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

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

**Timoshenko Beam Model**

\[ \frac{\partial}{\partial x} \left[ k'GA \left( \frac{\partial w_t}{\partial x} - \psi_t \right) \right] - m \frac{\partial^2 w_t}{\partial t^2} = 0 \quad \text{for } 0 \leq x \leq L_i \]

\[ L \text{ or } 0 \]

\[ w_i(0) = w_i(t) \]

\[ E \frac{\partial^2 \psi_t(0)}{\partial x^2} = 0 \]

\[ w_i(L_i) = 0 \]

\[ E \frac{\partial^2 \psi_t(L_i)}{\partial x^2} = T \]

\[ \psi_t(L_i) = S \]

\[ \frac{\partial}{\partial x} \left[ k'GA \left( \frac{\partial w_t}{\partial x} - \psi_t \right) \right] - m \frac{\partial^2 w_t}{\partial t^2} = 0 \quad \text{for } 0 \leq x \leq L_i \]

\[ k'GA \left( \frac{\partial w_t}{\partial x} - \psi_t \right) \bigg|_{x=L_2} - k' \frac{\partial^2 \psi_t}{\partial x^2} = 0 \]

\[ E \frac{\partial^2 \psi_t(L_2)}{\partial x^2} = 0 \]

\[ w_t(0) = 0 \]

\[ E \frac{\partial^2 \psi_t(0)}{\partial x^2} = T \]

\[ \psi_t(L_2) = S \]

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

Simulation of Timoshenko beam

Beam is Flexible

Hydraulic Actuator

Second order System for Servo Valve
\[ \dot{x}_c = -\omega_p^2 x_c - 2\zeta\omega_p \dot{x}_c + \omega_n^2 u \]

\( u \) – Input \( x_c \) – Spool displacement
\( \zeta, \omega_n \) – Damping ratio and Natural frequency

Turbulent Flow Equations for flow in A and B

\[ q_A = \begin{cases} \frac{c (-x_i) \sqrt{P_A - P_s}}{\omega_n} & x_i < 0 \\ \frac{c x_i \sqrt{P_A - P_s}}{\omega_n} & x_i > 0 \end{cases} \]

\[ q_B = \begin{cases} \frac{c (-x_i) \sqrt{P_B - P_s}}{\omega_n} & x_i < 0 \\ \frac{c x_i \sqrt{P_B - P_s}}{\omega_n} & x_i > 0 \end{cases} \]

\( q_i, P \) – Flow rate and Pressure
\( \alpha_{A,B} \) – 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

Set of Nonlinear Differential Equations

Actuator dynamic equations

\[ P_A \dot{a}_A - P_B \dot{a}_B = m \ddot{x} + F \]
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 at a frequency \( f \)

Actuator has nonlinear characteristics
Frequency Response of Beam

- Frequency response of Timoshenko beam

- Resonance Peak

Frequency of Operation

Amplitude Ratio vs. Frequency in Hz

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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