Self-Learning Backlash Inverse Control of Cooling or Heating Coil Valves Having Backlash Hysteresis

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**Motivations**

- HVAC valves often suffer from backlash type hysteresis
- Valve hysteresis leads to unsatisfactory control performance
- Unsatisfactory control leads to
  - Control variable fluctuation (comfort)
  - Plant chattering and cycling (efficiency and unit life span)
  - Higher power peaks (demand cost)

**Approach**

- Dynamic cooling coil + valve model as a test bed (trained with Living Lab AHU cooling coil data)
- Backlash inverse control implemented on top of a conventional PI controller
- Self-learning procedure to estimate the backlash magnitude
Valve Control System

- Data-driven valve and cooling coil models
- A feedback controller to maintain the supply air temperature setpoint
  - Conventional PI controller
  - Backlash inverse controller on top of an existing PI controller
- Resetting $T_{sup,sp}$ strategy
Valve Model

- Backlash type hysteresis is dominant (at least locally)
- From manufacturing tolerance of the actuator gearbox

- Relationship between opening and fluid flow
- Depend on valve design
Valve Model – Hysteresis Sub-model

- Backlash model is *dynamic*
- Input: cmd[t-1], cmd[t]
- State: x[t] (backlash position)
- Output: open[t] (valve opening)
- Parameter: x_{BL} (backlash magnitude)

\[
\begin{align*}
\text{If} \{ cmd[t] - cmd[t-1] &\geq x_{BL} - x[t-1] \} \\
x[t] &= x_{BL} \\
onopen[t] &= \alpha \times (cmd[t] - x_{BL}) \\
\text{Elseif} \{ cmd[t] - cmd[t-1] &< x_{BL} - x[t-1] \} \text{ and } \{ cmd[t] - cmd[t-1] &\geq -x[t-1] \} \\
x[t] &= x[t-1] + cmd[t] - cmd[t-1] \\
onopen[t] &= \alpha \times (cmd[t-1] - x[t-1]) \\
\text{Else} \\
x[t] &= 0 \\
onopen[t] &= \alpha \times cmd[t]
\end{align*}
\]

Fig. Backlash hysteresis
Valve Model – Flow Sub-model

• Flow model is *static* correlating the opening and the fluid flow
• Input: open
• Output: mass flow

*For flow equal percentage control*
• Flow increases exponentially in the low end
• Flow saturates in the high end due to loss of authority
• Generalized logistic model is used
• *Parameters*: a, b, c

\[
m = \frac{m_{\text{max}}}{\left(1 + a \cdot e^{-b(open-c)}\right)^{1/a}}
\]

*Fig. Flow relationship*
Valve Model – Training

- AHU cooling coil valve opening was randomly perturbed in the Living Lab #3 to generate training data
- Parameters in the hysteresis and flow sub-models were estimated simultaneously
- Estimated backlash magnitude = 7%

Fig. Model training results

Fig. Estimated model curves with training points
**Method and assumptions**

- Counter-flow assumption
- Energy balance for each CV
- Explicit solution scheme to avoid iterations
- Time step = 1 sec.
- Coil divided into 8 CVs
- Effective-NTU method to determine heat rate
- Neglect air dynamics

\[
\begin{align*}
\dot{\omega}_w &= 1 - \exp\left(-\beta_1 m_w^\beta_2\right) \\
\dot{\omega}_a &= 1 - \exp\left(-\beta_3 m_a^\beta_4\right) \\
\dot{\omega}_a^* &= 1 - \exp\left(-\beta_5 m_a^\beta_6\right)
\end{align*}
\]

**Control Volume**

\[
\begin{align*}
&\text{Control Volume} \\
&\begin{array}{ccc}
i-1 & i & i+1 \\
m_w & T_{w,i}^{i-1} & T_{w,i}^i & T_{w,i}^{i+1} & T_{w,i}^{i+2} \\
n_a & T_{a,i}^{i-1} & T_{a,i}^i & T_{a,i}^{i+1} & m_a \\
\end{array}
\end{align*}
\]

**Fig. Finite volume cooling coil model**

\[
\begin{align*}
C_w \frac{T_{w,i}^{i+1} - T_{w,i}^i}{\Delta t} + m_w c_{p,w} \left(T_{w,i}^i - T_{w,i}^{i-1}\right) + \frac{T_{w,i}^{i-1} - T_c^i}{R_w} &= 0 \\
(C) \quad C_c \frac{T_{c,i}^{i+1} - T_{c,i}^i}{\Delta t} + \frac{T_{c,i}^i - T_{c,i}^{i+1}}{R_a} + \frac{T_{c,i}^{i+1} - T_{w,i}^{i-1}}{R_w} &= 0 \\
(W) \quad C_c \frac{T_{c,i}^{i+1} - T_{c,i}^i}{\Delta t} + \frac{h_{s,c}^i[T] - h_{a}^{i+1}[T]}{R_a^*} + \frac{T_{c,i}^i - T_{w,i}^{i-1}}{R_w} &= 0
\end{align*}
\]

\[
\begin{align*}
R_a &= \frac{1}{\dot{\omega}_a m_a c_{p,a}} , \\
R_w &= \frac{1}{\dot{\omega}_w m_w c_{p,w}} , \\
R_a^* &= \frac{1}{\dot{\omega}_a^* m_a}
\end{align*}
\]
Cooling Coil Model

Fig. Model training results

- Training data with random step changes in the air and water flow was collected for the Living Lab #3 cooling coil
- Regression was performed to match leaving air temperature
Cooling Coil Model

Fig. Model validation results

- Validation data was collected from a different period of time
  - under normal operation;
  - and with SAT resetting strategy to reduce VAV reheat
Valve Controllers

**PI controller (baseline):**
- PI gains fine tuned by field engineers

**BI controller:**
- Same PI settings
- Estimated backlash magnitude in the BI block
Baseline PI Control Simulation Results

Temperature C

mWatt kg/s

Control cmd %

Time s
BI Control with 60% Backlash Estimate

- Temperature (°C)
- mWatt kg/s
- Control cmd %
BI Control with 95% Backlash Estimate

Graphs showing temperature, mWatt kg/s, and control cmd % over time.
BI Control with 110% Backlash Estimate

- Temperature C
- mWatts kg/s
- Control cmd %

Graphs showing temperature, mWatts, and control cmd over time.
Self-Learning BI Control

Fig. Chattering frequencies for BI controllers with different backlash estimates

- Self-learning algorithm: increase backlash estimate until chattering frequency shows a significant jump
Experimental Test Results

- Tested with the same cooling coil valve to train the models
- Resetting SAT strategy
Conclusions & Discussions

• A companion paper showed most HVAC valves suffer from hysteresis effects
• Valve and cooling coil models were developed as a simulation test bed to study valve control performance
• A backlash inverse controller was proposed with limited modification from a conventional PI controller
• A self-learning method was proposed to estimate the backlash magnitude used in a backlash inverse controller
• Significant control improvement was achieved with the proposed backlash inverse control approach in simulation and field tests
• Potential benefits:
  ▪ Improved comfort delivery (stable temperature control)
  ▪ Enhanced unit efficiency and longer life span (less chattering)
  ▪ Reduced electricity demand cost (reduced power peak)
Thank you!

Q&A