Active Disturbance Rejection Control of Waste Heat Recovery Systems With Organic Rankine Cycles

Jing Zhang, Yan Wang, Zhigang Wang, and Wencheng Fu

1Tianjin Key Laboratory for Control Theory and Applications in Complicated System, Tianjin, China
2School of Electrical Engineering, Tianjin University of Technology, Tianjin, China
fuwch@tjut.edu.cn

Keywords
Waste heat recovery, Organic Rankine Cycle, ADRC, ESO, disturbance, simulation

ABSTRACT
Organic Rankine Cycle (ORC) is an effective technology to recovery low grade waste heat from exhaust gas. Many advantages of ORC are high efficiency, simple system, low pressure of working to seal, environment friendly and so on. A novel control algorithm called Active Disturbance Rejection Control (ADRC) is applied to vapor temperature control at the outlet of evaporator of organic Rankine cycle (ORC) system. The disturbances imposed on the waste heat recovery system are estimated through an extended linear state observer and then compensated by a linear feedback control strategy, it can eliminate disturbance via disturbance compensation independent of the accurate mathematical model of the plant. It is reliable, efficient and simple. Simulation examples demonstrate the simplicity of the design procedure and the good tracking performance.

1. Introduction
In recent years, as a result of energy shortage crisis and global warming problem, the utilization of low-grade energy has drawn more and more attention. The great development of global economy leads to energy shortage and serious environmental problems. In recent years, due to the increasing concern over the energy dilemma, more attention is being paid to saving energy [1]. Almost all the countries in the world devote into the work of energy saving and emission reduction and the search of green. But the ever increasing demands on robustness and accuracy, coupled with the inherent limitations of PID, have driven engineers to seek better control algorithms elsewhere.

The result shows that the ADRC based control system possesses a level of steadiness that is rarely seen. It has good characters of model independence and it actively rejects both internal and external disturbances. It is well that organic Rankine cycle (ORC) can achieve better performance to recover low grade heat than traditional steam power cycle in this paper. ORC has also been widely applied in practical process, such as low-grade waste heat recovery in industrial process [2] and geothermal power generation system [3].

In this context, an effective control system is essential to attain satisfactory performance over a broad range of operating. The design is based on the concept of active disturbance rejection control (ADRC). Through simulation, it is shown that the proposed approach is superior to the current PID based technology. During the heat exchanging, the outlet temperature of organic working fluids at evaporator is a variable. According to the dynamics of evaporator, a proper control law based on the ADRC proposed for maintaining the outlet temperature of organic working fluids.

2. System Descriptions
The schematic diagram of the investigated ORC system is illustrated in Figure 1. The system consists of heat sources, throttle valves, evaporator, condenser, pump and other auxiliary equipments. The low temperature and pressure vapor
Zhang, et al.

is condensed into liquid state when passing through a condenser. The condensed fluid is pressurized by the feed pump and sent back to the evaporator, and a new cycle begins. Heat transfer efficiency could be evaluated by the efficiency of evaporator.

The active disturbance rejection concept is simply, as will be shown in the next section. A description of the system variables follows, using the nomenclature given in Tab 1.

3. LADRC Design for System

Active disturbance rejection control (ADRC) is a relatively new control algorithm. The second LADRC algorithm for the vapor temperature control of the organic Rankine cycle system is shown in Figure 2. It was further simplified to LADRC, using LESO in \[6\], which makes it very simple and exactly \[5\]. The purpose of this paper is to show analytically how LADRC achieves excellent performance. To illustrate the basic idea, consider an ADRC design for a second order system. ADRC has been shown to be an effective tool in dealing with real world problems of disturbances and nonlinearities, etc. ADRC is proposed so that good disturbance rejection is achieved while maintaining system stability. The ADRC controller possesses the following characteristics the algorithm is easy; the adjustment of the parameters is simpler. The default values are:

\[
\omega_0 = 2\omega_c
\]

\[
K_p = \omega_c^2
\]

\[
K_d = 2\omega_c
\]

3.1 ESO Model Output

Employing the extended state observer (LESO), the estimation both internal and external disturbances in this paper. The estimation problem of leads us to a unique state observer known as the Extended State Observer (ESO). It is indicated that the LESO has ability to get better simulation result. The LESO is given as:

\[
y_i^{(N)} = f_i + b_0 \cdot u_i
\]

where \(f\) is the total disturbance and let \(x_{ni} + 1, i = f_i\), assuming \(f\) is differentiable and let \(h_i = f_i\), it can be written in an augmented state space form:

\[
y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}, \quad \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \frac{dy_1}{dt} \\ \frac{dy_2}{dt} \end{bmatrix}, \quad \begin{bmatrix} \frac{dy_1}{dt} \\ \frac{dy_2}{dt} \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} + \begin{bmatrix} b_0 \\ b_1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}
\]

\[
y_1 = f_1 + b_0 \cdot u_1
\]

Table 1. Controlled and manipulated variables.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Power (kw)</td>
</tr>
<tr>
<td>P</td>
<td>Pressure (MPa)</td>
</tr>
<tr>
<td>T</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>w</td>
<td>Pump speed (r/min)</td>
</tr>
<tr>
<td>v</td>
<td>Velocity (m/s)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subscripts</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>Evaporator</td>
</tr>
<tr>
<td>a</td>
<td>Gas</td>
</tr>
<tr>
<td>g</td>
<td>Saturated vapor</td>
</tr>
<tr>
<td>l</td>
<td>Saturated liquid</td>
</tr>
<tr>
<td>p</td>
<td>Pump</td>
</tr>
<tr>
<td>T</td>
<td>turbine</td>
</tr>
<tr>
<td>v</td>
<td>Valve</td>
</tr>
<tr>
<td>c</td>
<td>Condenser</td>
</tr>
<tr>
<td>y</td>
<td>Output</td>
</tr>
<tr>
<td>u</td>
<td>Input</td>
</tr>
</tbody>
</table>

Figure 1. Model for the ORC system.

Figure 2. LADRC applied in evaporator of ORC system.
The augmented model of (4) is:

\[
\begin{align*}
\dot{x}_i &= Ax_i + Bu_i + Dh_i \\
y_i &= Cx_i
\end{align*}
\]  

(6)

\[
x_i = \begin{bmatrix} x_{1,i} & x_{2,i} & \cdots & x_{n,i} & x_{n+1,i} \end{bmatrix}^T_{(n+1)\times 1}
\]  

(7)

\[
A = \begin{bmatrix}
0 & 1 & 0 & \cdots & 0 \\
0 & 0 & 1 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & 1 \\
0 & 0 & 0 & \cdots & 0 \\
\end{bmatrix}_{(n+1)\times(n+1)}
\]  

(8)

\[
B = \begin{bmatrix}
0 \\
0 \\
M \\
b_{0,i} \\
0 \\
\end{bmatrix}_{(n+1)\times 1}
\]  

(9)

\[
C = \begin{bmatrix}
1 & 0 & \cdots & 0 & 0
\end{bmatrix}_{(n+1)\times 1}
\]  

(10)

\[
D = \begin{bmatrix}
0 & 0 & \cdots & 0 & 1
\end{bmatrix}_{(n+1)\times 1}
\]  

(11)

An ESO is designed for system (6) accordingly as:

\[
\hat{x}_i - x_i \quad (i = 1, L, n+1)
\]  

(12)

\[
L_i = \begin{bmatrix}
\beta_{1,i} & \beta_{2,i} & \cdots & \beta_{n,i} & \beta_{n+1,i}
\end{bmatrix}^T
\]  

(13)

\[
\dot{\hat{x}}_i = A\hat{x}_i + Bu_i + l(x_{1,i} - \hat{x}_{1,i})
\]  

(14)

to reduce the tuning parameters, all the controller poles are placed at \(w_{0,i}\). Then the approximate closed-loop characteristic polynomial becomes:

\[
\lambda_{0,i}(s) = |sI - (A - L_iC)| = (s + \omega_{0,i})^{n+1}
\]  

(15)

\[
= s^{n+1} + \omega_{0,i}\alpha_1 s^n + \cdots + \omega_{0,i}\alpha_n s + \omega_{0,i}\alpha_{n+1,1}
\]
where $\omega_{0,i}$ is the controller bandwidth and let $\alpha_{j,i} = \frac{(n_i + 1)!}{j!(n_i + 1 - j)!}$, $j = 1, 2, \ldots, n_i + 1$

### 3.2 Disturbance Compensation Model Output

Then (1) can be written as:

$$u_i = \frac{-\hat{f}_i + w_{0,i}}{b_{0,i}}$$

(16)

assume $f_i \rightarrow \hat{f}_i$ is founding, and let

$$y_{i}^{(n)} = (f_i - \hat{f}_i) + w_{0,i} \approx w_{0,i}.$$

### 3.3 SEF Model Output

The control law is given by:

$$u_i = K_{1,i} (y_{r,i} - \hat{x}_{1,i}) + L + K_{w,i} (y_{r,(n-1)} - \hat{x}_{w,i}) - y_{r,(n)}$$

(17)

where $y_{r,i}$ is the track system and

$$k_{j,i} = \frac{n_i!}{(j-1)!(n_i - j + 1)!} \omega_{c,i}^{n_i-j+1}$$

$j = 1, 2, \ldots, n_i$ is the controller gain matrix. In practice, this bandwidth is affected by system performance. It is expressed as follows:

$$\lambda_{c,i}(s) = s^n + K_{e,i} s^{n-1} + \cdots + K_{1,i} = (s + \omega_{c,i})^n$$

(18)

where $\omega_{c,i}$ is the observer bandwidth of the system loop. The implementation process is very simplified.

### 4. Simulation Study

In this paper, the proposed ADRC algorithm is applied in vapor temperature control at the outlet of the evaporator of the ORC system. The transfer function of evaporator is:

$$G_T(s) = \frac{T_h(s)}{Q(s)} = \frac{80.8e^{-7s}}{33.4s + 1}$$

(19)

where $T_h$ is the evaporator outlet temperature and $Q$ is the mass flow rate.

In this paper, the PID algorithm is applied in vapor temperature control at the outlet of the evaporator of the ORC system. Classical PID of the basic principle is applied in vapor temperature control, as shown in Fig 3.

The design parameters for ADRC algorithm are $\omega_0 = 10, \omega_x = 0.08, b = 2.4$. At $t=41.6s$, the vapor temperature $T_a$ at the stable of 100°C; and then the vapor temperature $T_a$ at the stable of 200°C when $t=34.2s$.

The design parameters for PID algorithm are $K_p = 0.008, T_1 = 13.333, T_d = 3.5$. At $t=245s$, the vapor temperature $T_p$ at the stable of 95°C; and then the vapor temperature $T_p$ at the stable of 200°C when $t=550s$.

The results show that the ADRC system has good anti-interference ability and good robustness. The simulation results demonstrate that the highly stable is well ADRC controlled is applied in the outlet responses of temperature of evaporator. In this section, we give a few simulation illuminate that are particularly instable to PID and particularly stable to ADRC in the comparison of outlet temperature. The output responses of temperature of evaporator are shown in Fig 4(a). Almost all the selected Vapor temperature anti-interference ability curves perform better at the ADRC algorithm than PID algorithm.

In this section, we give a few simulation illuminate that are particularly instable to PID and particularly stable to ADRC in the comparison of control quantity curves. From the aforementioned simulation illustration, it is apparent that ADRC has a much wider reliability than PID. Almost all the selected control quantity curves perform better at the ADRC algorithm than PID algorithm. Figure 4(b) show the corresponding control quantity.
5. Conclusions

ADRC algorithm is simulated in the environment of Simulink, the results show the stability of the proposed schemes. It is these fundamental limitations of PID that prompt us to use the ADRC algorithm. Ushered in by reliability and stability, ADRC will be accepted as a viable alternative to PID, as we obtain a result in experiment. ADRC is the result of investigation, largely performed experimentally in vapor temperature control with the system stability. From the aforementioned simulation illustration, it is apparent that ADRC has a much wider stability than PID. Waste heat recovery system with organic Rankine cycles has a great deal of disturbance and these disturbance can’t be estimate exactly. To deal with this characteristic, the ADRC is used to improve the system’s performance. Based on ADRC extended state observer (ESO) to get the model uncertainty and external interference of the system, the system shows good adaptability to noise and model uncertainty.

References


Figure 4(a). Vapor temperature anti-interference ability curves.

Figure 4(b). Control quantity curves.