Model Construction of Warm Water Temperature of Heat Source in an OTEC Experimental Plant via Stochastic Process

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Abstract

In this research, a model for warm water temperature of heat source in an ocean thermal energy conversion (OTEC) experimental plant is constructed. First, a model is constructed based on experimental data, where the model is assumed to be represented as the first order system. Secondly, in order to improve the difference between the model and experimental data, an improved model is considered by introducing a stochastic process which is assumed to be a white Gaussian process. Finally, the behavior of the constructed model in this research is verified through simulation results.

1 Introduction

In ocean thermal energy conversion (OTEC) [1] plant, electricity generation is conducted by using the temperature difference between warm surface seawater and cold deep seawater. The researches on not only OTEC plant itself but also its modeling and control have been conducted from both theoretical and practical point of view. (e.g., See [1, 2, 3, 4, 5, 6, 7].) In particular, the researches on the practical use of OTEC technology have been done in Institute of Ocean Energy, Saga University, Japan (IOES) [8] by constructing actual OTEC experimental plants. In order to simulate the arbitrary warm heat source condition for OTEC plant in IOES, heat source systems have also been implemented. For the stabilization control, the model construction of heat source in an OTEC experimental plant was considered in [4] based on experimental data which captures the characteristics between a valve opening and a temperature. However, the simulation result did not reflect the experimental result sufficiently by the complexity of the system and the noise, and sufficient accuracy of the temperature has not necessarily been obtained.

In this research, the improvement of the model of heat source in an OTEC experimental plant constructed in [4] is attempted by introducing a stochastic process [9, 10] expressed as a white Gaussian process. This is just the difference from the previous work [4], and also the originality of this research. The behavior of the proposed model in this research is verified through numerical simulations.

2 An OTEC Experimental Plant and its Heat Source

The overview of an OTEC experimental plant using Uehara cycle [5] in IOES is shown in Fig. 1. The OTEC experimental plant mainly consists of OTEC part and heat source part. In OTEC part, electricity is generated by the generator which is connected to the turbine. The turbine is rotated by vapor working fluid sent from evaporator. In the evaporator, liquid working fluid sent from condenser is vaporized by the heat exchanged for warm water. Therefore, warm water in the evaporator is important for the evaporation of liquid working fluid. In the condenser, the vapor working fluid from generator is condensed by the heat exchange for cold water. The other components in Fig. 1 are placed to realize higher thermal efficiency of OTEC plant. On the other hand, in heat source part, warm water and cold water are generated. In this research, the warm water temperature sent to the evaporator is considered.

The schematic diagram of the current heat source system in IOES is illustrated in Fig. 2. The temperature $T(t)$ of the warm water sent to the evaporator is changed by receiving the heat energy through the heat exchange between warm water and hot water in a warm source heat exchanger. The hot water (about 60 [°C]) is made by a boiler, and it is stored in a warm source (WS) storage tank. The heat energy to be exchanged in warm source heat exchanger is adjusted by changing the valve opening $u(t)$ of a three-way valve (i.e., the flow rate of hot water sent to the warm source heat exchanger). Thus, the temperature $T(t)$ of the inlet warm water sent to the evaporator for the generation
Fig. 1: Overview of an OTEC experimental plant using Uehara cycle

Fig. 2: A heat source system in an OTEC experimental plant
of vapor working fluid in OTEC part can be regulated by manipulating the valve opening $u(t)$ appropriately.

### 3 Model Construction

In this research, a model of heat source system to provide warm water for the evaporator in the OTEC experimental plant is constructed by integrating a conventional model obtained from experimental data with a stochastic process. The experimental data were obtained from an experiment by the actual OTEC experimental plant in IOES.

The experimental condition is listed in Table 1.

The experimental condition is listed in Table 1. Experimental result of warm water temperature $T(t)$ for fixed valve opening $u = 8$ [\%] is depicted in Fig. 3, where $T_0(=T_{\text{exp}}(0))$ and $T_{s}(=T_{\text{exp}}(82))$ are initial and final temperatures in experimental result, respectively. For the construction of the temperature control system, a model as the first order system:

$$\frac{dT(t)}{dt} = \frac{K u(t) - \bar{T}(t)}{\tau}$$

(1)

is constructed, where $\bar{T}(t):=T(t)-T_0$, and the time constant $\tau$ and the steady-state gain $K$ were determined from the experimental result in Fig. 3 as $\tau = (1-e^{-1})(T_s-T_0) = 23.28$ [s] and $K = (T_s-T_0)/u_s = 0.6331$ [\^\circ C/\%], respectively. The time delay was ignored for simplicity. However, as shown in the next section, the simulation result did not reflect the experimental result sufficiently by the complexity of the system and the noise, and sufficient accuracy of the temperature has not necessarily been obtained.

### 4 Simulation Results

To cope with this problem, in this research, an improved model

$$\frac{dT(t)}{dt} = \frac{K u(t) - \bar{T}(t)}{\tau} + w(t)$$

(2)

is proposed by introducing a stochastic process $w(t) \sim N(\mu, \sigma^2)$ which is assumed to be a white Gaussian process. The mean $\mu$ and the variance $\sigma^2$ (or standard deviation $\sigma$) are determined from simulation result by using the model (1) and the experimental result.

Define the error $e_M(t)$ between the temperature control $T(t)$ of (1) and the experimental result $T_{\text{exp}}(t)$ by

$$e_M(t) = T_{\text{exp}}(t) - T(t).$$

(3)

Then, we have

$$\frac{de_M(t)}{dt} = \frac{dT_{\text{exp}}(t)}{dt} - \frac{K u(t) - T_{\text{exp}}(t)}{\tau} + \frac{e_M(t)}{\tau}$$

(4)

or

$$\frac{dT_{\text{exp}}(t)}{dt} = \frac{K u(t) - \bar{T}_{\text{exp}}(t)}{\tau} + \eta(t),$$

(5)

where $\bar{T}_{\text{exp}}(t) := T_{\text{exp}}(t) - T_0$ and

$$\eta(t) = \frac{de_M(t)}{dt} + \frac{e_M(t)}{\tau}.$$

(6)

The relation (5) implies that if the behavior of the experimental result is governed by the first order system, $\eta(t)$ may be regarded as the modeling error. Therefore, in this research, the mean and the variance of $w(t)$ in (2) are determined by calculating those of $\eta(t)$. Indeed, from the simulation result shown in Fig. 4 estimated parameters $\mu = 2.482 \times 10^{-3}$ [\^\circ C/s] and $\sigma = 3.622 \times 10^{-2}$ [\^\circ C/s] were obtained, where the simulation was conducted by using Simulink with ode4 (Runge-Kutta).

![Fig. 4: Modeling error $\eta(t)$](image)

To confirm the behavior of the proposed model (2), some simulations for fixed valve opening $u(t) = 8$ [\%]
Table 2: IAE on simulation results

<table>
<thead>
<tr>
<th>Seed</th>
<th>IAE [°C·s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.48</td>
</tr>
<tr>
<td>1</td>
<td>19.48</td>
</tr>
<tr>
<td>2</td>
<td>18.45</td>
</tr>
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<td>3</td>
<td>16.62</td>
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<tr>
<td>4</td>
<td>22.17</td>
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<tr>
<td>5</td>
<td>18.23</td>
</tr>
<tr>
<td>6</td>
<td>20.65</td>
</tr>
<tr>
<td>7</td>
<td>13.55</td>
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<td>8</td>
<td>13.74</td>
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<tr>
<td>9</td>
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<td>18</td>
<td>18.93</td>
</tr>
<tr>
<td>19</td>
<td>19.14</td>
</tr>
</tbody>
</table>

Mean 17.94
Standard deviation 3.095
Min. (Seed No. 14) 13.17
Max. (Seed No. 9) 23.29

without \( w(t) \) 18.02

were carried out. Indeed, 20 simulations with different seeds to generate the random sequence for \( w(t) \) were carried out by using MATLAB/Simulink.

For the evaluation of the simulation results, IAE (integral of absolute value of error) \( \int_0^\infty |e_M(t)| \, dt \) is employed. The results are listed in Table 2 and depicted in Fig. 5, where “without \( w(t) \)” means \( w(t) \equiv 0 \) in (2) (i.e., conventional model (1)). Three simulation results for minimal IAE (best case in this research), maximal IAE (worst case in this research) and an IAE near the average are also shown in Figs. 6-8, respectively, where (a) is the temperatures, and (b) is the modeling error \( \eta(t) \) and modeled error \( w(t) \).

The simulation result for minimal IAE indicates that the improvement of the temperature model can be achieved by introducing a stochastic process \( w(t) \). However, the simulation results for maximal IAE and IAE near the average also imply that the accuracy of the simulation result may not be improved by the stochastic process \( w(t) \). From Fig. 5 and Figs. 6-8 (a) we see

![Fig. 5: Histogram of modeling error on simulation results](image)

![Fig. 6: Time response in minimal IAE result (Seed No. 14)](image)

(a) Temperature \( T(t) \)

(b) Modeling error \( \eta(t) \) and modeled error \( w(t) \)
Fig. 7: Time response in maximal IAE result (Seed No. 9)

Fig. 8: Time response in an IAE result (neat the average) (Seed No. 5)
that since the modeling error $\eta(t)$ calculated by (6) do not necessarily seem to have Gaussian property, further improvement of the model of warm water temperature of heat source is required.

5 Conclusions

In this research, a model of warm water temperature of heat source in an OTEC experimental plant was constructed by introducing a stochastic process which is assumed to be a white Gaussian process. The mean and variance of the white Gaussian process were determined through simulation using conventional model and experimental data. Simulation results for the proposed model implies that it can improve the behavior of conventional warm water temperature model. However, it is necessary to verify the effectiveness of the proposed method more precisely by using different experimental data.

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References


