific situations, continuous casting had entirely replaced ingot casting in the United States, and it improved yield dramatically [5]. The country then made about 95 million tons of cast products a year. The slab caster of this chapter withdraws about 52 kg/s of steel from one strand.

The simulator is built against one misconception, that an oscillation is a tuning problem until proven otherwise. The broader class is loop performance diagnosis, which appears wherever a control valve can stick and a disturbance can be periodic: paper machine headboxes, flotation cells, drum levels, and others [1, 6]. The shape of the diagnosis is the same in all of them. Opening the loop separates an internal oscillation from an external one. Moving the frequency of a suspected external source confirms or rules it out. Plotting the controller output against the valve position exposes stiction as a parallelogram rather than a line [7].

This chapter works with a mold level simulator in which all three causes can be switched on alone or together, the diagnostic tests can be run as they are on a plant, and each remedy can be applied to each cause and priced in level variation and gate wear. Stick-slip models, stiction compensation by pulse injection and bulging cancellation are all established methods. The mold, gate, strand and sensor model is written out completely enough to be rebuilt, the diagnostic instruments are drawn in the interface, and the scenarios are ordered so that diagnosis comes before treatment. Section 6.2 gives the domain history. Section 6.3 sets out the model: the mold as an integrator, the slide gate, two-parameter stiction, bulging, clogging and the sensor. Section 6.4 describes the level controller, the knocker, the bulging canceller and the diagnostic instruments. Section 6.5 reports the measured results: the healthy reference, the three signatures, combined faults with the order of repairs, and the graded challenge. Section 6.6 turns to the real sensor, gate and controller platform, Section 6.7 states the limitations and Section 6.8 draws the conclusions. The exercises follow.

6.2 Mold Level Control on Continuous Casters

Continuous casting displaced ingot casting for most of the world's steel over the second half of the twentieth century, because it removes the reheating and primary rolling of ingots and raises yield [8]. Liquid steel runs from a ladle into a tundish, a refractory buffer vessel about a meter deep, and from the tundish through a flow control device and a submerged entry nozzle into a bottomless water-cooled copper mold. A shell freezes against the copper and is withdrawn continuously while support rolls contain it until the core has solidified. Mathematical modeling of the fluid flow, heat transfer and solidification in this process has been reviewed at length [9].

The meniscus is where surface quality is decided. Mold flux floats on it and the first shell forms against it, so level fluctuations either entrain flux into the solidifying steel or disturb the initial shell, and both appear later as surface and subsurface defects. Instrumenting the mold to understand and prevent those defects was a central theme of caster research in the 1980s [10]. Level measurement moved from floats and radioactive sources to eddy-current and electromagnetic sensors, and flow control from stopper rods alone to stopper rods and slide gates, the latter being two refractory plates with round bores slid across each other by a hydraulic cylinder.

> ⧖ HISTORY **Automatic Mold Level Control (1955 to 1984)**
>
> The first continuous casting machine in Japan was installed in 1955, and by 1982 almost all common steels there were cast this way [11]. A paper of that year called the development of a mold level sensor one of the most important and difficult tasks of the process. Sensors using gamma rays, thermocouples and eddy currents had been tried, and only a few could work beside the electromagnetic stirrers then being added for high grade steel. By 1984 one slab caster held its mold level within 3 mm by moving the tundish slide gate continuously with a hydraulic unit [12]. Casting then started at the push of a button, and the mold operator was freed from the lasting tension of controlling the level by hand. The same note tied level fluctuation to entrapped scum and to longitudinal cracks.

Once the level was measured continuously it was put under closed-loop control, and the history of the loop since is largely a history of its disturbances. Robust controllers were designed against the variation in nozzle gain and the measurement delay [13], and supervisory schemes, including fuzzy supervision of the level controller, were used to handle changing operating conditions [14]. As casting speeds rose and shells thinned, unsteady bulging became a recognized source of periodic level fluctuation, and its mechanism was measured and simulated in detail [4]. Because its period is the roll pitch divided by the casting speed, dedicated cancellation schemes that exploit the known frequency were developed and validated on plants [15].

Stiction in slide gates is a maintenance reality with a separate literature of its own. The data-driven two-parameter model of a sticking valve gives a stick band and a slip jump that reproduce the characteristic trends of industrial loops [7], a friction compensator that adds short pulses to

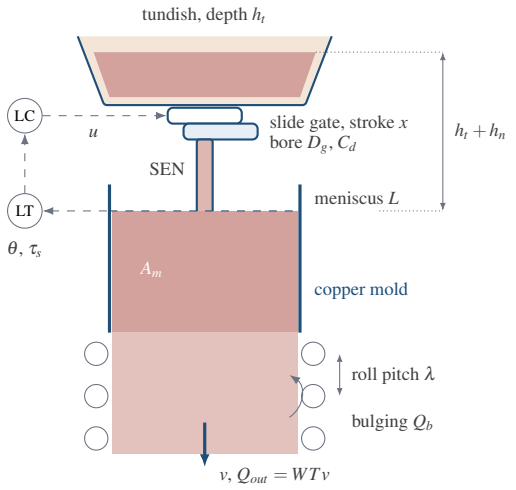


Figure 6.1 Mold level loop on a slab caster. Steel from a tundish of depth h_t passes a slide gate of bore D_g at stroke x and a submerged entry nozzle (SEN) into a mold of free-surface area A_m. The strand of width W and thickness T leaves at casting speed v between support rolls of pitch λ, and bulging between the rolls adds a periodic flow Q_b. The level transmitter LT reads the meniscus L after a delay θ and a filter τ_s, and the controller LC sets the gate command u.

Table 6.1 Classification of Variables at the Design Operating Point

Symbol	Role	Nominal	Range
L	CV, true meniscus level	100 mm	0–190 mm (lip)
L_m	measured level	100 mm	0–200 mm span
u	MV, gate command	57.0 %	0–100
x	state, gate position	57.0 %	0–100
c	state, clog fraction	0	0–0.6
ϕ	state, bulging phase	—	—
v	DV, casting speed	1.20 m/min	0.6–2.0
h_t	DV, tundish depth	1.00 m	0.5–1.3
S, J	DV, gate stiction	0, 0 %	0–8, 0–4
a_b	DV, bulging amplitude	0 mm	0–10
r_c	DV, clogging rate	0 %/min	0–3
n	DV, level noise (1σ)	0.2 mm	0–2

the valve command, the knocker, was proposed for pneumatic control valves [16], and methods to detect stiction from routine data, including in integrating loops where the signature differs, have been compared extensively [2, 3, 6]. Volume 1, Chapter 13 applies such loop-performance tests to recorded loops, one of them this caster's overtuned case. The level loop on a caster therefore sits at the intersection of three mature literatures that are rarely taught together.

6.3 Process Model

The simulated caster makes a slab 1.60 m wide and 0.23 m thick at 1.2 m/min. The strand withdraws 7.36 L/s of steel, about 52 kg/s, from a free surface of 0.353 m^2 once the nozzle is subtracted, and the slide gate balances that withdrawal at 57 % of its stroke. The arrangement is shown in Figure 6.1.

The variables are classified in Table 6.1. The level is measured from the zero of a 200 mm sensor span, with the mold lip 190 mm above that zero and the setpoint at 100 mm. Four states are integrated: the level L, the gate position x, the clog fraction c and the bulging phase ϕ.

6.3.1 The Mold as an Integrator

A volume balance on the steel above the strand gives the level derivative, as shown in Equation (6.1).

$$A_m \frac{\mathrm{d}L}{\mathrm{d}t} = Q_{in}(x, c, h_t) - Q_{out}(v) + Q_b(t) \tag{6.1}$$

where $A_m = WT - \pi D_{SEN}^2/4$ is the slab section less the nozzle, and the withdrawal is $Q_{out} = WTv$. No term on the right depends on L, so the mold has no self-regulation. Every imbalance ramps the level at a constant rate, and the only thing that stops the ramp is the gate.

6.3.2 The Slide Gate

Two plates with equal round bores slide across each other, so the open area is the lens where two circles of radius $D_g/2$ overlap. With the stroke $s = x/100$ and the center offset $d = 2(1-s)$ in bore radii, the open fraction of the bore is given by Equation (6.2).

$$f(s) = \frac{1}{\pi}\left[2\cos^{-1}\frac{d}{2} - \frac{d}{2}\sqrt{4-d^2}\right] \tag{6.2}$$

The gate flow is an orifice driven by the tundish head, reduced by the clog, as shown in Equation (6.3).

$$Q_{in} = C_d \frac{\pi D_g^2}{4}\sqrt{2g\,(h_t + h_n)}\, f(s)\,(1-c) \tag{6.3}$$

The lens opens slowly from closed and fastest near full open, so the process gain depends on where the gate sits. At the design point each percent of stroke is worth 0.18 L/s and the integrating gain is $K_I = 0.51\,\mathrm{mm/s}$ per percent of stroke.

The hydraulic cylinder follows the position delivered by the stiction model, x_s, as a first-order lag with a speed limit, Equation (6.4).

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \mathrm{clamp}\left(\frac{x_s - x}{\tau_a}, -R_a, R_a\right) \tag{6.4}$$

with $\tau_a = 0.15\,\mathrm{s}$ and $R_a = 15\,\%/\mathrm{s}$.

6.3.3 Two-Parameter Stiction

The plates stick according to the two-parameter model of stiction, a stick band plus dead band S and a slip jump J [7], written in the simulator as a force balance on the plate evaluated at every controller scan. With the static band $f_s = (S+J)/2$ and the kinetic band $f_d = (S-J)/2$, a stuck plate at x_s stays put until the command u satisfies $|u - x_s| > f_s$, slips to $x_s = u - \mathrm{sgn}(u - x_s) f_d$, and then tracks at the kinetic distance until the command stops or reverses, Equation (6.5).

$$x_s \leftarrow \begin{cases} u - \mathrm{sgn}(u - x_s)\, f_d, & |u - x_s| > f_s, \text{ or moving} \\ & \text{and } |u - x_s| > f_d \\ x_s \text{ (stuck)}, & \text{otherwise} \end{cases} \tag{6.5}$$

A reversal therefore costs S of dead command travel, and every breakaway ends in a jump of J. With $S = 0$ the plate follows the command exactly. The stiction scenarios use $S = 5\,\%$ and $J = 1.5\,\%$, so the plate needs 3.25 % of command pressure to break away.

6.3.4 Bulging, Clogging and the Sensor

Bulging is one sinusoid at the roll-passing frequency, Equation (6.6).

$$Q_b = A_m a_b\, \omega \cos\phi, \qquad \frac{\mathrm{d}\phi}{\mathrm{d}t} = \omega = \frac{2\pi v}{\lambda} \tag{6.6}$$

Table 6.2 Model Parameters. Class marks what the application shows: visible parameters are adjustable in the parameter panel, hidden ones are not

Symbol	Meaning	Value	Class
W, T	slab width, thickness	1.60, 0.23 m	visible
D_{SEN}	nozzle outside diameter	0.14 m	visible
λ	support roll pitch	0.25 m	visible
D_g	slide-gate bore	70 mm	visible
C_d	discharge coefficient	0.75	visible
h_n	tundish floor to meniscus	0.50 m	visible
τ_a	actuator lag	0.15 s	visible
R_a	actuator speed limit	15 %/s	visible
θ	measurement and flow delay	0.30 s	visible
τ_s	sensor filter	0.10 s	visible
—	slag-entrainment band	±5 mm	visible
—	level alarm	±20 mm	visible
—	casting speed ramp rate	0.30 m/min/min	hidden
g	gravity	9.81 m/s^2	fixed

where a_b is the level swing the bulging would cause with the gate held still. At 1.2 m/min on 0.25 m rolls the period is 12.5 s. The frequency is set by a length and a speed, the case of Section 1.4.5, as a road feature under a moving car sets the frequency in Volume 7, Chapter 11. The clog grows at $\mathrm{d}c/\mathrm{d}t = r_c/6000$ per second while $c < 0.6$, and a clog release event resets it to zero.

The eddy-current sensor sees the level after a transport and measurement delay $\theta = 0.30$ s, adds colored noise with a 0.25 s time constant, and passes the sum through a first-order filter $\tau_s = 0.10$ s before clamping it to the 200 mm span. The level itself is clamped at the lip, where an overflow is flagged, and a level alarm is raised at 20 mm from setpoint.

The parameters are listed in Table 6.2. The casting speed does not jump when its setting changes, because it is ramped at 0.30 m/min per minute in the post-step correction.

6.3.5 Assumptions

The meniscus is flat and single-valued. Standing waves, jet impingement from the nozzle ports and argon bubbling are represented only as band-limited sensor noise, although on a real caster they are a large part of the measured level signal [9].

The gate flow is an orifice with a constant discharge coefficient through the geometric overlap of two bores. Erosion of the bore, argon injection and flow separation in the nozzle are not modeled.

Solidification, mold oscillation and mold flux are outside the model, and the withdrawal is exactly slab section times speed. Shell shrinkage and the density difference between liquid and solid steel are neglected.

Bulging is a single sinusoid at a single roll pitch with an amplitude that does not depend on speed. Real unsteady bulging combines several pitches and grows with speed and shell temperature [4].

Stiction is evaluated at the 50 ms controller scan with the two-parameter model. Velocity-dependent friction and backlash are not included. Clogging is uniform and is removed only in one piece.

6.4 Implemented Controller

6.4.1 Velocity Form PI Loop

The level controller is the framework's velocity-form PID of Section 1.6.2, which differentiates the measurement rather than the error and executes every $\Delta t = 0.05$ s. The algorithm as coded for this

loop is given by Equations (6.7) to (6.10).

$$e_k = L_{SP} - L^f_{m,k} \tag{6.7}$$

$$P_k = K_c e_k, \qquad D_k = -K_c \tau_D \frac{L^f_{m,k} - L^f_{m,k-1}}{\Delta t} \tag{6.8}$$

$$\Delta u^I_k = \frac{K_c}{\tau_I} e_k \Delta t \tag{6.9}$$

$$\begin{aligned} s_k &= s_{k-1} + (P_k - P_{k-1}) + (D_k - D_{k-1}) \\ c_k &= u_{ff,k} + s_k + I_{k-1} \\ u_k &= \text{clamp}(c_k, 0, 100) \\ I_k &= I_{k-1} + \Delta u^I_k + \frac{\Delta t}{T_t}(u_k - c_k) \end{aligned} \tag{6.10}$$

where L^f_m is the measured level after the optional level filter τ_f, s_k is the running sum of the proportional and derivative increments, c_k is the demanded output, u_{ff} is the canceller feedforward of Section 6.4.3, and $T_t = \tau_I$ is the tracking time. In the symbols of Equations (1.14) and (1.15), s_k is S_k, c_k is v_k and u_{ff} takes the place of the bias u_b. Anti-windup is the back-calculation term of Equation (6.10), which removes $\Delta t/\tau_I = 1/92$ of the excess per scan at the default $\tau_I = 4.6\,\text{s}$ and runs only when integral action is present. The knocker pulse is added after the clamp, $u_{cmd,k} = \text{clamp}(u_k + u_{kn,k}, 0, 100)$, and only u_{cmd} reaches the gate plates, so the integral never sees the pulses. Physics advances by a fourth-order Runge-Kutta step of 0.01 s. The process gain from stroke to level is positive, so a low level gives a positive error and opens the gate. The loop is therefore reverse acting, $a = +1$ in the convention of Section 1.6.2. The derivative time defaults to zero and the optional level filter τ_f to zero, because the measured level is full of surface waves. Transfer between manual and automatic is bumpless in both directions, as Section 1.6.2 describes.

The default tuning follows the SIMC rule for an integrating plant with dead time [17]. The apparent dead time is the measurement delay, the sensor filter, the actuator lag and half a scan, $\theta_a \approx 0.30 + 0.10 + 0.15 + 0.025 = 0.58\,\text{s}$. With the closed-loop time constant $\tau_c = \theta_a$ the rule gives Equation (6.11).

$$\begin{aligned} K_c &= \frac{1}{K_I(\tau_c + \theta_a)} \approx 1.7\,\%/\text{mm} \\ \tau_I &= 4(\tau_c + \theta_a) \approx 4.6\,\text{s} \end{aligned} \tag{6.11}$$

For the same plant the ultimate gain is about $\pi/(2K_I\theta_a) \approx 5.3\,\%/\text{mm}$ and the ultimate period about $4\theta_a \approx 2.3\,\text{s}$. The simulated loop tolerates a little more for small upsets, which still decay at 5.5 %/mm and grow at 6.0 %/mm, because the sensor filter and the actuator lag also lower the loop gain at that frequency, which the dead-time approximation ignores. The top of the integral time slider, 60 s, means no integral action. Volume 2, Chapter 5 identifies and tunes another integrating level, a cooling tower basin, by the same rule.

6.4.2 The Knocker

The knocker adds short pulses to the command in the direction the controller output has been moving [16]. Every period $h_k = 0.5\,\text{s}$ the sign of the change in controller output since the previous pulse is recorded, ignoring changes under 0.005 %, and for the pulse width $\tau_k = 0.1\,\text{s}$ a pulse u_{kn} of amplitude a_k and that sign is added to the command. The default amplitude is 2.0 %, and about half the stick band is the usual starting point. Each pulse carries the plate across part of its stick band, so the gate moves when the controller asks rather than after the error has grown enough to break it free.

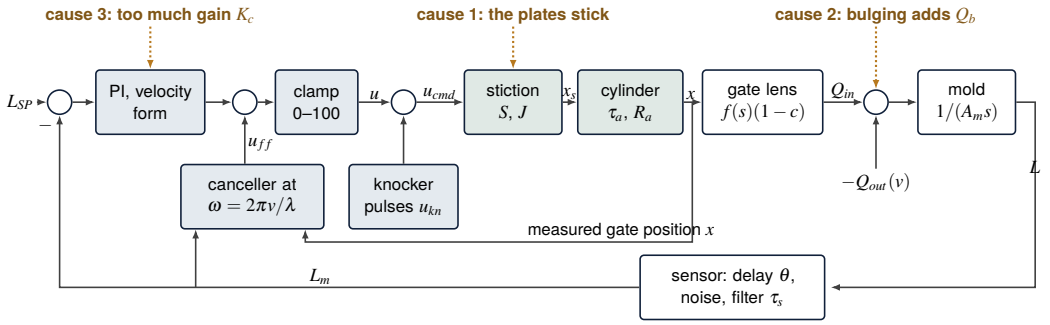


Figure 6.2 The control structure as a block diagram. The PI output and the canceller's feedforward u_{ff} are summed before the clamp, and the knocker's pulses are added after it. The three causes of the chapter enter at three different blocks: the plates' stiction sits between command and gate, bulging adds flow at the mold, and too much gain lives in the PI block. Notice that the mold integrates every flow imbalance, so each cause can make the level swing, and only a test that separates the blocks tells them apart.

> ⧖ HISTORY **The Slide Gate (1885 to 1986)**
>
> The idea of the sliding gate was patented in the United States in 1885, but it was first put into practice at a West German steelworks in 1964 [18]. Its use spread internationally from 1968, and by 1973 it served 115 plants of 80 firms in Japan alone. With no stopper rod in the ladle, pouring could be run by remote control, and its rate was easier to control automatically. Sticking soon showed up as a control problem. A 1986 note reported large level swings caused by solidified steel adhering to the gate and delaying its motion [19]. Its remedy superposed a vibratory signal on the gate command, so that the gate vibrated all the time, and the level fluctuation fell by about 80 percent. The knocker of this chapter pursues the same aim with pulses in one direction only.

6.4.3 The Bulging Canceller

The canceller exploits the fact that the bulging frequency $\omega = 2\pi v/\lambda$ is known. Two least-squares tone estimators track the phasors of the measured level and the measured gate position at that frequency, after a 20 s high-pass, with an averaging time $T_a = 12$ s. The level phasor is moved back through the sensor filter and forward through the delay to the mold, and a flow balance at the one frequency, $j\omega A_m \hat{L} = (\partial Q_{in}/\partial x)\hat{X} + \hat{Q}_b$, turns the two phasors into the phasor of the bulging flow. The gate motion that cancels it is advanced by $\omega\tau_a$ for the actuator lag and corrected for the phase lead of the high-pass, then capped at 15 % of stroke and added to the command as the feedforward u_{ff} in Equation (6.10), in automatic mode only. It ramps in over 5 s when switched on. The estimators run in both modes, so the canceller is warm when it is engaged. Figure 6.2 assembles the level controller, the canceller and the knocker into one block diagram.

6.4.4 Diagnostic Instruments

The interface computes the dominant oscillation period of the last minute of measured deviation once per second. Whether the level is oscillating is decided by the height of the second peak of the autocorrelation, and the period is the mean spacing of upward zero crossings with hysteresis at 30 % of the amplitude, which is $\sqrt{2}$ times the standard deviation of the same minute. It also shows the RMS of the true level and the gate travel per minute, both exponentially weighted with a 30 s time constant, the share of the run outside the slag-entrainment band, the gate reversal rate, and a plot of the controller output against the gate position over the last 40 s, with the healthy diagonal dashed. A thin line along the diagonal is a healthy gate, and a parallelogram whose width is the stick band is stiction [7].

6.5 Results

The nine teaching scenarios and the challenge are listed in Table 6.3 in the order the application offers them, with the teaching point of each and what completes it. A case is credited when the learner performs the listed actions and the simulation reaches the listed state, as Section 1.6.4 describes. The challenge is judged on the case as given, and changing a model parameter or a disturbance voids the attempt. All reported values come from the running application at its default seed, with each setting made before the run starts unless a time is given. Every case with stiction starts with the plate stuck at 57.6 % of stroke, 0.6 % open of balance, because a plate stuck exactly at balance never has a reason to move.

> **+ DID YOU KNOW? A Remedy That Only Adds Wear**
>
> From the simulator: with bulging present and a healthy gate, switching the knocker on moves the level only from 1.93 to 1.78 mm RMS, while the gate travels 2.1 times as far (Table 6.4, case 8). The pulses meant for a sticking gate find nothing to free.

6.5.1 The Integrator and the Healthy Reference

In scenario 1 the gate starts 0.4 % of stroke too far open, a surplus of 0.07 L/s, and the level rises about 0.19 mm/s. Setting the gate to the exact balance stops it, and a clog of half a percent per minute then turns the perfect balance into a 3.2 mm error in one minute (1.9 mm with the stroke rounded to 0.1 %, as the application's balance helper sets it). The manual case makes the absence of self-regulation something the student has to fight rather than read about.

Scenario 2 is the reference. With 0.2 mm of sensor noise the true level holds to 0.13 mm RMS, a 3 mm setpoint step overshoots by 0.99 mm, and the gate still travels 47 % of its stroke per minute chasing noise, which is the baseline wear on a healthy loop.

6.5.2 Three Signatures

The signatures of the three causes are summarized in Table 6.4. With $S = 5\,\%$ and $J = 1.5\,\%$ the level cycles with an RMS of 1.11 mm and a mean period of 13.7 s, although single cycles range from 9.8 to 18.2 s. The gate trace becomes a staircase under a sawtooth command, and the signature plot opens into a parallelogram, as shown in Figure 6.3. Removing integral action does not stop it (1.02 mm RMS in slower, irregular ramps), because the plate breaks free only when the error reaches $f_s/K_c \approx 1.9\,\text{mm}$ and the mold integrates the leftover imbalance in between. Half the gain makes the cycle slower and larger, 3.1 mm in amplitude at a mean period of 24 s, and double the gain makes it smaller, 0.67 mm RMS, while the gate travels 71 % of its stroke per minute against 23 %. The knocker at its default 2.0 % takes the RMS to 0.36 mm, and at 2.5 %, half the stick band, to 0.22 mm, at the price of 83 % per minute of gate travel.

Pause. Try Exercise 6.2 before reading on.

> **TRY IT IN THE APP 3 · A Sticking Slide Gate**
>
> Load scenario 3, A sticking slide gate, and press Run. Watch the gate signature plot in the scene for half a minute. A healthy gate would draw a thin line along the dashed diagonal. This one opens into a parallelogram about one stick band wide, while the gate position on the lower trend climbs in steps under a sawtooth command.

Bulging of 4 mm open-loop amplitude at 12.5 s appears as a 2.7 mm amplitude in automatic. Opening the loop with the gate held at the balance stroke increases it to 3.9 mm, which identifies an external disturbance, and raising the speed to 1.5 m/min shortens the period to 10.0 s, exactly roll pitch over the new speed, which identifies bulging. More gain shrinks this oscillation too, which is why the gain alone cannot tell it from stiction. Double the gain gives 1.3 mm, and half the gain

Table 6.3 Scenarios and Completion Requirements

#	Scenario, teaching point and kind	Required to complete
1	Hold the meniscus by hand *the integrator, manual* (experiment)	In Manual, let the level drift at least 1.5 mm from 100 mm, move the gate command to bring it back, then hold it within 1 mm of 100 mm and moving less than 0.05 mm/s for 5 s, and leave the gate alone in Manual for 60 s.
2	A healthy loop *reference trend* (experiment)	After 30 s in Auto, raise the setpoint from 100 to 103 mm and hold the level within 0.5 mm of 103 mm for 10 s.
3	A sticking slide gate *stiction signature* (experiment)	Watch 30 s of the stick-slip cycle at the shipped tuning, run 60 s proportional only ($\tau_I = 60$ s), then 30 s with $\tau_I = 4.6$ s restored and the knocker on.
4	Bulging between the support rolls *open the loop, move ω* (experiment)	Run in Auto until an oscillation period is measured, open the loop with the gate at the balance stroke for 60 s without a level alarm, return to Auto and raise the speed by 0.3 m/min, then run 30 s at 1.5 m/min with the canceller on.
5	Too much gain *the delay ceiling* (demonstration)	Run to 100 s at $K_c = 5.0\,\%/\text{mm}$ through the setpoint step at 20 s, then 30 s at $K_c = 2.5\,\%/\text{mm}$, then 20 s at $K_c = 5.5\,\%/\text{mm}$.
6	All three at once *the order of repairs* (experiment)	Watch 30 s as loaded, then 30 s each at $K_c = 1.7\,\%/\text{mm}$, with the canceller added, and with the knocker added, in that order.
7	Two faults, one trend *the speed-change test* (experiment)	Read the oscillation period before the speed rise at 90 s, run 60 s at 1.6 m/min with both add-ons off, then 30 s with the canceller on and 30 s more with the knocker added.
8	The knocker on the wrong fault *the price of a wrong remedy* (experiment)	Run 60 s with the knocker on, Reset and switch it off, run 60 s without it, then 30 s with the canceller on instead.
9	A clogging nozzle *a leading indicator* (demonstration)	Run until the gate passes 62 % with the level within 1 mm of setpoint, through the clog release at 240 s with the level more than 2 mm high, until it holds within 0.5 mm of 100 mm for 10 s.
10	Challenge *graded run* (challenge)	Keep the true level within ± 1.5 mm of setpoint from 200 to 300 s, through the speed rise from 1.2 to 1.5 m/min at 60 s, with the model parameters and disturbances as given.[a]

[a] With the shipped settings ($K_c = 3.0\,\%/\text{mm}$, no add-ons) the largest deviation over the scored window is 3.34 mm, more than twice the band. With the suggested settings ($K_c = 1.7\,\%/\text{mm}$, $\tau_I = 4.6$ s, knocker at 2.5 %, canceller on) it is 0.77 mm, inside the band with 0.73 mm to spare. The knocker and the canceller together are enough at the shipped gain (1.24 mm with the default 2.0 % knocker), as the challenge text states.

gives 4.8 mm, larger than with the loop open because the loop then amplifies at this frequency. The canceller takes the level back to 0.14 mm RMS, the noise floor of the healthy loop (0.13 mm).

Pause. Try Exercise 6.1 before reading on.

TRY IT IN THE APP 4 · Bulging Between the Support Rolls

Load scenario 4 and run until the Oscillation period tile shows a value near the 12.5 s of the Bulging period at this speed tile. Switch to Manual and press Gate to balance: the swing grows from 2.7 to about 3.9 mm, so the cause lies outside the loop. Back in Auto, press Speed +0.3 m/min, and the period falls to 10.0 s.

Tripling the gain to 5.0 %/mm produces the third signature. A 3 mm setpoint step overshoots by 3.8 mm, and the gate spends most of the next 12 s at its 15 %/s speed limit, so the first swings are 3.8 s apart and shorten to 2.3 s as they decay. The loop then keeps ringing on the sensor noise with a mean period of 2.7 s, far faster than either of the other two, and the gate travels 380 % of its stroke

Table 6.4 Measured Oscillation Signatures

Case and change	Level	Other
3, stiction, SIMC	1.11 mm RMS	period 13.7 s
3, proportional only	1.02 mm RMS	irregular
3, half gain	3.1 mm amplitude	period 24 s
3, double gain	0.67 mm RMS	travel ×3.1
3, knocker 2.0 %	0.36 mm RMS	travel ×1.5
3, knocker 2.5 %	0.22 mm RMS	travel ×3.6
4, bulging, automatic	2.7 mm amplitude	period 12.5 s
4, loop opened[a]	3.9 mm amplitude	external
4, speed 1.5 m/min	—	period 10.0 s
4, double gain	1.3 mm amplitude	—
4, half gain	4.8 mm amplitude	amplified
4, canceller	0.14 mm RMS	noise floor
5, $K_c = 5.0$[b]	overshoot 3.8 mm	ring 2.7 s
5, $K_c = 5.5$[b]	runs away	saturation
8, knocker, no stiction	1.93 to 1.78 mm RMS	travel ×2.1
9, clog release[b]	4.4 mm spike	gate 57.0 to 64.4%

Each change is made before the run. RMS and amplitude ($\sqrt{2}$ times the standard deviation) are of the true level, and they, the mean period and the gate travel ratio are taken from 120 to 480 s unless marked. [a] One minute in manual at the balance stroke from 36 s. [b] Scripted events as loaded (setpoint step at 20 s, clog release at 240 s).

per minute over the minute after the step. Half the gain removes the ringing, with a 1.6 mm overshoot and 0.19 mm RMS at 120 s. The speed limit also turns the stability margin into a cliff. With the gain at 5.1 %/mm or more when the step arrives, the swings grow instead of decaying, and at 5.5 %/mm the gate saturates 9.8 s after the step and the level alarm follows at 37 s. The same 5.5 %/mm set after the step has passed rings with swings of up to 2.4 mm over the next four minutes but does not run away, so where the cliff lies depends on the size of the upset as well as on the gain.

6.5.3 Combined Faults and the Order of Repairs

Scenario 6 combines all three at $K_c = 4.5\,\%/\text{mm}$. The level RMS is 0.97 mm and the gate travels 205 % of its stroke per minute, more than four times the healthy loop. Bringing the gain back to 1.7 %/mm first makes the RMS jump to 3.1 mm, because the high gain was holding the bulging down. The canceller then takes it to 1.29 mm and the knocker to 0.49 mm, with the gate traveling 87 % per minute. Adding the knocker while the gain is still 4.5 %/mm, with or without the canceller, pushes the loop over its stability cliff (29 mm RMS with both, the gate saturated 67 % of the time), so the order of the repairs matters as well as their choice.

🕮 **Pause.** Try Exercise 6.3 before reading on.

Scenario 7 has stiction and bulging together with nearly the same period at 1.2 m/min, which is the case the trend alone cannot resolve. The speed starts to rise toward 1.6 m/min at 90 s and reaches it at 170 s. The bulging then moves to 9.3 s (9.4 s computed), while stiction on its own cycles at 13.7 s at 1.2 m/min and 13.4 s at 1.6 m/min. The canceller alone takes the RMS from 3.7 mm to 1.3 mm over two minutes. It needs 5.0 % of gate motion either way at the higher speed, and that motion has to get through plates that stick by 5 %, so adding the knocker brings the RMS to 0.50 mm.

A remedy applied to a cause that is not present costs wear and buys nothing. The knocker on a healthy gate with bulging present doubles the gate travel, from 104 to 220 % per minute, while the level RMS moves only from 1.93 mm to 1.78 mm. The canceller in its place gives 0.14 mm with 86 % per minute of travel. A clog of 4 % per minute walks the gate from 57.0 % to 64.4 % while the true level stays within 0.41 mm of setpoint, and the process gain drifts from 0.51 to 0.44 mm/s per percent. The release at 240 s spikes the level 4.4 mm within 2 s, and the loop holds it within 0.5 mm again from 248 s. The gate position is the leading indicator of the clog, not the level.

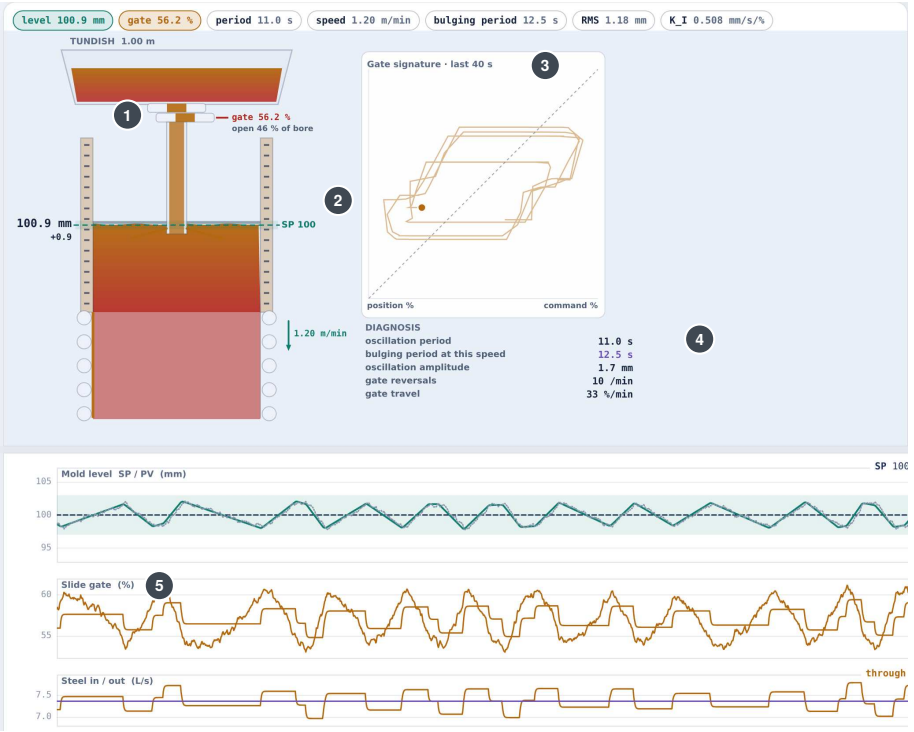


Figure 6.3 Mold level loop with a sticking slide gate, scenario 3, at 190 s with the SIMC tuning in automatic, cropped to the caster view and the trends. The caster section on the left shows the tundish, the slide gate (1) at 56.2 % stroke, the mold with the setpoint and the slag-entrainment band (2), and the strand between its rolls. The gate signature (3) plots controller output against gate position over the last 40 s and has opened into a parallelogram about one stick band wide, and the diagnosis readouts (4) sit below it. The trends show the true level cycling about 4 mm peak to peak with the sensor reading dotted, the gate position (5) moving as a staircase under a sawtooth command, and the gate flow stepping about the constant withdrawal of 7.36 L/s. The level RMS reads 1.18 mm at this instant.

6.5.4 The Graded Challenge

The challenge combines stiction, 4 mm bulging and a gain of 3.0 %/mm, with a speed rise from 1.2 to 1.5 m/min starting at 60 s. It is met when the true level stays within 1.5 mm of setpoint from 200 to 300 s, read from the 10 Hz record. Table 6.5 reports the largest deviation in that window for each combination of remedies, and Figure 6.4 draws the same numbers as a chart.

Retuning alone makes the peak worse, 5.31 against 3.34 mm, for the same reason as scenario 6. Each remedy on its own removes only its own cause, so neither the knocker (3.86 mm) nor the canceller (2.22 mm) meets the target after the retuning or at the shipped gain, and neither passes on its own at any gain tried from 1.7 to 4.0 %/mm. The three together give 0.77 mm with a level RMS of 0.26 mm at the end of the run. The two add-ons also pass without the retuning, at 0.87 mm, because 3.0 %/mm is well below the gain at which the loop of scenario 5 tips over. The retuning buys margin, 0.77 against 0.87 mm, rather than the pass itself, and the application's challenge text says so.

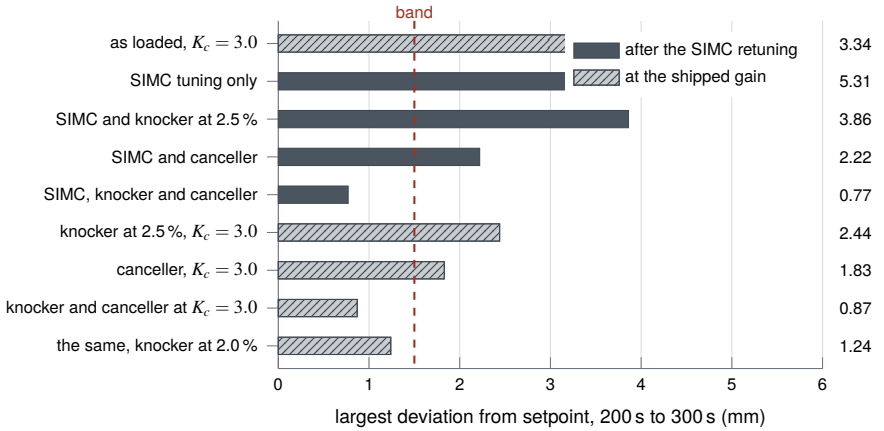


Figure 6.4 The graded challenge of Table 6.5 as a chart: the largest deviation of the true level in the scored window for each combination of remedies, after the SIMC retuning (solid) and at the shipped gain (hatched), against the band of 1.5 mm (dashed). Values are in the column at the right. Notice that retuning alone makes the peak worse than as loaded, that no single remedy passes, and that the knocker and the canceller together pass at either gain.

Table 6.5 Challenge: Largest True Level Deviation From 200 to 300 s

Configuration	Deviation (mm)
as loaded, $K_c = 3.0$	3.34
SIMC tuning only	5.31
SIMC and knocker at 2.5 %	3.86
SIMC and canceller	2.22
SIMC, knocker and canceller	0.77
knocker at 2.5 %, $K_c = 3.0$	2.44
canceller, $K_c = 3.0$	1.83
knocker and canceller at $K_c = 3.0$	0.87
the same, knocker at 2.0 %	1.24

6.6 Technology in Practice

What Measures It

The controlled variable of this chapter is the meniscus level, read by a sensor above the mold. Not every mold level sensor is an eddy-current coil. An electrode-type sensor of 1982 kept its electrode at a constant electrical resistance in the slag layer with a servo drive, over a range of 500 mm with a response time of 1 s [11].

TECHNOLOGY Sensor: The Eddy-Current Mold Level Meter

An eddy-current meter hangs a coil a short distance above the meniscus. The coil carries a high-frequency alternating current that induces eddy currents in nearby metal, and the closer the metal, the stronger the currents and the heavier the load on the oscillator that drives the coil [20]. The mold powder conducts too once it melts, but at a low frequency such as 10 kHz the coil impedance is almost unaffected by the thickness of the molten layer [21]. A non-contact meter of this kind described in 1984 read the steel level through the powder to within 1 mm with a quick response, and a differential coil made it more stable against the position of the mold wall [22]. A detector 30 mm across fitted billet molds.

In the model of Section 6.3 the sensor is the 0.30 s delay, the colored noise and the 0.10 s filter, clamped to a 200 mm span. A real meter also sees the surface waves and jets that the model represents only as band-limited noise.

What Moves It

The flow from the tundish into the mold is controlled by a stopper rod or by a slide gate [23]. Where a stopper is used, the most common measure of clogging in a plant is the rise of the stopper rod position. It climbs sharply when the clog is severe, and the casting speed must then be reduced and the nozzle replaced. The final element is thus also the plant's clog gauge, as the gate position is in scenario 9.

TECHNOLOGY Final Element: The Slide Gate

A slide gate controls the flow by sliding one refractory plate across another, so that their holes overlap more or less [18]. The sliding faces are polished very precisely so that steel cannot leak between them, and the plates must keep their strength when hot and resist abrasion and corrosion, and a hydraulic cylinder moves the plate. A plate that sticks jumps to a new position only when enough force has built up, and on an integrating process the measurement then changes slope at every slip [20]. Deposits in the nozzle below act on the same flow: slight clogging may at first raise the flow rate, but heavy clogging restricts the channel [23].

The simulated gate is the lens of two 70 mm bores, moved by a cylinder with a 0.15 s lag and a 15 %/s speed limit, and its sticking is the stick band S and slip jump J of Equation (6.5). Figure 6.5 draws the loop with these devices in place.

Where the Controller Runs

A loop this fast runs in a local controller. Programmable logic controllers serve as local controllers within the supervisory scheme of a distributed control system and carry proportional integral derivative (PID) control among their functions, and control loops run with cycle times from milliseconds to minutes [24]. The simulated controller executes every 0.05 s. Its velocity-form PI block, the knocker added after the clamp and the canceller feedforward would share one fast task. Records kept for analysis are often slower than the loop: one forecasting study used plant data sampled at 1 Hz [25].

IN PRACTICE Check the Gate Before You Retune

Before any tuning, a field handbook advises checking instrument health with small up-and-down steps of the output in manual, after asking operations how far the output may move and the measurement may drift [20]. The steps show how much stiction the final element has. The same text warns that a sticky valve cannot be fully overcome by tuning: on an integrating process, less proportional gain lowers the frequency of the cycle but does not end it. A study of ten refinery loops adds the cost argument [1]. Special tests cost labor and lost production, and where the signature points to a valve nonlinearity there is little benefit in retuning. The valve is better examined at a scheduled shutdown and replaced if necessary.

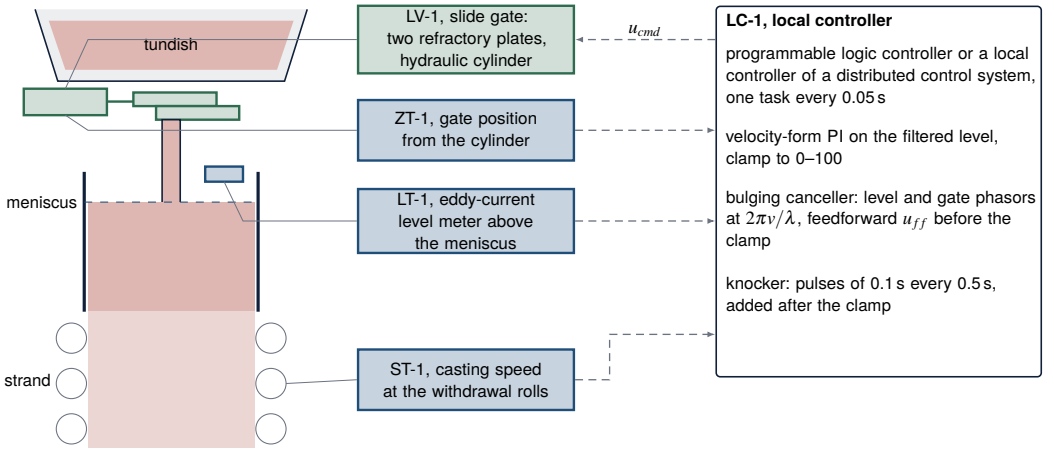


Figure 6.5 The mold level loop drawn with its hardware. The eddy-current meter LT-1 reads the meniscus, ZT-1 the gate position and ST-1 the casting speed, and the local controller LC-1 sends one gate command to the slide gate LV-1. Notice that the canceller and the knocker need no extra hardware: both live in the controller task, and the one gate command carries the sum of all three.

What Is Modernizing It

Loop performance assessment computes figures of merit from routine data without taking loops off line, and in 1997 it was becoming widely used in the petrochemical, chemical and paper industries [1]. Its oscillation signatures point the engineer to the special test that is most likely to confirm the cause, the approach of Volume 1, Chapter 13. Learning-based forecasting is a second development. A sequence model trained on plant records from 13 casts, 2.2 million points in all, predicts the next ten one-second samples of the mold level fluctuation, and in its tests the mean absolute error fell from 0.517 to 0.150 against a benchmark of the same kind trained with a plain squared-error loss [25]. A third acts on the flow itself. Superimposed alternating and direct magnetic fields in the mold roughly halved the surface defects on steel sheet in trials on an industrial caster, compared with a direct field alone [26]. The present model has no electromagnetic brake, as Section 6.7 states.

6.7 Limitations

The flat meniscus leaves out the surface waves and jet effects that dominate real mold level signals [9]. Their absence makes the signature plot cleaner than it is on a plant, where the same test is run on a noisier signal with more averaging.

Bulging is one tone. Real unsteady bulging carries several frequencies from roll segments of different pitch, and a canceller built for one of them leaves the others [4, 15].

> ⚠ **OPEN CHALLENGE** **Bulging at High Casting Speed**
>
> Mold level hunching from unsteady bulging has been called a main obstacle to raising the casting speed of thin slab casters, which cast strands 50 to 100 mm thick at about three times the speed of conventional slab casters [27]. In 2002 its origin and detailed mechanism were still not clearly known. Casters suppress it with more secondary cooling water and roll pitches that do not repeat [4], and the roll gap on a running caster is hard to measure directly. Progress would be a roll layout and a cooling practice that keep the bulging below what the level loop can reject at the highest speed.

The stiction model is data-driven rather than physical, so it reproduces the signature of a sticking gate but not the effect of temperature and refractory wear on the stick band [7].

The oscillation period reading wanders on an irregular stick-slip cycle, between 10.9 and 16.6 s over the first eight minutes of scenario 3, because it averages the three to five upward crossings of the last minute while single cycles range from 9.8 to 18.2 s. The level RMS and the gate travel are steadier, and the stick-slip periods quoted here are means over six minutes.

There is no stopper rod, no argon control and no electromagnetic braking, all of which interact with the level loop on modern casters.

OPEN CHALLENGE **Clogging Nozzles in New Steel Grades**

Alumina clogging was still a major issue in slab casting in 2000 [5], and a 2024 review finds it unsolved for two growing families of steel [23]. High aluminum steels for lighter cars change the inclusions and the reaction with the nozzle refractory, and rare earth treated steels form solid inclusions that are hard to remove. Most remedies in use touch the steel, such as nozzle materials and coatings, and can affect its cleanliness. The review points to non-contact treatment by external magnetic or electric fields, and to several methods coordinated together.

6.8 Conclusion

A mold level loop that oscillates can be oscillating for three unrelated reasons, and the simulator of this chapter makes each of them identifiable with the test that plant engineers use. A sticking gate with a 5 % stick band cycles at 1.11 mm RMS with integral action and 1.02 mm without it and draws a parallelogram on the command against position plot, and a knocker at half the stick band takes it to 0.22 mm. Bulging survives opening the loop, growing from 2.7 mm to 3.9 mm, and moves with the casting speed exactly as roll pitch over speed predicts, and a canceller at that one frequency returns the level to the 0.14 mm noise floor. Too much gain rings at about 2.7 s and is cured by halving it. Applied to the wrong cause, each remedy costs gate travel and fixes nothing, and in the challenge no single remedy meets the target while the three together bring the largest deviation from 3.34 mm to 0.77 mm. The model leaves out surface waves, multiple bulging frequencies and the physics behind the stick band. A fuller model would add a stopper rod, multiple roll pitches, electromagnetic braking and an automated stiction test. The caster is an accessible browser case for diagnosing an oscillation before treating it.

KEY POINTS

- The level in the mold can swing because the gate sticks, the strand bulges or the controller pushes too hard, and the three swings look alike.
- A sticking gate cycles even without integral action, and a knocker at half the stick band takes the level to 0.22 mm RMS.
- Bulging survives opening the loop and moves with the casting speed, and a canceller at its frequency returns the level to the 0.14 mm noise floor.
- A remedy on the wrong cause costs gate travel and fixes nothing. In the challenge only all three remedies together bring the peak from 3.34 to 0.77 mm.

Where else this applies. A sticking steam valve in Volume 2, Chapter 4 and a disturbance whose frequency the speed sets in Volume 7, Chapter 11 call for the same diagnosis before treatment.

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6.9 Exercises

6.1 Concept check · 2 min

In scenario 4, Bulging between the support rolls, the true level swings with an amplitude of 2.7 mm in automatic at the SIMC tuning. With the loop switched to Manual and the gate held at the balance stroke, the swing grows to 3.9 mm. What does this test show?

(a) The loop makes the oscillation itself, and opening it removed the damping the controller supplied

(b) The oscillation enters from outside the loop, and the controller had been taking part of it off

(c) The gate plates stick, because a held gate cannot move and the mold integrates whatever imbalance is left

(d) The sensor delay sets the period, so the swing in Manual is the true one and the swing in Auto is filtered

6.2 Concept check · 1 min

In scenario 3, A sticking slide gate, the integral time is set to 60 s, which removes integral action. The level still cycles, at 1.02 mm RMS against 1.11 mm with the SIMC tuning. Why does the cycle survive?

(a) The knocker keeps adding pulses that break the plate free at regular intervals

(b) The proportional gain of 1.7 %/mm lies above the ultimate gain of the loop

(c) The mold integrates the imbalance while the plate is stuck, until the error breaks it free

(d) The setting of 60 s still leaves a slow integral that winds up between the slips

6.3 Concept check · 2 min

Scenario 6, All three at once, ships at $K_c = 4.5\,\%/\mathrm{mm}$ with a sticking gate and 4 mm of bulging, and the level RMS is 0.97 mm. Lowering the gain to 1.7 %/mm first raises the RMS to 3.1 mm. What is the right reading of that rise?

(a) The SIMC tuning does not suit this plant, so the gain should go back to 4.5 %/mm

(b) The lower gain has enlarged the stiction cycle, which shows that stiction is the main cause

(c) The lower gain has brought the loop to its stability limit, where it amplifies every upset

(d) The high gain was holding the bulging down, and the retuning has unmasked it for the canceller

6.4 Theory and calculation · 5 min

The mold has the integrating gain $K_I = 0.51\,\mathrm{mm/s}$ per percent of stroke. The measurement delay is 0.30 s, the sensor filter 0.10 s, the actuator lag 0.15 s and the controller scan 0.05 s.

(a) Find the apparent dead time θ_a, counting half a scan, to two decimals. *Checkpoint:* 0.58 s.

(b) With $\tau_c = \theta_a$, find the SIMC gain and integral time of Equation (6.11). *Checkpoint:* $K_c \approx 1.7\,\%/\mathrm{mm}$, $\tau_I \approx 4.6\,\mathrm{s}$.

(c) Derive the ultimate gain and period of an integrator with dead time θ_a, evaluate them, and find the gain margin of the SIMC loop. *Checkpoint:* 5.3 %/mm, 2.3 s, a margin of about 3.1.

6.5 Theory and calculation · 6 min

The gate of scenario 3 has $S = 5\,\%$ and $J = 1.5\,\%$ and starts stuck at 57.6 % of stroke, where the balance stroke is 57.0 %. Each percent of stroke is worth 0.18 L/s, the free surface is $A_m = 0.353\,\mathrm{m}^2$ and $K_c = 1.7\,\%/\mathrm{mm}$.

(a) Find the static and kinetic bands f_s and f_d, and show that every breakaway ends in a jump of J. *Checkpoint:* $f_s = 3.25\,\%$, $f_d = 1.75\,\%$, jump 1.5 %.

(b) Find the surplus flow while the plate stays stuck and the rate at which the level rises. *Checkpoint:* 0.11 L/s and 0.31 mm/s.

(c) With proportional action only and the level starting at setpoint, find the measured error at which the plate breaks free and estimate when that happens. *Checkpoint:* 1.9 mm, after about 6 s plus the sensor delay.

6.6 Theory and calculation · 5 min

Bulging of open-loop amplitude $a_b = 4\,\text{mm}$ acts on a mold with $A_m = 0.353\,\text{m}^2$ between rolls of pitch $\lambda = 0.25\,\text{m}$. At 1.2 m/min the gate gives 0.180 L/s per percent of stroke, and at 1.6 m/min, where it sits further open, 0.190 L/s per percent.

(a) Find the bulging period and angular frequency at each speed. *Checkpoint:* 12.5 s and 0.503 rad/s; 9.4 s and 0.670 rad/s.

(b) Find the amplitude of the bulging flow Q_b at each speed. *Checkpoint:* 0.71 L/s and 0.95 L/s.

(c) Find the gate motion a canceller must make to cancel it at each speed, and compare it with the stick band of the gate in scenario 7. *Checkpoint:* 3.9 % and 5.0 %, against $S = 5\,\%$.

6.7 App challenge · 9 min

Load scenario 3, A sticking slide gate, at the default seed. Make three runs to 480 s at speed 10 (48 s of wall time each), reloading the case with the reload button before each and making the change before Run: (i) as loaded, (ii) Knocker on, (iii) Knocker on with Knocker amplitude at 2.5 % (Knocker settings). Export the CSV file after each run. Use the rows from 120 to 480 s.

(a) Compute the RMS of `level_error_mm`, the true level minus setpoint, for each run, within 0.02 mm. *Checkpoint:* 1.11, 0.36 and 0.22 mm.

(b) Compute the gate travel per minute as the sum of the absolute changes of `gate_pos_pct` divided by 6 min, within 2 %/min, and its ratio to run (i). *Checkpoint:* 23, 34 and 83 %/min; ratios 1.5 and 3.6.

Which run would you keep on a plant until the plates are changed, and why is 2.5 % called half the stick band?

6.8 App challenge · 8 min

Load scenario 4, Bulging between the support rolls, at the default seed, and run at speed 5. Read each tile within 0.2 s.

(a) Run to about 120 s as loaded and read the Oscillation period and the Bulging period at this speed tiles. *Checkpoint:* 12.5 s and 12.5 s.

(b) Reload the case, pause at about 60 s, press Speed +0.3 m/min, run on to about 180 s and read the same two tiles. *Checkpoint:* 10.0 s and 10.0 s.

(c) Reload the case, set Proportional gain to 3.4 %/mm before Run, run to 480 s at speed 10 and export the CSV file. Compute the amplitude, $\sqrt{2}$ times the standard deviation of `level_error_mm` from 120 to 480 s, within 0.05 mm. Repeat at 0.85 %/mm. *Checkpoint:* 1.27 mm and 4.81 mm.

Which result names the cause, and why can the gain alone not tell bulging from stiction?

6.9 App challenge · 9 min

Load the challenge, A speed change on a bad day, at the default seed. Run each attempt the full 300 s at speed 10 and read the result the app gives at 300 s, the worst level error from 200 to 300 s (the largest $|$`level_error_mm`$|$ from 200 s in the CSV file gives the same value), within 0.02 mm.

(a) Run the case as loaded. *Checkpoint:* 3.34 mm, a fail.

(b) Press Reset, switch the Knocker and the Bulging canceller on with Proportional gain left at 3.0 %/mm, and run again. *Checkpoint:* 1.24 mm, a pass.

(c) Press the reload button, set Proportional gain to 1.7 %/mm with both add-ons off, and run again. *Checkpoint:* 5.31 mm, a fail.

Explain why the retuning alone makes the result worse, and what the retuning adds once both add-ons are on.

6.10 Application area · 4 min

In scenario 9, A clogging nozzle, the clog grows at 4 % per minute until it breaks away at 240 s. The withdrawal is 7.36 L/s and $A_m = 0.353\,\mathrm{m}^2$.

(a) Find the clog fraction at the release and the share of extra steel the same gate stroke passes once the clog is gone. *Checkpoint:* 0.16 and 19 %.

(b) Find the extra flow and the rate at which the level starts to rise, and compare the measured 4.4 mm spike with the ± 5 mm slag-entrainment band. *Checkpoint:* 1.40 L/s, 4.0 mm/s; inside the band by 0.6 mm.

What should the operator trend to see the clog coming, and why does the level trend not show it?

6.11 Application area · 3 min

The model's bulging is one tone at one roll pitch. Suppose a strand has segments of 0.25 m and 0.30 m pitch.

(a) Find the two bulging periods at 1.2 m/min and at 1.5 m/min. *Checkpoint:* 12.5 and 15 s; 10 and 12 s.

(b) What would the speed-change test show, and what would a canceller locked to the 0.25 m frequency leave in the level? *Checkpoint:* Both periods shorten by the same ratio. The 0.30 m component is left.

6.12 Review the agent · 5 min

A process engineer asks an AI assistant about scenario 4. The assistant replies: "The level swings 2.7 mm at $K_c = 1.7\,\%/\mathrm{mm}$, and doubling the gain cut it to 1.3 mm. So the bulging is a tuning problem. Raise K_c to 4.5 %/mm and the swing will fall below 1 mm with no new equipment." Find the flaw, and say how you would check the claim in the app before acting on it.