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Modeling and Control of Mold Oscillation

Vivek Natarajan (Ph.D. Student),
Joseph Bentsman

Department of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign

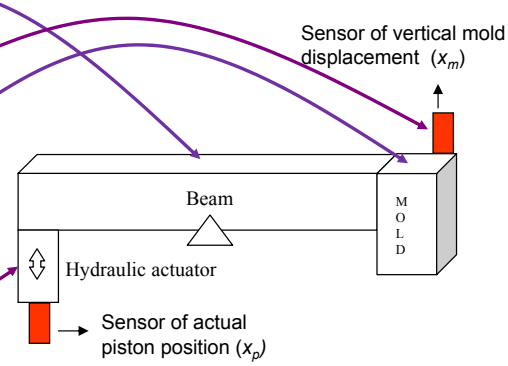
Mold oscillation system at NUCOR

System Objective: Provide vertical oscillatory mold motion characterized by distortion-free pure sinusoidal mold displacement and velocity profiles

Problem:
1. Resonance mode of primary beam gets excited when the actuator oscillates at ***one-third*** the resonance frequency
2. This unwanted resonance distorts the mold displacement and velocity profiles

Project Objective: Model this mold oscillation system, simulate it, identify the source of disturbance and control it

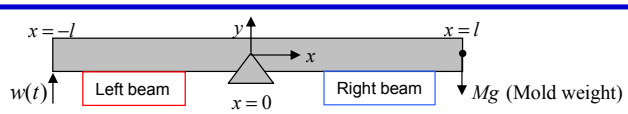
Simplified instrumented mock-up



- Mock-up captures similar resonance problem
  - 1) resonant frequency = 9.6Hz
  - 2) input at 4.8Hz excites 9.6Hz
- Hydraulic valve/actuator – Nonlinear behavior (same model as plant)

Note: Although the velocity signal is of importance, we focus on position signals, since a distortion free pure sinusoidal position signal guarantees a distortion free velocity signal.

Timoshenko beam model



1D dynamic beam transverse displacement PDE

$$\frac{\partial}{\partial x}\left(k'GA\left(\frac{\partial y_L}{\partial x}-\psi_L\right)\right)-mg-\gamma_L\frac{\partial y_L}{\partial t}-m\frac{\partial^2 y_L}{\partial t^2}=0$$

$$\frac{\partial}{\partial x}\left(k'GA\left(\frac{\partial y_R}{\partial x}-\psi_R\right)\right)-mg-\gamma_R\frac{\partial y_R}{\partial t}-m\frac{\partial^2 y_R}{\partial t^2}=0$$

1D dynamic beam bending angle PDE

$$\frac{\partial}{\partial x}\left(EI\frac{\partial \psi_L}{\partial x}\right)+k'GA\left(\frac{\partial y_L}{\partial x}-\psi_L\right)-\gamma_L\frac{\partial \psi_L}{\partial t}-k^2m\frac{\partial^2\psi_L}{\partial t^2}=0$$

$$\frac{\partial}{\partial x}\left(EI\frac{\partial \psi_R}{\partial x}\right)+k'GA\left(\frac{\partial y_R}{\partial x}-\psi_R\right)-\gamma_R\frac{\partial \psi_R}{\partial t}-k^2m\frac{\partial^2\psi_R}{\partial t^2}=0$$

Boundary conditions

$$y_L(-l)=w(t)\qquad EI\frac{\partial\psi_L(-l)}{\partial x}=0$$

$$y_L(0)=0\qquad EI\frac{\partial\psi_L(0)}{\partial x}=M\qquad \psi_L(0)=S$$

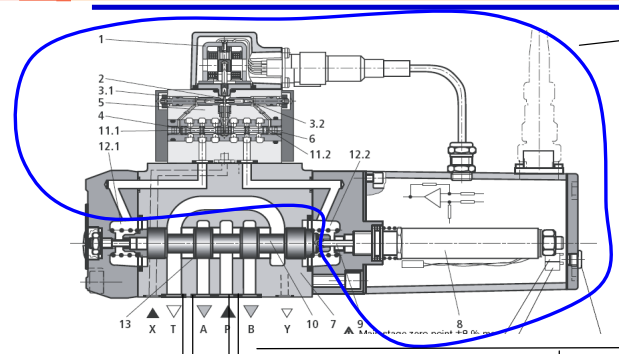
$$y_R(0)=0\qquad EI\frac{\partial\psi_R(0)}{\partial x}=M\qquad \psi_R(0)=S$$

$$k'GA\left(\frac{\partial y_R(l)}{\partial x}-\psi_R(l)\right)+Mg+M\ddot{y}_R(l)+\gamma\frac{\partial y_R(l)}{\partial t}=0\qquad EI\frac{\partial\psi_R(l)}{\partial x}=0$$

Mock-up parameters

$E=200Gpa$ Youngs modulus	$G=82GPa$ Shear Modulus for steel
ρ=7870 Kg/m^3 - density of steel	$Area=0.0088m^2$ cross section area of beam
$I=2.2\times10^{-5}m^4$ Moment of inertia of beam	$m=69Kg/m$ Mass per unit length of beam
M=2250 Kgs	$k'=0.83$ Shear constant
Beam width = 5.13'(hollow with thickness 0.94')	$l=34.5'$
Beam breadth = 6' (hollow with thickness 0.38')	
Damping coefficients $\gamma_L=\gamma_R=10$	$\gamma=10$Kg / sec

Hydraulic servo valve and actuator model



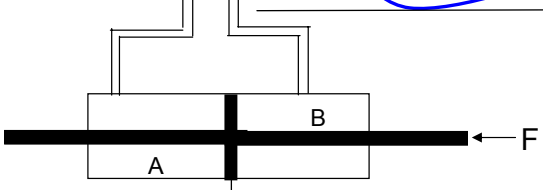
Electronic control of spool position
Fast dynamics - Hence not modelled in simulations

Turbulent Flow Equations for flow in A and B

$$q_A = \begin{cases} c(d-x_s)\sqrt{P_s-P_A} & x_s < -d \\ c(d-x_s)\sqrt{P_s-P_A} - c(x_s+d)\sqrt{P_A-P_t} & -d < x_s < d \\ -c(x_s+d)\sqrt{P_A-P_t} & x_s > d \end{cases}$$

$$q_B = \begin{cases} c(d-x_s)\sqrt{P_B-P_t} & x_s < -d \\ c(d-x_s)\sqrt{P_B-P_t} - c(x_s+d)\sqrt{P_s-P_B} & -d < x_s < d \\ -c(x_s+d)\sqrt{P_s-P_B} & x_s > d \end{cases}$$

x_s is positive when the spool moves to the right. Its mean position is 0 with valve underlap gap of d on both sides.
q_A is positive when oil flows in to chamber A
q_B is positive when oil flows out of chamber B
q, P – Volume flow rate and Pressure
$\alpha_{A,B,s,t}$ – Chamber connected to A and B, source, tank



Actuator dynamic equations

$$m\ddot{x}_p = (P_A - P_B)A + F - (fric)\dot{x}_p$$

Pressure equations

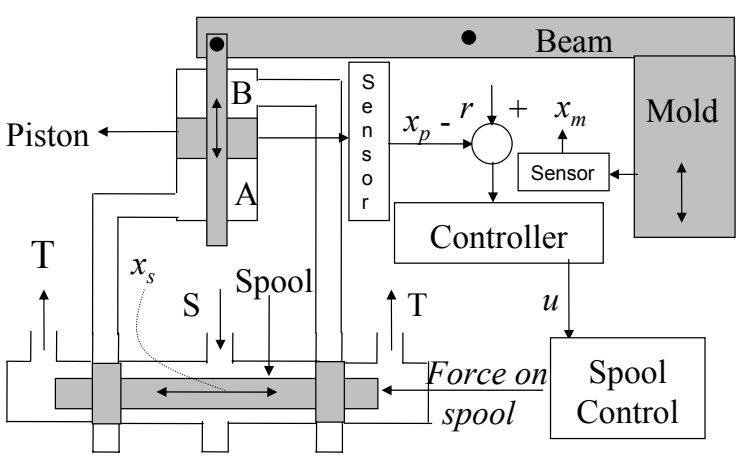
$$\dot{P}_A = \frac{\beta}{\left(V_A + A(L+x_p)\right)}\left(q_A - A\dot{x}_p\right)$$

$$\dot{P}_B = \frac{\beta}{\left(V_B + A(L-x_p)\right)}\left(-q_B + A\dot{x}_p\right)$$

x_p – positive if it moves to right of midpoint of cylinder
V_A, V_B – Static volume of chambers A and B
$A(L+x_p)$ – dynamic volume of chamber A and B
L – Half the piston stroke length
A – Surface area of piston

Set of Nonlinear Differential Equations

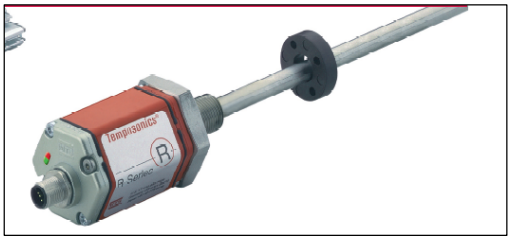
Working of the servo-beam structure



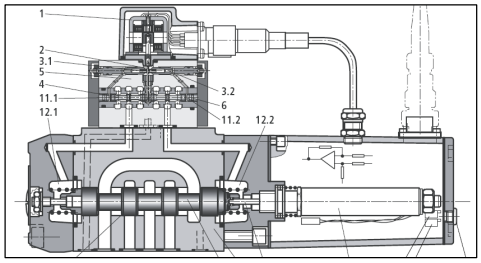
- Spool moves to left – S (pressure supply) connected to chamber A; T (tank) connected to chamber B; piston pushed up
- Spool moves to right – S (pressure supply) connected to chamber B; T (tank) connected to chamber A; piston pushed down
- Controller uses error between r (desired piston position) and x_P (actual piston position) to generate control signal u that moves spool suitably to get desired piston motion
- Typically proportional controller is used. $u=K(r-x_p)$

Important signals:
x_p - Actual piston position; x_m - Mold position
r – Desired piston position (reference)

Instrumentation and data acquisition



Temposonic position sensor from MTS Sensors; resolution less than 2 microns



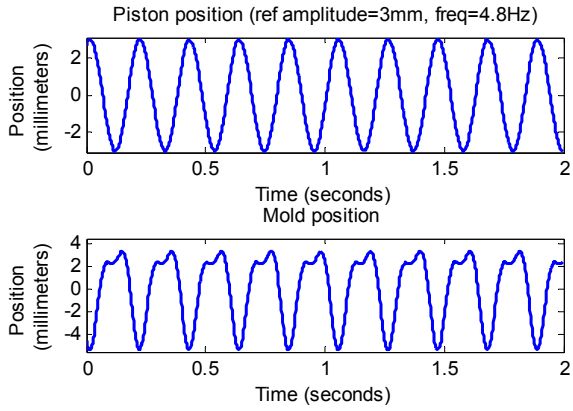
4/3 way directional control valve from Bosch Rexroth; Type 4WRDE

Top view of real time CRIO, FPGA (field programmable gate array) and chassis from National Instruments

I/O module

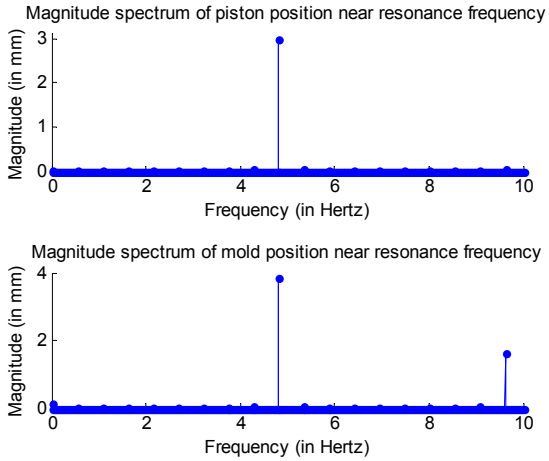
1. Data transfer from the sensor and to the actuator occur through the I/O modules.
2. Control algorithm runs in the FPGA and real time CRIO
3. The software used is LabView from National instruments

Experimental data from mock-up exhibiting resonance problem



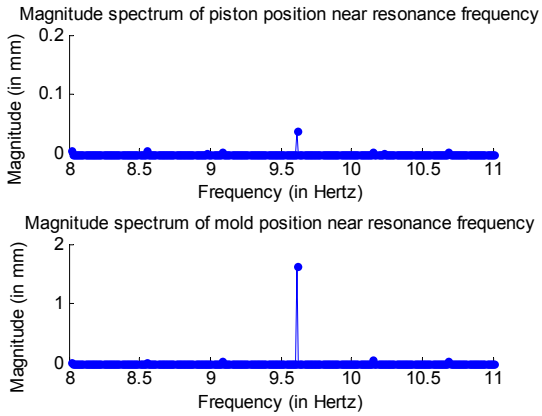
- The desired position for the actuator is chosen to be a sine wave of frequency 4.8 Hz (half the resonance frequency) and amplitude 3 mm
- P controller with gain *K*=2 is used
- Piston position signal looks almost perfect
- But large distortion (deviation from sinusoidal profile) at the mold end

Spectral analysis of piston and mold position signals



- Obtain the frequency content of the position signals using DFS (discrete Fourier series) calculation through Matlab FFT algorithm.
- As expected piston and mold position signals have peaks of magnitude 3 mm and 4 mm, respectively, at 4.8 Hz
- Mold position exhibits an unexpected peak at 9.6 Hz unseen in the piston position spectrum

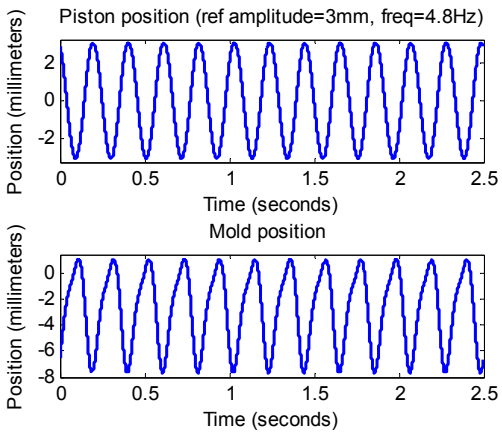
Spectral analysis of piston and mold position signals (zoomed near 9.6 Hz)



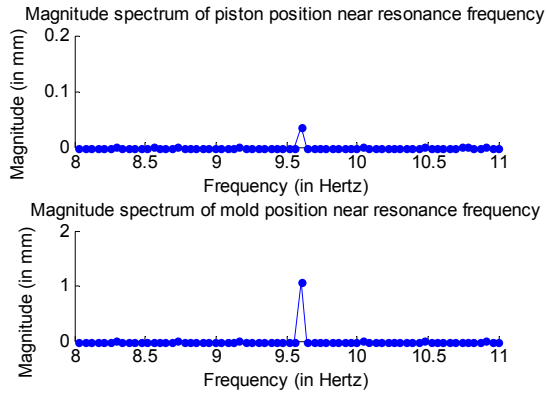
- Zooming the plot, clearly notice a small peak in the piston position at 9.6 Hz and a large peak at same frequency in mold position
- Note the peak in piston position signal is very small

Hypothesis: The small peak in piston position being at resonance frequency excites the beam and creates the large peak in the mold position. Hence, by removing the small peak in the piston position, the large peak in the mold position can be eliminated

Simulation data from models exhibiting resonance problem and related spectra



Simulation result: piston and mold position with piston reference at 4.8 Hz



Simulation result: magnitude spectra of piston and mold position near resonance frequency

In short, our models generate the resonance problem and can be used as test beds for the controllers we develop. Note that modeling is NOT necessary for the solution approach we have developed.

Question?

What causes this undesired small peak?

Answer:

The INPUT to OUTPUT servo dynamics is slightly nonlinear.

INPUT (the desired piston position or “reference”)
- typically sinusoidal with frequency “w”

OUTPUT (actual piston position)
- mainly sinusoidal at frequency “w”;
- but in addition contains small amplitude sinusoidal harmonics at frequencies, 2w, 3w, 4w …..

Consequence:
For desired 4.8 Hz, the piston position contains a small peak at 9.6 Hz.

The problem and the objective

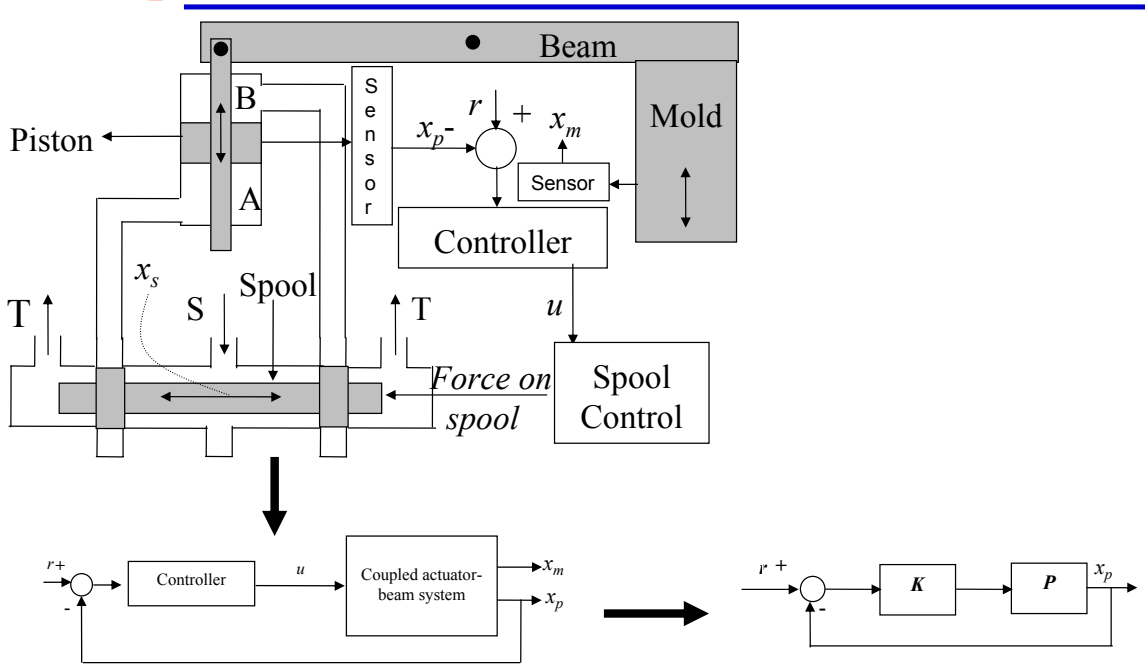
The Problem

The small-amplitude harmonic caused by the nonlinear servo dynamics is amplified into a severe problem when the desired frequency is a sub-multiple of resonance frequency of the beam

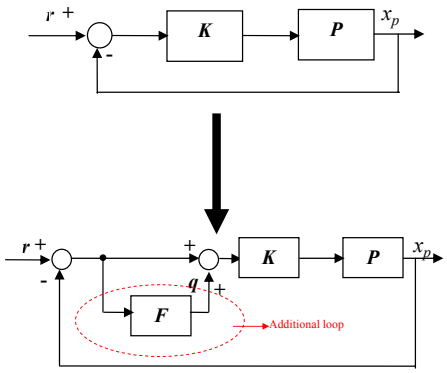
The Objective

Design *a* filtering technique that removes the small-amplitude harmonic that excites the beam resonance without affecting the already achieved good tracking at other desired frequencies.

Simplifying the representation of the pre-existing stable servo system



Solution technique (for mockup)

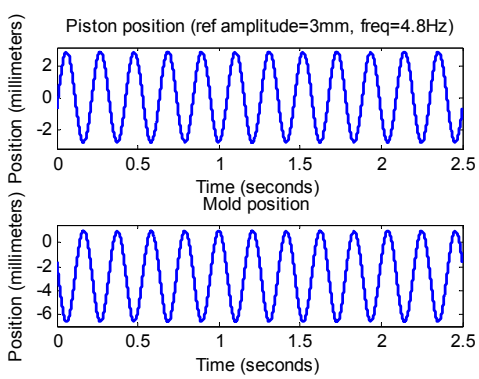


x_p tracks *r* well, but has a small undesired sinusoidal component at frequency w

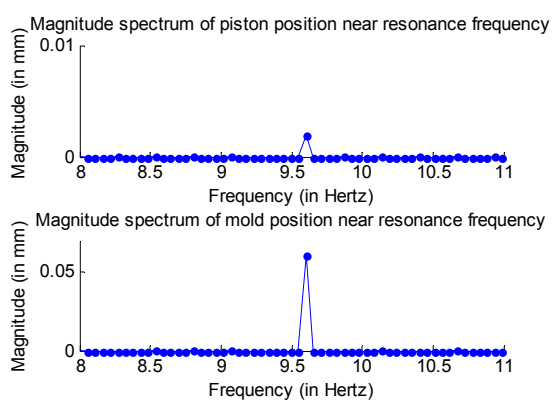
Augmenting a closed loop with a filter *F* as shown ensures that x_p continues tracking *r* well and has no undesired sinusoid at frequency w

- The additional component *F* is a simple internal model based filter. It internally generates a sinusoid at frequency 'w' to cancel the unwanted sinusoid of the same frequency
- Before augmenting the closed loop with the filter *F*, the response of the servo at frequency 'w' must be measured and this measured quantity must satisfy a technical condition
- In the mock-up and the simulations, this condition can be satisfied
- In case the condition cannot be satisfied (for example on the caster), using a modified loop topology, this approach can still be used

Simulation results with the filter



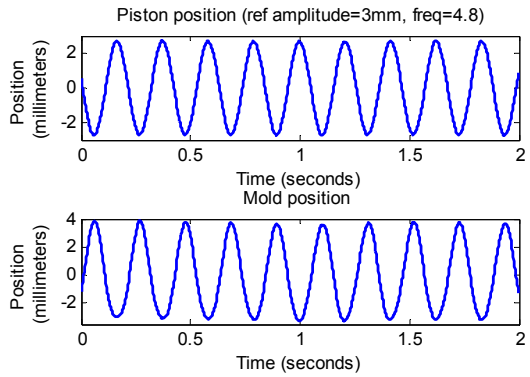
Piston and mold position with reference at 4.8 Hz with augmented loop



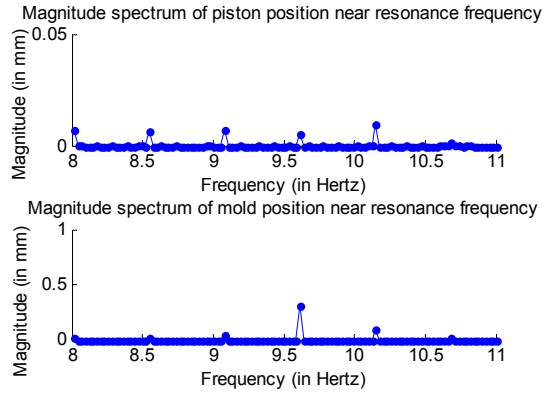
Magnitude spectra of piston and mold position around resonance frequency after loop augmentation

- Clearly the distortion visible in the mold position signal has disappeared
- The spectrum shows the peak in the piston position at 9.6 Hz has been minimized and as a consequence, the peak in the mold position spectrum has also been reduced from 1.1 mm to 0.06 mm

Experimental results from mock-up with the filter



Piston and mold position with reference at 4.8 Hz with augmented loop



Magnitude spectra of piston and mold position around resonance frequency after loop augmentation

- Clearly the distortion visible in the mold position signal has disappeared
- The spectrum shows the peak in the piston position at 9.6 Hz has been minimized and as a consequence, the peak in the mold position spectrum has also been reduced from 1.6mm to 0.3mm

Features of the solution technique

- The solution approach can be used for all linear/perturbed linear systems where periodic disturbances need to be rejected or where periodic signals must be tracked.
- The closed loop augmentation by a filter is non-intrusive and has minimal effect on the existing servo loop performance while removing the unwanted sinusoid. It does not affect the existing speed of response of the loop.
- There is no need for modeling. Only minimal measurements are necessary to implement this filter.
- The approach continues to be applicable even if the system behavior changes within a certain limit. This may prove important in industrial applications.
- It does not involve tuning procedures that involve making the system unstable. This may again prove important in industrial applications.

Conclusions and future work

- The cause of the distortions in the mold position signal in the mock-up has been identified
- A closed loop augmentation procedure has been developed that remedies this problem
- This procedure is expected to apply to a wide range of linear industrial problems involving periodic motion
- This filtering approach has been demonstrated successfully on both model simulations and the experimental mock-up of the oscillator
- Next step is to collect data from the caster (without steel) to verify that the source of the distortion in the caster is also related to the servo-hydraulic actuator, and is linear, which is expected.
- Future work will implement the solution at the caster, first testing without steel flow, and finally in production. This will involve investigating and identifying the effect of mold friction.

Acknowledgements

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Continuous Casting Consortium

Questions?