

# Control of Mold Oscillation with New Periodic Disturbance Rejection System

Vivek Natarajan

and

Joseph Bentsman



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



## Introduction to the project

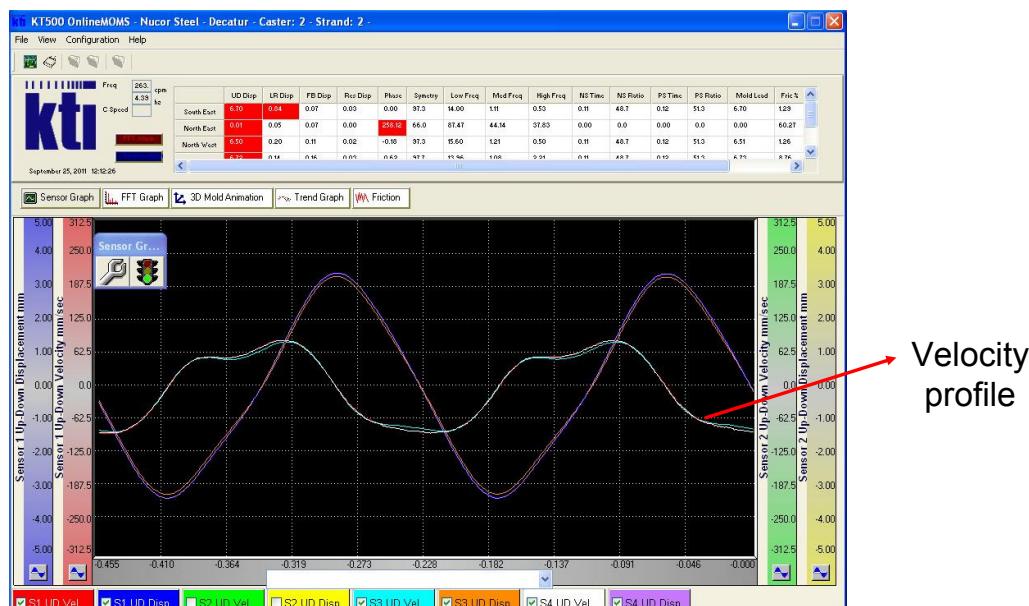
---

- Mold oscillation leads to the formation of defects called oscillation marks - sites for initiation of cracks
- These marks can be made shallower by increasing frequency and reducing amplitude of oscillation
- Current oscillation frequency at Nucor Steel, Decatur is less than 3.6 Hz
- The desired range of frequency for future operation is 3.8 Hz – 5.2 Hz to improve surface quality
- In this frequency range mold velocity profile is highly distorted
- Goal – Design controller to remove these distortions

# Importance of mold velocity profile

- **Negative strip time** is the period during each cycle of oscillation when the mold moves down faster than the shell
- In this period, the mold exerts a compressive force on the shell and any steel sticking to the mold wall will be stripped off it and squeezed on to the existing shell which prevents problems such as sticker breakouts
- To maintain constant negative strip time, the profiles of the mold displacement and the corresponding velocity must be undistorted, especially at high frequencies where the tolerance for error is smaller.

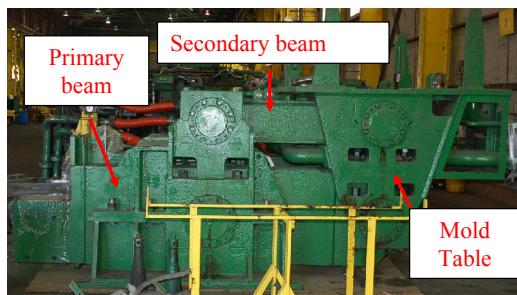
# Mold velocity profile at 4.4 Hz



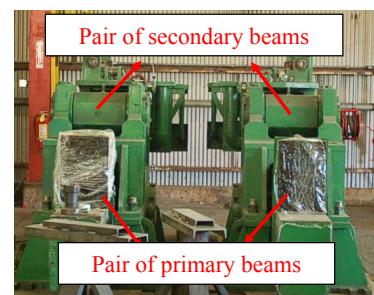
GOAL – Eliminate the distortions in the velocity profile

# Mold oscillation system

- Mold oscillation system at Nucor Steel, Decatur consists of subsystem of beams hinged at the center
- Mold is located at one end and the sinusoidal excitation is applied through an electro-hydraulic actuator with piston attached at the other end



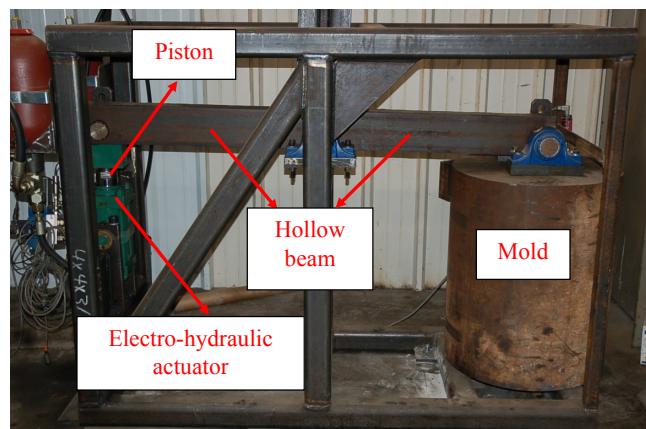
Sideview of mold oscillation system



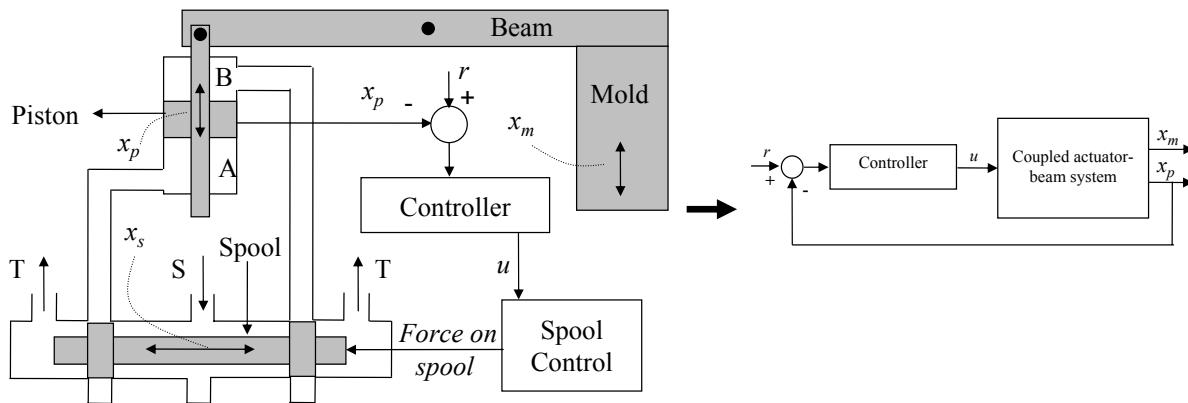
Backview of mold oscillation system

# Experimental testbed

- Resembles the mold oscillation system
- Consists of a hollow beam that is hinged at the center, supporting a mold like mass at one end and excited by an electro-hydraulic actuator at the other end



# Testbed operation

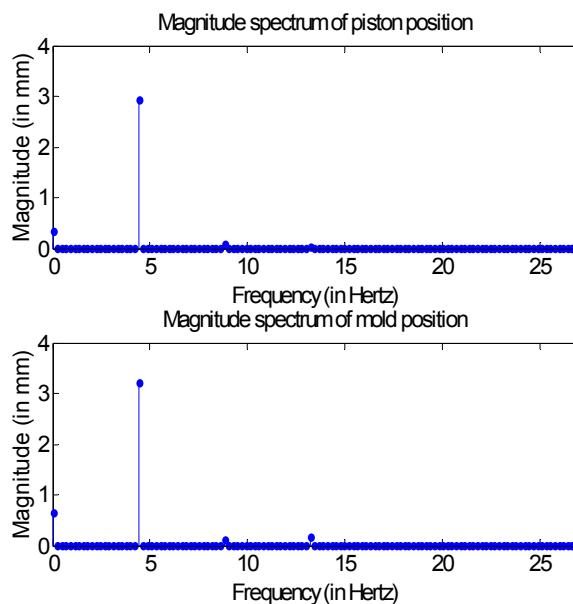


- Spool moves to the right – S (pressurized fluid) connects to chamber B to push piston down
- Spool moves to the left – S connects to chamber A to push piston up
- For desired piston motion, move spool appropriately
- Accomplished in the testbed via a proportional controller (gain 2) using the error between **reference  $r$**  and **actual piston position  $x_p$**

## Identifying source of distortion

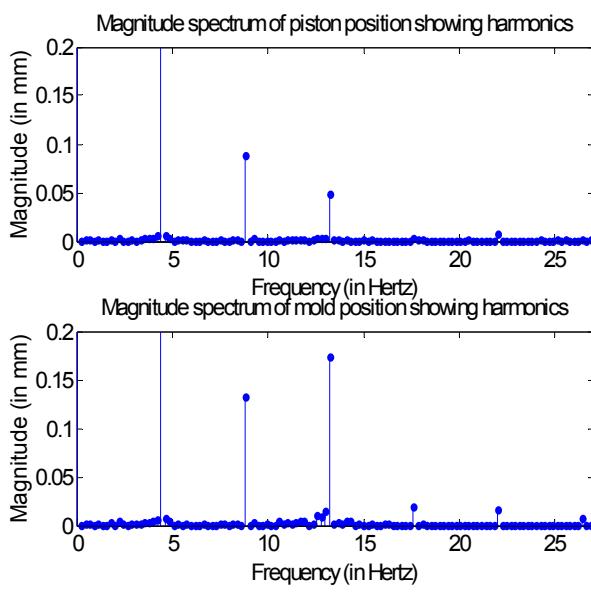
- Mold velocity profile in the testbed exhibits distortions like in the actual production unit
- An analytical model of testbed was developed that could recreate these distortions in the velocity profile
- Via detailed experiments, simulations and analysis it was concluded that the actuator produces **harmonics** of the reference sinusoid in the **piston position**
- These harmonics get amplified by the beam and distort the mold velocity profile in the testbed
- The same phenomenon was conjectured to be the problem in the production unit

# Magnitude spectrum of position signals



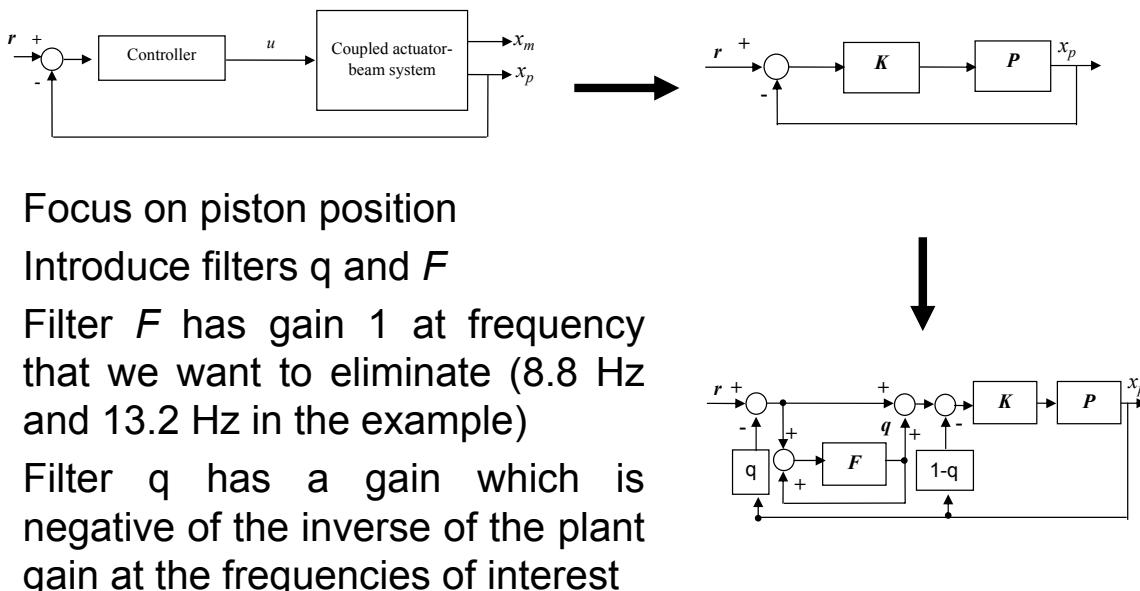
- Magnitude spectrum of actuator piston position and mold position when reference sinusoid is at 4.4 Hz
- The main peak is at 4.4 Hz as expected

# Magnitude spectrum zoomed in



- Zooming in to the spectrum, there are small peaks at 8.8 Hz and 13.2 Hz in the piston position signal (harmonics)
- These small peaks get amplified and create large peaks at the same frequency in the mold position
- Conjecture is verified
- Goal – remove small peaks from piston position

# Control scheme



V. Natarajan and J. Bentsman, '*Robust Rejection of Sinusoids in Stable Nonlinearly Perturbed Unmodelled Linear Systems: Theory and Application to Servo*', Proceedings of the American Control Conference 2011, San Francisco, pp. 3289-3294.

University of Illinois at Urbana-Champaign MechSE

• Control systems Design and Applications Lab

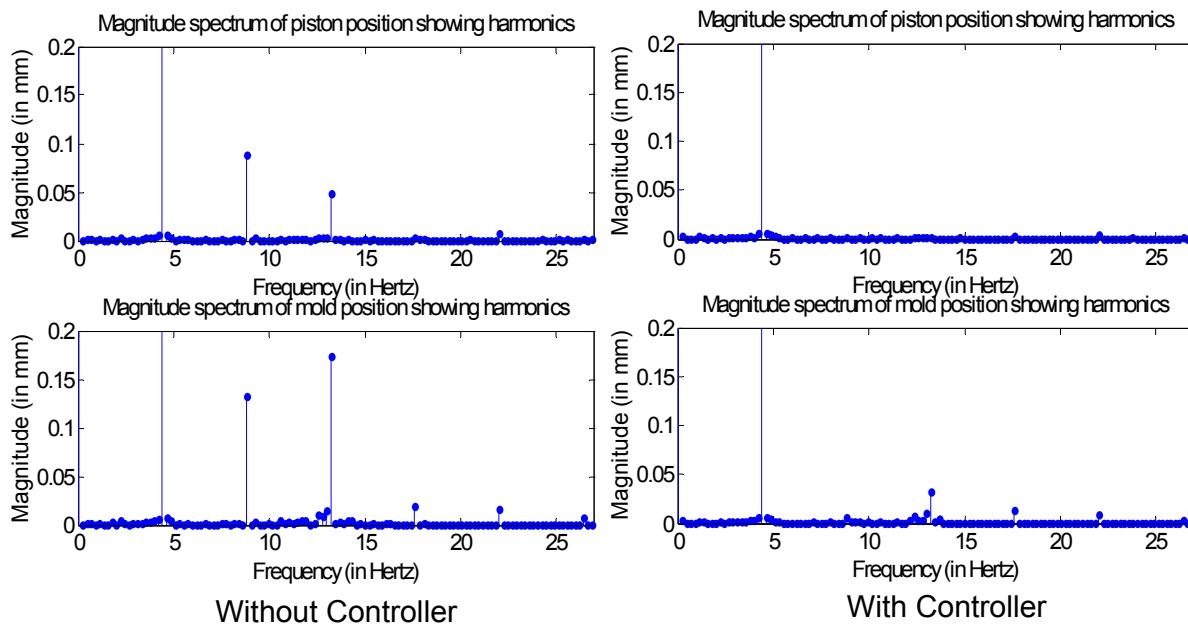
• Natarajan and Bentsman

• 11

## Features of the control scheme

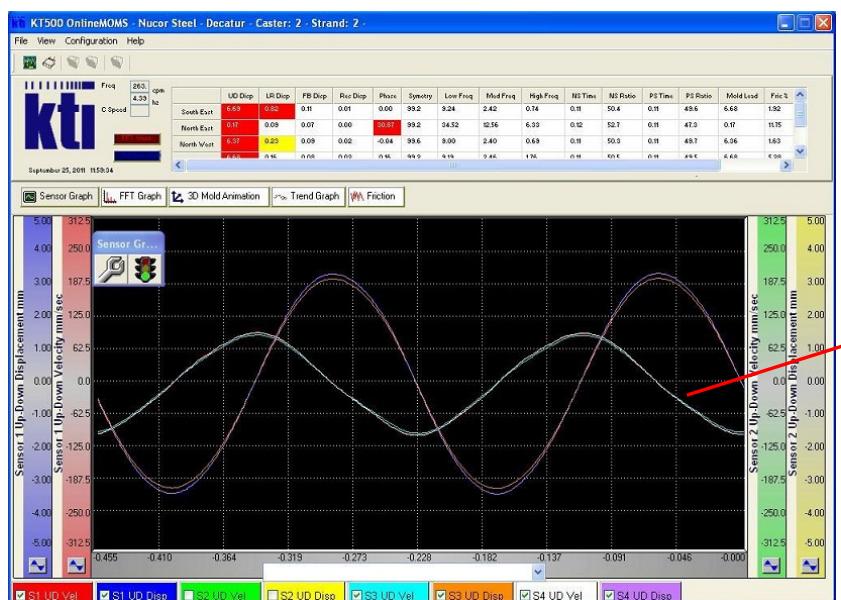
- The gain of the filter  $F$  at the frequencies of interest ensures that the unwanted harmonics are removed
- The gain of filter  $q$  at the frequencies of interest guarantees stability of the scheme
- Note that only plant data at frequency of interest is used – control scheme is **non-model based**
- As long as the plant data at frequency of interest changes by less than 100%, stability of loop is guaranteed – control scheme is **robust**
- Robustness is crucial since the plant gain does change during production

# Results of controller testing on the mold oscillation system



Peaks at 8.8 Hz and 13.2 Hz significantly reduced, so mold velocity should be undistorted

## Mold velocity profile at 4.4 Hz with controller

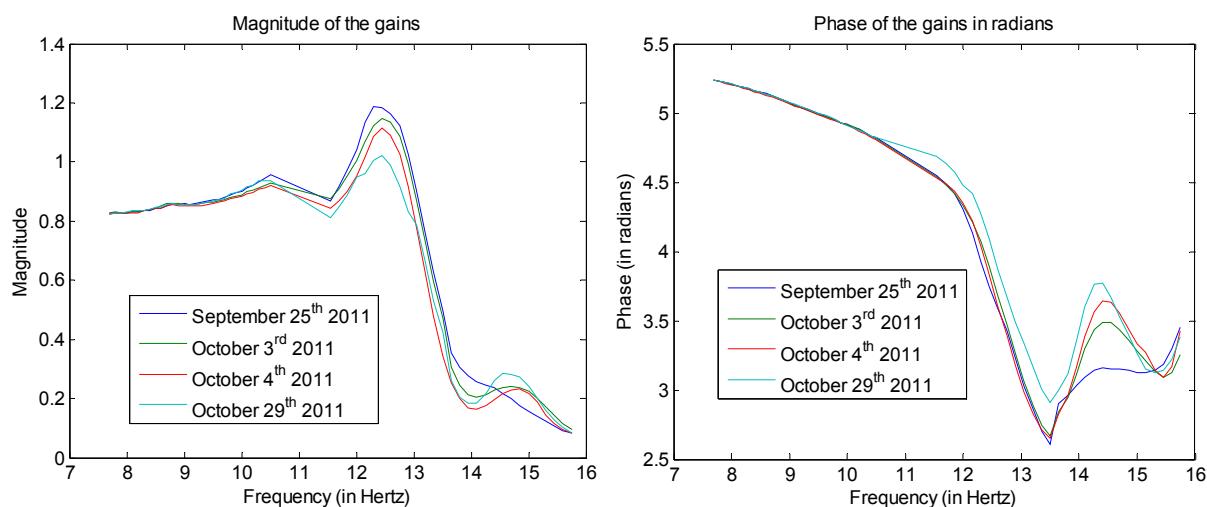


Distortions in the velocity profile eliminated

# Implementing controller

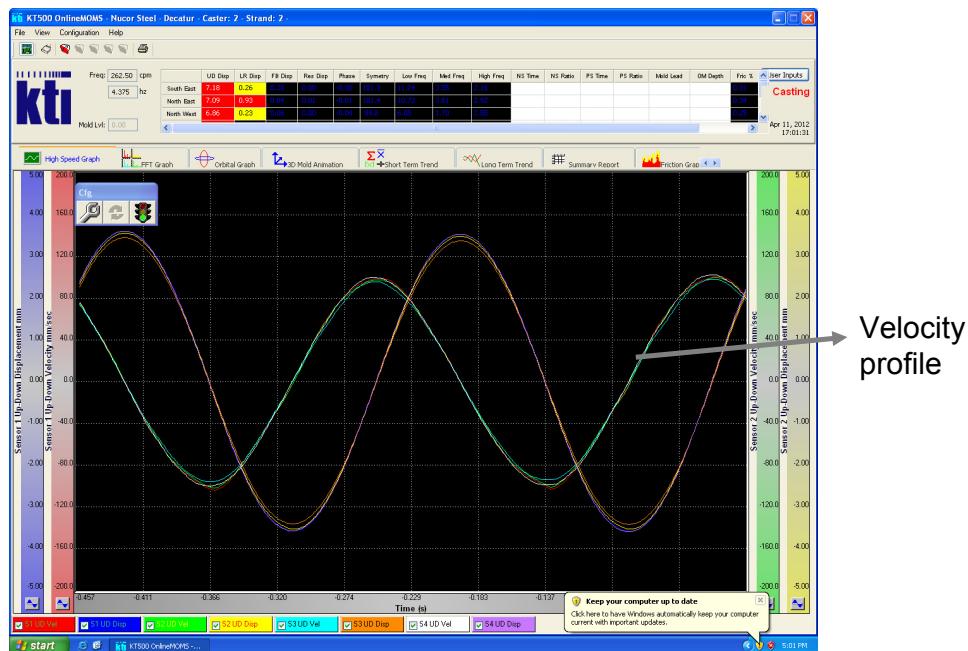
- Controller is implemented in LabVIEW using Compact RIO and FPGA setup
- Although, result at one frequency (4.4 Hz) is shown, the controller must work when the frequency of oscillation is changed during casting (3.8 Hz – 5.2 Hz)
- Hence the controller coefficients must change when frequency of oscillation changes
- Such a code has been developed in LabVIEW – an effort simplified by the non-model based nature of the control scheme
- Another code that collects the plant gain at the frequencies of interest automatically has also been developed

# Plant gains



- Plant gains change by less than 100% over a 1 month period and hence the controller is guaranteed to be stable
- Plant gain is typically collected every 2 weeks

# Mold velocity profile at 4.37 Hz (in production)



## Oscillation marks



Casting at a lower frequency of oscillation for the mold enforced by simple proportional controllers

Casting at a higher frequency of oscillation for the mold enabled by the proposed controller - shallower surface marks and hence lesser probability of surface cracks



# Conclusions

- The mold velocity distortion problem at Nucor Steel, Decatur has been solved for a hinged beam-type mold oscillation system by implementing a new feedback control law based on the disturbance model.
- The new control law eliminates periodic mold velocity disturbances, such as those caused by excitation of system natural frequencies by actuator nonlinearity, without the need for system model.
- This improves the surface quality of the steel being produced and also enables the production of other crack sensitive grades of steel
- Currently the controller implemented in LabVIEW is being integrated with the existing Siemens hardware so as to make it a permanent feature of caster operation

# Acknowledgements

- Dr. Ronald O'Malley, Matthew Smith, Glynn Elliott, Sunil Hanumanthe and other Nucor personnel
- National Science Foundation (Grant # CMMI-0900138)
- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Tata Steel, Goodrich, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech/ Posco, SSAB, ANSYS-Fluent)