Experimental Study on Extremum Seeking Control for Efficient Operation of Air-side Economizer

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Outline

• Research Background

• Extremum Seeking Control (ESC) for Air-side Economizer

• Experimental Study
  – Testing with Direct Expansion Air-side Economizer
  – Testing with Chilled-water Based AHU
Extremum Seeking Control for Air Handling Unit

• For an air-handling unit (AHU), a supply air temperature controller can achieve the desired room temperature setpoint for various outdoor air flow, but the energy consumption of mechanical cooling may vary significantly under load variation and ambient condition.

• Need to search for the optimal damper opening so as to minimize the chilled water flow rate.

Air-side Economizer Operation
• Existing Control Strategies
  
  – **Fixed dry bulb temperature**
  – **Differential dry bulb temperature**
    • Not good for 1A, 2A, 3A, and 4A
  – **Fixed enthalpy**
    • Not good for 1B, 2B, 3C, 4B, 4C, 5B, 6B, 7, and 8
  – **Differential enthalpy**
    • Theoretically the most energy efficient
    • Not good for hot dry climates
While the model-based strategies achieved modest energy savings over the traditional strategies for perfect sensors, the performance of all the strategies suffered when sensor errors were introduced (for all four strategies).
Solution: Self-optimizing Control

Model Free & Sensor Free??

Extremum Seeking Control (ESC): on-line self-optimizing control scheme
• Li et al. (2010) validated the ESC based economizer control strategy with Modelica based dynamic simulation model.

Previous Work on ESC Economizer Control

Water Flow Rate (Kg/s)

OAD Opening (%)

Start of ESC

Time (sec)
Overview of Extremum Seeking Control

- Extremum Seeking Control (ESC) deals with the on-line optimization problem of finding an optimum input to maintain the output at the extremum (maximum/minimum) value.

- This is different from traditional regulation control problem that aims to stabilize system output at a known setpoint.

- ESC is a nearly Model-Free control strategy, which requires little model knowledge

- Great benefit and convenience for HVAC applications
  - Air-side economizer
  - Chiller plant
  - Heat pumps
**Extremum Seeking Control**

Demodulator converts the 1st harmonic signal proportional to gradient into DC component:

\[ d_1(t) \cdot y_{hp} = \sin(\omega t) \cdot a \cdot \sin(\omega t) \cdot \frac{dl}{du} + \cdots \]

\[ = \frac{a}{2} \cdot \frac{dl}{du} - \frac{a}{2} \cdot \cos(2\omega t) \cdot \frac{dl}{du} \]

Low-pass filter retains the DC component:

\[ a \cdot \frac{dl}{du} = \frac{2}{du} \]

Demodulation signal

\[ d_1(t) = \sin(\omega t) \]

Dither signal

\[ d_2(t) = a \sin(\omega t) \]

The integrator eliminates steady state error \( \Leftrightarrow \) achieving zero gradient \( \Leftrightarrow \) achieving the optimal search

Integrator

Low-pass Filter

High-pass Filter

\[ l(t, u) \]

Output: Rotor Power

\[ l[u + a \sin(\omega t)] = l(u) + a \sin(\omega t) \frac{dl}{du} + \cdots \]

High-pass filter removes DC component, keeping harmonics:

\[ a \sin(\omega t) \frac{dl}{du} + \cdots \]

Dither signal is added to the input \( u \):

\[ u_d = u + \sin(\omega t) \]
Overview of Extremum Seeking Control

• Actuator saturation for air-side economizer optimization.
  • OAT around 53°F: the outdoor air damper 100%
  • OAT > 100°F, the outdoor air damper at the minimum opening
• On the averaging sense, ESC can be deemed as a linear system that regulates the gradient with a PI controller at a larger time scale ⇒ integrator windup is unavoidable when saturation occurs

Solution: Back-calculation based anti-windup ESC
ESC without Anti-Windup

**Graphs:**
- **Water Flow Rate (Kg/s):**
  - X-axis: Time (sec)
  - Y-axis: Water Flow Rate
  - The graph shows a step change in flow rate at different time points.
- **OAD Opening (%):**
  - X-axis: Time (sec)
  - Y-axis: OAD Opening
  - The graph displays the opening percentage of the OAD over time, showing a reduction and recovery.
- **Temperature (K):**
  - X-axis: Time (sec)
  - Y-axis: Temperature
  - The graph illustrates the temperature changes with time, indicating different states.

**States:**
- **State 1:**
  - Descriptive note: ESC On
- **State 2:**
  - Descriptive note: ESC Failed
- **State 3:**
  - Descriptive note: ESC Failed

**Legend:**
- Saturated Control Input
- Unsaturated Control Input
- Outdoor Air Temperature
- Return Air Temperature

**Notation:**
- **ESC On/Failed** indicates the operational status of the ESC.
Simulation of Anti-Windup ESC

Now it works!
Objective of Study

• Perform experimental study to further validate the ESC economizer control strategy

• Study #1: Direct Expansion System based AHU (in lab at UT-Dallas)

• Study #2: Chilled-water System based AHU (Iowa Energy Center)
Outdoor unit: Lennox XC-25 Air Conditioner
Indoor unit: Lennox CBX40UHV Variable Speed Air Handler
Air-side Economizer

Zone 16’x8’x8’

Belimo Damper Actuators
The power meter (WattNode Pulse WNB-3D-240-P) measures the total power of the indoor and outdoor units (AC system).
Fan Speed Measurement

Locations of Indoor and Outdoor Fan Speed Sensors
Testing with Direct Expansion Air-side Economizer

• Two experiments are then performed to investigate the performance of proposed ESC controller under different outdoor air and return air conditions.

• Initially, a 6,000 W heat load is applied to the test chamber. The room temperature and relative humidity are allowed to be maintained at pre-specified setpoints by the controls of Lennox AC unit and humidifiers and dehumidifiers.

• After that, the ESC controller was turned on to test its performance of energy saving.
The electric power consumption of the AC unit was reduced from 540 W to 450 W with an energy efficiency increase of 16.67%.
The power consumption of the AC unit was reduced from 640 W to 610 W with an energy efficiency increase of 4.69%. 
The proposed ESC algorithm was recently implemented on an air-handling unit of a chilled-water system for commercial buildings at Energy Resource Station of Iowa Energy center.

The Iowa Energy Center building is equipped with two identical air-handling units (A & B), each with its own dedicated and identical chiller.

- One air-handling unit serves four test rooms designated as A rooms for AHU-A, and B rooms for AHU-B.
- Each test room is a mirror image of its match with identical construction.

In this experimental study, the performance of anti-windup ESC controller was tested on AHU-B and B rooms.
Testing with Chilled-water Based AHU

Air-handling Unit

Air-cooled Liquid Chiller
The corresponding chilled water valve position is reduced from 40% to 30% with an energy efficiency increase of 25%.
Ongoing Work

Decisions made by traditional economizer control methods
• Temperature and relative humidity (RH) sensors have a crucial impact on the energy savings for existing economizers.

• The economizers may do not operate as expected and even waste more energy than before installation due to the wrong decision by on-off controllers because of the sensor errors.

• The National Building Controls Information Program (NBCIP) performed long term performance tests on 20 RH sensors for six manufactures.

• Nine of them failed during the tests, and the remaining had many measurements outside the specifications with largest mean error of 10%RH, and largest standard deviation error of 10.2%.

Data Analysis

Sensors with different accuracy were used.

Faulty Sensors | Accuracy
---|---
OAHUMDB | off by more than 50%
OAHUMDV | uncalibrated
OAHUMDM | uncalibrated
Data Analysis

Temperature sensors of different accuracy

Humidity sensors

Temperature sensors

OATEMP (°F)  OATEMPV (°F)

RH sensors of different accuracy

Humidity sensors

RAHUMD (%)  RAHUMDB (%)  RAHUMDV (%)
Data Analysis

Decisions made by sensors of different accuracy

[Graphs showing damper position over time for different sensor data sets]
Data Analysis

Simplified Psychrometric Chart

- OA Conditions
- RA Conditions

Temperature transition line

Differential enthalpy transition line

Relative Humidity:
- 10%
- 20%
- 30%
- 40%
- 50%
- 60%
- 70%
- 80%
- 90%

Specific Humidity (gm vap/kg dry air)

Dry Bulb Temperature (°F)
Conclusions

• This study presents the initial experimental results for applying the ESC based controller for optimizing the real-time operational efficiency of an air-side economizer.

• First, an AHU with direct-expansion AC unit is tested, and two ESC experiments under different outdoor-air and return-air conditions, showed energy efficiency increase of 16.67% and 4.69%, respectively.

• Then, the ESC is tested on a chilled-water based AHU system on the ERS facility at the Iowa Energy Center.

• The ESC algorithm performance is validated with one experiment under tested outdoor-air and return-air conditions with energy efficiency increase of 25%.
Acknowledgements

• Financial support from Building Efficiency Research Group, Johnson Controls, Inc. (JCI)
• Dr. John House and Dr. Tim Salsbury from Johnson Controls
• Dr. Xiaohui (Joe) Zhou from Iowa Energy Center
Thank you!

Any Questions?