Online control of spray cooling using Cononline

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Outline

• Brief overview of Cononline project
• Challenges in dynamic control of spray cooling
  – Saturation and anti-windup
  – Setpoint choice
  – Sticker slowdowns
• Offline simulator
• Simulation example: sticker slowdown
Overview

Overview: Consensor

- **Con1d**
  - Fundamentally-based heat transfer and solidification model of continuously cast strand
  - Assumes heat transfer in axial direction is dominated by flow of material at casting speed (true at typical casting speeds)
  - Simulates a 1-D “slice” through the centerline of the strand, moving down the caster at casting speed

- **Goal:**
  - Apply Con1d as the basis of a real-time model of the strand
  - Then, use model for “feedback” control of water cooling sprays instead of relying on pyrometers
Overview: Consensor

- Consensor: “Software sensor”
  - Manages 200 Con1d slices
  - Each second, gets updated casting conditions from Level 2, simulates each slice for 1 second of travel at casting speed
  - Uses “delay interpolation” for points in between slices

Nucor Decatur cooling sprays

4 x 1 + 3 x 2 = 10 separate spray zones, along centerline
Overview: Concontroller

• Each spray zone is controlled by a separate PI controller
• Every second, for each zone, $j$
  1. Calculate the average tracking error:

$$\Delta T_j = \text{measured} - \text{predicted}$$

2. Calculate the spray-water flow rate command for the next time interval, via the classic PI control law:

$$u_j(t + \Delta t) = u_j^*(t + \Delta t) + u_j'\Delta t$$

$$u_j^*(t + \Delta t) = k^j \Delta T_j(t)$$

$$u_j'(t + \Delta t) = u_j'(t) + k^j \Delta T_j(t)\Delta t - k^j_{\text{predicted}} [u_j^*(t) - u_j(t)]$$

• Additional term on integral is anti-windup correction to prevent delays after saturation

3. Send spray rates to all other programs

Overview: Programs

• Programs run on separate computers for stability and speed
  – Consensor runs on CentOS Linux
  – Concontroller runs on Slackware Linux
  – Communicate with each other and Level 2 via TCP/IP programs written by Rob Oldroyd (Nucor Decatur)
  – Also send information to Windows PCs via monitor programs
Overview: Monitor

Anti-windup: benefits

• In normal casting conditions, some valves may be fully open or closed
• After the valve can’t move any further, the integral controller continues to integrate (windup) and takes a while to return to normal
• Anti-windup subtracts the difference between controller and actuator to reduce this delay

Valve fully open, not hitting setpoint
Anti-windup: problems

- However, too aggressive anti-windup was found to over-react to chattering in the spray valves
  \[ u_j'(t + \Delta t) = u_j'(t) + k_j' \Delta T_j(t) \Delta t \]
  \[ -k_j^m \left[ T_j(t) - T_j(t) \right] \]

- We responded to this by averaging the error signal before anti-windup
  \[ u_j'(t + \Delta t) = u_j'(t) + k_j' \Delta T_j(t) \Delta t \]
  \[ -k_j^m \frac{1}{N} \sum_{n=0}^{N-1} \left[ \frac{T_j(t - n\Delta t) - T_j(t - (n-1)\Delta t)}{\Delta t} \right] \]

Flow rate legend
- Measured flow rate
- Concontroller suggest flow rate

Setpoints

- Cononline setpoints are based on spray table, estimate mold heat removal based on mold flux properties
  \[ f = 4.63 \times 10^4 \mu^{0.54} T_m^{1.26} \exp \left[ 1 - 0.152 \exp \left( \frac{0.107 - \rho \gamma}{0.027} \right) \right] \]

- Formerly, interpolated setpoints in top 4 zones with respect to actual mold conditions
- Nucor Decatur wants to use Cononline to fix the temperature in the bender (zones 2 and 3)
- PI control reacts to differences in mold heat removal by changing the sprays drastically in upper zones

Setpoints

• Regenerated setpoints
  – instead of equation (*), used average recorded mold heat removal at Nucor Decatur over last year

• Results are much better, but there may be other differences to account for
  – Grade?
  – Mold flux?

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26% increase

Sticker slowdowns

• Dynamic controller also may have problems dealing with unusual casting conditions, e.g. sticker slowdowns

• Sticker detection:
  – Shell surface touches mold hot face, leading to thin spot in shell
  – Nucor Decatur breakout detection alarm is triggered when mold thermocouples drop suddenly in temperature
  – Typically have more false positives than actual detections

• Caster response:
  – Immediately slowed to 20 ipm to prevent breakout
  – Sprays are taken from spray table at 80 ipm (higher spray rates than 20 ipm) to prevent bleeders
Sticker slowdowns

- Cononline response
  - Cononline is only given average heat removal rate in mold, so it does not predict the localized thin spot in the shell
  - Because of sudden drop in temperature due to the slowdown, the PI controller reaction is turn all sprays down

- Added some extra logic to Concontroller to handle this:
  - In first three zones (through the bender) the controller uses the 80 ipm flow rates instead of applying temperature control

Light blue boxes: spray table at 80 ipm
Dark blue outlines: spray table at 20 ipm

Tuning Con1d to Nucor
Decatur caster: pyrometers

Original heat transfer coefficients

New heat transfer coefficients

(Xiaoxu Zhou)
Offline simulator

- Implementing Cononline as an offline simulator
  1. “Offline” monitor allows direct user input of casting conditions
  2. Database querier in Excel pulls conditions by caster, sequence, heat, slab, and/or time and date, sends to “replay” program that feeds data to Consensor

- Potential uses:
  - Testing out new casting practices prior to implementation
  - Defect or event investigation
  - Operator training

Nucor Decatur database querier
Offline simulator

Simulation – Sticker slowdown
Thank you

- NSF grants
  - GOALI DMI 05-00453 (Online)
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  - Xiaoxu Zhou, Huan Li (former student), Sami Vapalahti, Hemanth Jasti
- Nucor Decatur
  - Level 2 programmers: Rob Oldroyd, Teri Morris, Kris Sledge, James
  - Metallurgists: Ron O’Malley, Bob Williams
  - Electrical: Steve Dunnivant, George, Bill James, Jeff White
  - Caster supervisors and operators: Scott Ridgeway, Caster Green, Rodney Thrasher, Bryan Thornton, Josh
  - Everyone else
- Continuous Casting Consortium members (ABB, Arcelor-Mittal, Baosteel, Corus, LWB Refractories, Nucor Steel, Nippon Steel, Postech, Posco, ANSYS-Fluent)