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Modeling of Mold Oscillation

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Mold Oscillation System

Mold Oscillation:

Required to avoid sticking of molten steel to mold wall, to induce required stress on the shell and get desired surface Quality

Function of Oscillation System:

To ensure mold tracks the desired displacement and Velocity profile

Components:

Primary beam, support beam, hydraulic actuator, counter weight, Pivot, Mold table, Mold

Operation, Problem & Objective

Operation Principle:

- Hydraulic actuator applies force on counter weight and forces it to oscillate
- Counter weight is attached to the beam, hence beam oscillates and consequently mold oscillates

Problem:

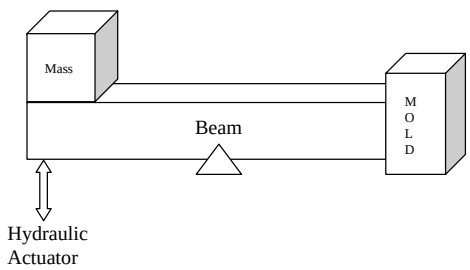
- Increasing the speed of casting requires increased frequency of mold oscillation.
- Increasing frequency of oscillation leads to resonance frequency of the beam getting excited. This distorts mold displacement and velocity profile

Objective:

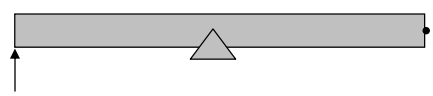
- To develop a controller so as to ensure tracking of desired displacement and velocity profile by mold

System Model

- Resonance occurs due to primary beam
- System is symmetric
- Beam Length to thickness ratio <3, hence Euler-Bernoulli model for beam not suitable
- Hydraulic actuator – Nonlinear behavior
- Mold has significant weight and hence relevant dynamics



Timoshenko Beam Model



$$\frac{\partial}{\partial x}\left(k'GA\left(\frac{\partial u_1}{\partial x}-\psi_1\right)\right)-m\frac{\partial^2 u_1}{\partial t^2}=0$$

$$\frac{\partial}{\partial x}\left(EI\frac{\partial \psi_1}{\partial x}\right)+k'GA\left(\frac{\partial u_1}{\partial x}-\psi_1\right)-k^2 m\frac{\partial^2 \psi_1}{\partial t^2}=0 \qquad 0\le x\le L_1$$

$$u_1(0)=w_1(t)$$

$$EI\frac{\partial \psi_1(0)}{\partial x}=0$$

$$u_1(L_1)=0$$

$$EI\frac{\partial \psi_1(L_1)}{\partial x}=T$$

$$\psi_1(L_1)=S$$

$$\frac{\partial}{\partial x}\left(k'GA\left(\frac{\partial u_2}{\partial x}-\psi_2\right)\right)-m\frac{\partial^2 u_2}{\partial t^2}=0$$

$$\frac{\partial}{\partial x}\left(EI\frac{\partial \psi_2}{\partial x}\right)+k'GA\left(\frac{\partial u_2}{\partial x}-\psi_2\right)-k^2 m\frac{\partial^2 \psi_2}{\partial t^2}=0 \qquad 0\le x\le L_2$$

$$k'GA\left(\frac{\partial u_2(L_2)}{\partial x}-\psi_2(L_2)\right)-M\ddot{u}_2(L_2)+D(t)=0$$

$$EI\frac{\partial \psi_2(L_2)}{\partial x}=0$$

$$u_2(0)=0$$

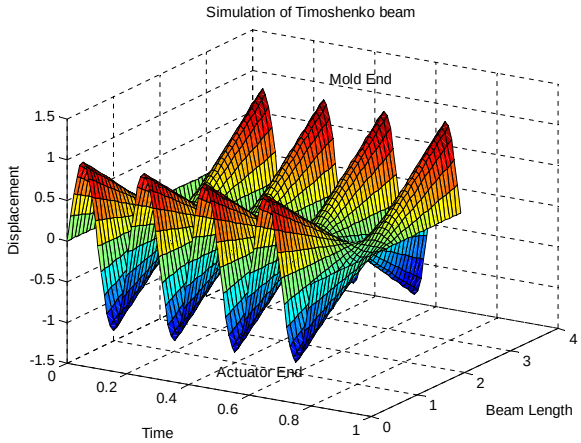
$$EI\frac{\partial \psi_2(0)}{\partial x}=T$$

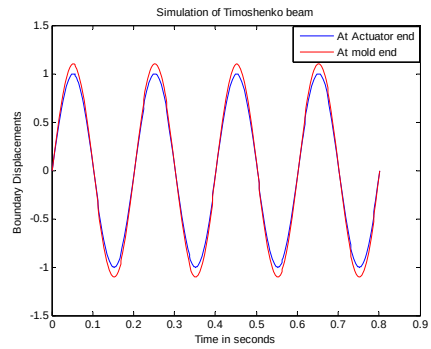
$$\psi_2(0)=S$$

M – Mass of the mold
G – Shear modulus
A – Area of cross-section
I – Moment of Inertia
m – Mass density
E – Young's Modulus
L_1, L_2 – Length of beam from edge to the hinge, 1.6 meters
$w_1(t)$ – The input displacement at the boundary

•Friction between Mold wall and Steel - Additional disturbance at the mold end
•Can be estimated using a Disturbance Observer

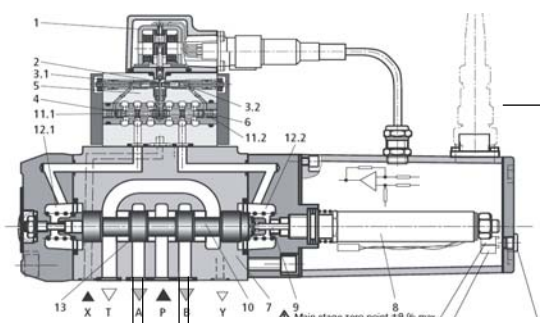
Beam Simulations

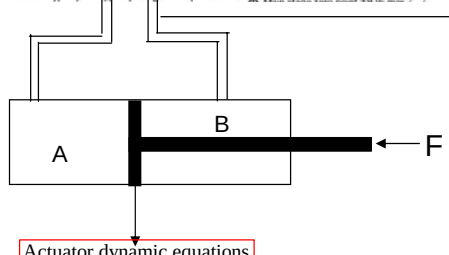




Beam is Flexible

Hydraulic Actuator





Second order System for Servo Valve

$$\ddot{x}_s = -\omega_e^2 x_s - 2\zeta_e \omega_e \dot{x}_s + \omega_e^2 u$$

u – Input x_s – Spool displacement

ζ_e, ω_e – Damping ratio and Natural frequency

Turbulent Flow Equations for flow in A and B

$$q_A = \begin{cases} c(-x_s)\sqrt{P_A - P_t} & x_s < 0 \\ c x_s \sqrt{P_s - P_A} & x_s > 0 \end{cases}$$

$$q_B = \begin{cases} c(-x_s)\sqrt{P_s - P_B} & x_s < 0 \\ c x_s \sqrt{P_B - P_t} & x_s > 0 \end{cases}$$

q, P – Flow rate and Pressure

$\alpha_{A,B,s,t}$ – Chamber connected to A and B, source, tank

Pressure equations

$$\dot{P}_A \frac{V_A}{\beta} = q_A - \dot{V}_A$$

$$\dot{P}_B \frac{V_B}{\beta} = q_B - \dot{V}_B$$

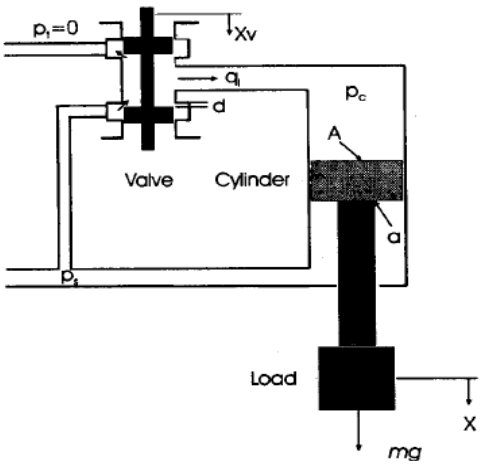
V_A, V_B – Volume of chambers A and B

Actuator dynamic equations

$$P_A a_A - P_B a_B = m\ddot{x} + F$$

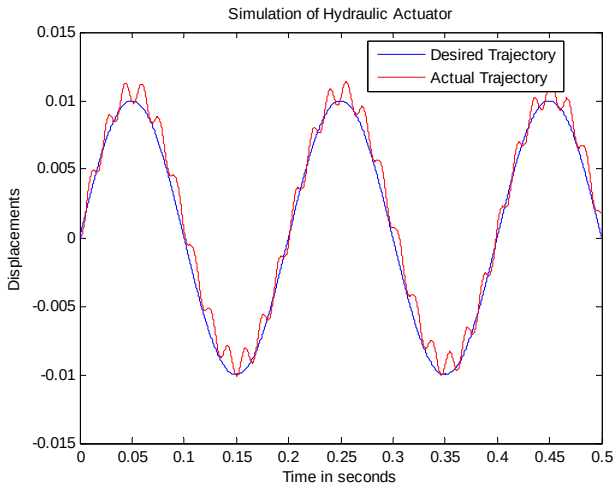
Set of Nonlinear Differential Equations

Simplified Model



- Three - way valve configurations as opposed to four-way valve configuration
- Parameters available from reference
- Similar Nonlinear Characteristics
- PID controller implemented on this model , the feedback signals being the error between the desired and actual displacement and velocities of the Piston

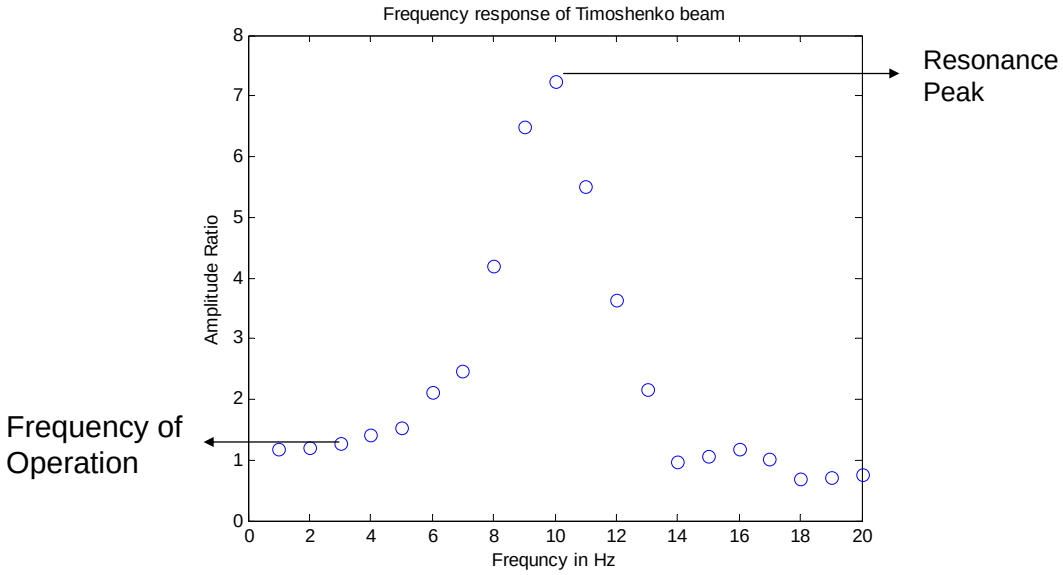
Actuator Simulation



Linear Systems – If input is at frequency ‘f’, output is also is at a frequency ‘f’

Actuator has nonlinear characteristics

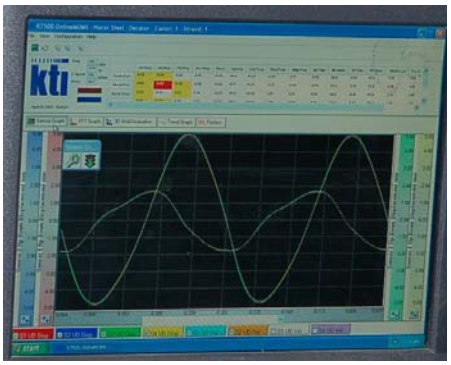
Frequency Response of Beam



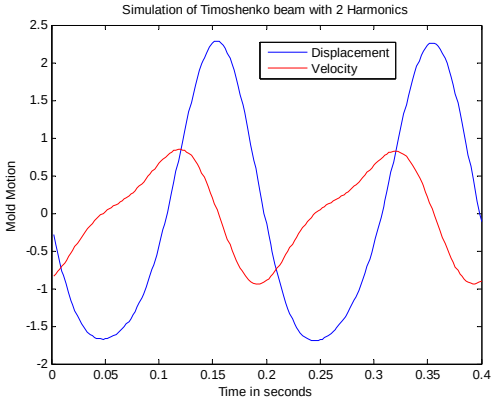
Higher Harmonics

Causes for higher Harmonics

- Actuator-Beam coupled – Characterized by force
- Actuator Nonlinearities – could give rise to frequencies that are multiples of frequency of oscillation and excite resonant mode



Screenshot of Mold profiles



2 Harmonics in Input - Resonant mode excited

Mold Wall Friction

- Friction between Mold wall and Steel - Additional disturbance at the mold end
- Time varying Frictional force – Stick-Slip effect
- Might be another source of higher harmonics
- Identifying Disturbance
  - Improve controller performance
  - Estimate of frictional force - useful as tool for monitoring casting process
- Method of Identification
  - Choose a friction model (e.g. viscous friction, but with time dependant co-efficient of friction)
  - Based on model, design Disturbance Observer (a computer code) that gives disturbance estimate from displacement and velocity measurements

Conclusions and Future work

- Models for Beam and Actuator identified
- Simulations of models show expected behavior – Flexibility and Resonance feature of Beam, Nonlinearities of Actuator
- Identified probable source of Resonance excitation

Future Work

- Further verify beam model using FEM and obtain actual system parameters
- Study the effect of coupling between actuator and beam
- Develop Control Strategy to overcome Resonance problem and ensure satisfactory tracking by mold
- Develop Disturbance observer to estimate mold wall friction

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