Construction of a state-space model with multiple flow rate inputs for an OTEC plant using Rankine cycle

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\begin{abstract}
Recently, the importance of sustainable energy using renewable resources has been recognized. As one of the sustainable energy resources, ocean thermal energy conversion (OTEC) is important for the development of a next-generation energy source. This paper proposes a method to construct a state-space model for an OTEC plant using the Rankine cycle. The state-space model is constructed based on a linear approximation of a simple dynamic model. The flow rates of warm seawater, cold seawater, and working fluid are considered as inputs to the model, and the power output is selected as the output of the model. The state-space model, described as a time-invariant system, is derived numerically. The constructed model is evaluated through numerical simulations of the step response; the power generation control is verified using proportional integral controllers, and the advantage as a state-space model is verified using a linear quadratic regulator. The simulation results demonstrate the effectiveness and limitation of the proposed model. Because the simple dynamic model to be approximated is constructed based on the physical laws, various kinds of state-space models corresponding to the physical parameters can be obtained easily.
\end{abstract}

\section{Introduction}

The importance of sustainable energy using renewable resources such as sunlight, geothermal heat, wind, tides, waves, etc., has been recognized in recent years, as evidenced in the formulation of sustainable development goals (SDGs) [1].

Ocean thermal energy conversion (OTEC) is a power generation method, which uses the temperature difference between surface warm seawater and deep cold seawater [2]. Because OTEC uses only seawater of different temperatures, the heat source is available semi-permanently. Furthermore, there is no emission of CO\textsubscript{2} during the operation. Therefore, OTEC is important for the development of a next-generation energy source.

Recently, studies on the OTEC technology have been vigorously conducted. In [3], an optimization method for an OTEC plant using an organic Rankine cycle was proposed. In [4], the performance simulation and multi-objective optimization of an OTEC plant using an innovative organic Rankine cycle were investigated based on a multi-objective particle swarm optimization algorithm, where the levelized cost of energy and exergy efficiency were considered. In [5], the OTEC resources were assessed using an ocean general circulation model. In particular, the OTEC potentials of the ocean in Florida and Indonesia were estimated in [6,7], respectively.

The modelling and control of OTEC plants have also been studied. In [8], a model for an OTEC plant using the Uehara cycle was constructed based on the mass and energy conservation laws. The model was used to realize power generation control of OTEC plants using the Uehara cycle in [9]. To study the dynamics of heat exchangers, a simple dynamic model was investigated in [10]. Furthermore, a simple dynamic model for an OTEC plant using a double-stage Rankine cycle [11] was constructed in [12]. The model was used in [13–15] to investigate the control methods of OTEC plants using a double-stage Rankine cycle with warm seawater temperature variation. In [13], power generation control was considered by manipulating either the warm or cold seawater flow rate. In [14], the control system was designed based on the simultaneous regulation of multiple flow rates. In [15], power generation control with target power output variation was considered.

It should be noted that the simple dynamic model [10,12] cannot be easily applied to the control system design directly because the model has nonlinearity in the static calculation. (see [16].) To address this issue, a state-space model with the flow rate of warm seawater as the input was constructed in [16] for an
OTEC plant using the Rankine cycle through linear approximation of the simple dynamic model. In [17], a state-space model with flow rate of cold seawater as the input was constructed in a similar manner for an OTEC plant using the Rankine cycle. Furthermore, in [18], a state-space model with the flow rates of warm and cold seawater as the inputs was constructed for an OTEC plant using the Rankine cycle. However, in [16–18], the flow rate of the working fluid was not considered as the input to the model. In [19], a state-space model with the flow rate of the working fluid as the input was constructed for an OTEC plant using the Rankine cycle.

In this study, by integrating the concepts of model construction in [16–19], a novel state-space model with the combined inputs of seawater flow rate and working fluid flow rate was constructed for an OTEC plant using the Rankine cycle.

The key contributions of this study are listed below.

1. As verified in [16], the relation between the inputs such as seawater flow rates, working fluid flow rate and the steady-state quantities in most of the models constructed using thermophysical properties is complicated, and it is difficult to directly apply existing control theories to the control problems. This study gives a method to easily obtain time-invariant state-space models by linear approximation of a simple dynamic model.
2. The effectiveness and limitation of the linear approximation were verified by constructing a state-space model from a simple dynamic model numerically. Furthermore, the usefulness was confirmed by not only the simulation of step response but also the control simulations.

The rest of this paper is organized as follows: In Section 2, the structure of an OTEC plant using the Rankine cycle and its power generation principle are explained. The simple dynamic model is also reviewed. In Section 3, a method for constructing a state-space model for an OTEC plant using a Rankine cycle with multiple flow rates as inputs is proposed. In Section 4, the simulation results to evaluate the proposed model are presented. In Section 5, the proposed model and simulation results are discussed. Finally, concluding remarks are presented in Section 6.

2. Simple dynamic model of OTEC plant using Rankine cycle

The structure of the OTEC plant using the Rankine cycle is shown in Figure 1. In the Rankine cycle, an evaporator, a turbine, a generator, condenser, and pump are connected by pipes. A fluid with a low boiling point, such as ammonia, is used as the working fluid. The principle of power generation is explained below. First, the working fluid is sent to the evaporator by the working fluid pump. The working fluid is then vaporized in the evaporator by heat exchange with the warm seawater. Next, electricity is generated when the working fluid rotates the turbine connected to the generator. Then, the working fluid moves to the condenser and is condensed by heat exchange with the cold seawater. Finally, the working fluid is sent to the evaporator.

Here, a simple dynamic model of an OTEC plant using the Rankine cycle in [10] is reviewed.

In the simple dynamic model, the dynamics of the heat transfer in the heat exchanger are represented by the following first-order systems:

\[
\begin{align*}
\tau_1 \frac{dT_{wso}(t)}{dt} + T_{wso}(t) &= T_{wso}^{ss}(t), \\
\tau_2 \frac{dT_{cso}(t)}{dt} + T_{cso}(t) &= T_{cso}^{ss}(t), \\
\tau_3 \frac{dQ_c(t)}{dt} + Q_c(t) &= Q_c^{ss}(t), \\
\tau_4 \frac{dQ_s(t)}{dt} + Q_s(t) &= Q_s^{ss}(t),
\end{align*}
\]

where \( T_{wso}(t) \) is the warm seawater temperature at the evaporator outlet; \( T_{cso}(t) \) is the cold seawater temperature at the condenser outlet; \( Q_c(t) \) is the heat flow rate from the warm seawater to the working fluid; \( Q_s(t) \) is the heat flow rate from the working fluid to the cold seawater. The right-hand sides of (1)–(4) are the quantities in the steady state. The coefficients \( \tau_i (i = 1, 2, 3, 4) \) are time constants.

The quantities \( T_{wso}^{ss}(t), T_{cso}^{ss}(t), Q_c^{ss}(t), \) and \( Q_s^{ss}(t) \) are calculated based on the static calculations. In other words, given the warm seawater temperature \( T_{wsi}(t) \) at the evaporator inlet, cold seawater temperature \( T_{csi}(t) \) at the condenser inlet, overall heat transfer coefficient, heat transfer area, warm seawater flow rate \( m_{ws}(t) \), cold seawater flow rate \( m_{cs}(t) \), working fluid flow rate \( m_{wf}(t) \), specific heat of seawater, and error bound \( \varepsilon \), the quantities at each point (Points 1–4 in Figure 1) are determined such that the heat flow rates \( Q_c^{ss}(t), Q_s^{ss}(t), Q_c^{ss}(t), Q_s^{ss}(t) \) satisfy

\[
1 - \frac{Q_c^{ss}(t)}{Q_{wsi}(t)} \leq \varepsilon
\]
\[
1 - \frac{Q_e^s(t)}{Q_s^w(t)} \leq \varepsilon \quad (6)
\]

for temperatures \(T_{wso}^s(t), T_{cs}^s(t)\), where \(Q_{wso}^s(t)\) is the heat flow rate from the warm seawater to the working fluid, and \(Q_s^w(t)\) is the heat flow rate from the working fluid to the cold seawater. The conditions (5) and (6) are considered for sufficiently small \(\varepsilon\). This means that the quantities at each point are calculated under the condition that \(Q_e^s\) and \(Q_s^w\) are sufficiently close to \(Q_{wso}^s\) and \(Q_{cs}^s\), respectively. The power output \(W(t)\) is calculated by using the calculation results explained above:

\[
W(t) = \eta m_{wf}(t)(h_1(t) - h_2(t)),
\]

where \(\eta = 0.85\) is the turbine efficiency and \(h_i(t)\) \((i = 1, 2)\) is the specific enthalpy at Point \(i\) \((i = 1, 2)\). The enthalpies \(h_i(t)\) are calculated using the static calculation.

Here, let us review the relationship between the flow rates and the steady state quantities. The details are included in [16] and references therein. The quantities \(Q_e^s\), \(Q_s^w\), \(Q_{cs}^s\) and \(Q_{wso}^s\) are represented by

\[
Q_e^s = m_{wso}c_p(T_{wsi} - T_{wso}^s) \quad (8)
\]

\[
Q_s^w = m_{cs}c_p(T_{cs}^s - T_{csi}) \quad (9)
\]

\[
Q_{wso}^s = m_{wso}(h_1 - h_4) \quad (10)
\]

\[
Q_{cs}^s = m_{wso}(h_2 - h_3). \quad (11)
\]

In (8)–(11), \(h_i\) \((i = 1, 2, 3, 4)\) are the specific enthalpy at Point \(i\), and \(c_p\) is the specific heat of seawater. The quantities \(h_i\) depends on \(T_{wso}^s, T_{cs}^s, T_{wsi}, T_{csi}\) nonlinearly. This means that the relationship is so complicated.

### 3. Construction of state-space model

In this study, the state-space model of an OTEC plant using the Rankine cycle was constructed based on a simple dynamic model. The flow rates \((m_{wsi}(t), m_{csi}(t), m_{wf}(t))\) of seawater and working fluid are selected as the input \(u(t)\), and the power output \(W(t)\) is the output \(y(t)\).

\[
u(t) = [m_{wso}(t) \quad m_{cs}(t) \quad m_{wf}(t)]^T \quad (12)
\]

\[
y(t) = W(t), \quad (13)
\]

where the superscript \(^T\) denotes the transpose. Defining the state vector \(x(t)\) as

\[
x(t) = [T_{wso}^s(t) \quad T_{cs}^s(t) \quad Q_e^s(t) \quad Q_s^w(t)]^T, \quad (14)
\]

we have the following representation:

\[
\dot{x}(t) = Ax(t) + \zeta_u(t) \quad (15)
\]

from (1)–(4), where

\[
A = \text{diag}\left(\begin{array}{cccc}
-1/\tau_1 & -1/\tau_2 & -1/\tau_3 & -1/\tau_4
\end{array}\right), \quad (16)
\]

\[
\zeta_u(t) = \left[\begin{array}{cccc}
1/T_{wso}^s(t) & 1/T_{cs}^s(t) & 1/Q_e^s(t) & 1/Q_s^w(t)
\end{array}\right]^T. \quad (17)
\]

It was verified in [16] that the relation between the warm seawater flow rate \(m_{wso}(t)\) and the steady-state quantities \(T_{wso}^s(t), T_{cs}^s(t), Q_e^s(t),\) and \(Q_s^w(t)\) in a simple dynamic model is complicated, and it is difficult to directly utilize it. Unfortunately, the relationship between the flow rates \((m_{wso}(t), m_{cs}(t), m_{wf}(t))\) and the steady state quantities \(T_{wso}^s(t), T_{cs}^s(t), Q_e^s(t),\) and \(Q_s^w(t)\) in the simple dynamic model is also complicated. Therefore, in this paper, the relationship is approximated by using linear regression:

\[
\zeta_u(t) \approx Bu(t) + B_0. \quad (18)
\]

Substituting (18) into (15), we obtain

\[
\dot{x}(t) = Ax(t) + Bu(t) + B_0. \quad (19)
\]

Here, an example of the linear regression is explained. The calculation conditions are listed in Table 1. The warm and cold seawater flow rates \((m_{wso}, m_{cs})\) were changed in the range of 35–45 (kg/s) at intervals of 0.5 (kg/s), and the working fluid flow rate \(m_{wf}\) was changed in the range of 0.1–0.5 (kg/s) at intervals of 0.02 (kg/s). In all cases \((m_{wso}, m_{cs}, m_{wf})\), the quantities \(T_{wso}^s, T_{cs}^s, Q_e^s,\) and \(Q_s^w\) were calculated. Then, the matrices \(B, B_0\) were obtained as follows:

\[
B = \left[\begin{array}{cc}
5.539 \times 10^{-2} & -2.486 \times 10^{-4} \\
-3.485 \times 10^{-4} & -5.316 \times 10^{-2} \\
-7.271 & 7.107 \\
57.92 & 7.836 \\
1.208 \times 10^6 & 1.181 \times 10^6
\end{array}\right]. \quad (20)
\]

\[
B_0 = \left[\begin{array}{ccc}
26.77 & 11.12 & 1.684 \times 10^3 \\
11.12 & 1.181 \times 10^6 & -876.8
\end{array}\right]^T. \quad (21)
\]

### Table 1. Conditions for numerical simulation.

| Parameter | Value |
|-----------|-------|
| Warm seawater inlet temperature \(T_{wso}^\circ\) | 29.0 |
| Cold seawater inlet temperature \(T_{csi}^\circ\) | 9.0 |
| Overall heat transfer coefficient [\(W/(m^2 \cdot K)\)] | 2000 |
| Heat transfer area of evaporator (m\(^2\)) | 87.4 |
| Heat transfer area of condenser (m\(^2\)) | 87.4 |
| Error bound \(\varepsilon\) | 10\(^{-4}\) |
| Specific heat of seawater [\(J/(kg \cdot ^\circ C)\)] | 4179 |
| Time constant \(\tau_1\) (s) | 3.0 |
| Time constant \(\tau_2\) (s) | 3.1 |
| Time constant \(\tau_3\) (s) | 4.0 |
| Time constant \(\tau_4\) (s) | 4.0 |
The approximated results are shown in Figures 2–4, where the horizontal axes are the warm seawater flow rate $m_{ws}$, cold seawater flow rate $m_{cs}$, and working fluid flow rate $m_{wf}$, respectively. The black dots denote the results of the original model, and the red dots denote the results of the approximated model. Evaluation by the absolute value of difference of calculation results between original model and approximated model in Figures 2–4 was performed as shown in Table 2. These figures and table indicate that the results were nearly the same.

In addition, because the relation between the power output $W(t)$ and the quantities $T_{ws0}(t), T_{cs0}(t)$ is also very complicated, linear regression is applied to obtain the approximated output equation.

$$W(t) \simeq C_1 T_{ws0}(t) + C_2 T_{cs0}(t) + C_0$$

(22)

In this study, we assume that the output $W(t)$ is represented well by the states $T_{ws0}(t), T_{cs0}(t)$, and

$$C = [C_1 \ C_2 \ 0 \ 0].$$

(23)

Next, an example of linear regression for the power output $W(t)$ is examined. The flow rates ($m_{ws}, m_{cs}$) of both warm and cold seawater were changed in the range of 35–45 (kg/s) at intervals of 0.5 (kg/s), and the working fluid flow rate $m_{wf}$ was changed in the range of 0.1–0.5 (kg) at intervals of 0.02 (kg/s). In all cases ($m_{ws}, m_{cs}, m_{wf}$), the temperatures ($T_{ws0}, T_{cs0}$) and the power output $W$ were calculated. Then, the matrices $C$ and $C_0$ were obtained as follows:

$$C = [-1.646 \ 1.516 \ 0 \ 0],$$

(24)

$$C_0 = 39.91.$$  

(25)

The approximated results are shown in Figure 5. The black dots denote the results of the original model, and the red dots denote the results of the approximated model. This figure indicates that the results were different.
4. Simulation results

To evaluate the constructed state-space model, the simulations of step response and power generation control using a PI controller and linear quadratic regulator were conducted. The simulations of power generation control using PI controller were performed to verify the usefulness of the frameworks of control systems that were considered in the past works such as [16–19] for the proposed model. The simulations of LQR were carried out to provide a method for the application of the proposed model to the control system design.

4.1. Step response

First, let us check the step responses for 3 cases:

Case S-1: Both the flow rates \( m_{ws}(t) \) and \( m_{cs}(t) \) are changed from 38 (kg/s) to 43 (kg/s) at \( t = 20 \) (s), and the flow rate \( m_{wf}(t) \) is changed from 0.35 (kg/s) to 0.40 (kg/s) at \( t = 20 \) (s).

Case S-2: Both the flow rates \( m_{ws}(t) \) and \( m_{cs}(t) \) are changed from 60 (kg/s) to 65 (kg/s) at \( t = 20 \) (s), and the flow rate \( m_{wf}(t) \) is fixed at 0.35 (kg/s).

Case S-3: Both the flow rates \( m_{ws}(t) \) and \( m_{cs}(t) \) are changed from 38 (kg/s) to 43 (kg/s) at \( t = 20 \) (s), and the flow rate \( m_{wf}(t) \) is fixed at 0.35 (kg/s).

The simulation results for Cases S-1, S-2, and S-3 are shown in Figures 6–8, respectively.

4.2. Power generation control based on PI control

Next, we check the control simulation results of power generation using PI controllers. The simulation conditions are listed in Table 1. The target output \( W_{ref} \) is given as \( W_{ref} = 13 \) (kW). The PI controllers are represented by

\[
m_{ws}(t) = m_{ws0} + K_{mws} \left( e(t) + \frac{1}{T_{mws}} \int_0^t e(\tau) \, d\tau \right),
\]

(26)

\[
m_{cs}(t) = m_{cs0} + K_{mcs} \left( e(t) + \frac{1}{T_{mcs}} \int_0^t e(\tau) \, d\tau \right),
\]

(27)

\[
m_{wf}(t) = m_{wf0} + K_{mwf} \left( e(t) + \frac{1}{T_{mwf}} \int_0^t e(\tau) \, d\tau \right),
\]

(28)

\[
e(t) = W_{ref} - W(t),
\]

(29)

where the PI parameters \( K_{mws} = 0.3 \) [(kg/s)/kW], \( T_{mws} = 0.5 \) (s), \( K_{mcs} = 0.3 \) [(kg/s)/kW], \( T_{mcs} = 0.5 \) (s), \( K_{mwf} = 0.004 \) [(kg/s)/kW], and \( T_{mwf} = 0.2 \) (s). These parameters were determined from the simulation results through trial and error by using the original model. The standard warm seawater flow rate \( m_{ws0} \), standard cold seawater flow rate \( m_{cs0} \), and standard
working fluid flow rate $m_{wf0}$ were set as 39.72 (kg/s), 38.89 (kg/s), and 0.2 (kg/s), respectively. The simulation results are shown in Figure 9. The black line represents the simulation result of the original model, and the red line that of the proposed model.

To verify the effect of the approximation (22) with respect to the power output $W(t)$, another simulation using the state-space model (19) without the output equation (22) was conducted, and the power output was calculated by using the static calculation of the simple dynamic model (i.e. (7)). The simulation results are shown in Figure 10.

### 4.3. Linear quadratic regulator

To confirm the advantage of the proposed model as a state-space model, a linear quadratic regulator (LQR) [20] was constructed, where the state $x(t)$ was assumed to be perfectly measurable.

For a target state $x_{\text{ref}}$ and target input $u_{\text{ref}}$, consider the errors

$$x^*(t) = x(t) - x_{\text{ref}}$$

$$u^*(t) = u(t) - u_{\text{ref}}$$

where $x_{\text{ref}}$ and $u_{\text{ref}}$ are assumed to be constant. Then, we have

$$\dot{x}(t) = Ax^*(t) + Bu^*(t).$$

For (32), a feedback control law

$$u^*(t) = K_{\text{opt}}x^*(t)$$

is designed, where the matrix $K_{\text{opt}}$ is determined so as to minimize

$$J = \int_0^\infty \{x^T(t)Qx^*(t) + u^T(t)Ru^*(t)\} \, dt$$

with the weighting matrices $Q(\geq 0)$ and $R(>0)$.

The initial state $x(0)$ and target state $x_{\text{ref}}$ corresponding to the initial input and target input

$$u_0 = [39.72 \ 38.89 \ 0.25]^T$$

$$u_{\text{ref}} = [42 \ 42 \ 0.3]^T$$

were calculated using the static calculation of a simple dynamic model,

$$x(0) = [27.1497 \ 10.8011 \ 307.122 \ 292.724]^T$$

$$x_{\text{ref}} = [26.9044 \ 11.0034 \ 367.801 \ 351.646]^T,$$

respectively, where the target power output $W_{\text{ref}}$ corresponding to the target input $u_{\text{ref}}$ was 13.914 (kW).

In this simulation, the weighting matrices were expressed as

$$Q = \text{diag}(q_1, q_2, q_3, q_4)$$

$$R = \text{diag}(r_1, r_2, r_3)$$

with $q_1 = 86$, $q_2 = 127$, $q_3 = 1.4 \times 10^{-9}$, $q_4 = 1.5 \times 10^{-9}$, $r_1 = 1.0$, $r_2 = 0.54$, and $r_3 = 2.1 \times 10^3$. 

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Figure 9. Simulation results of PI control using state-space model (19) with (22).

Figure 10. Simulation results of PI control using state-space model (19) with static calculation of power output.
Then, the feedback gain $K_{opt}$ was calculated as follows:

$$K_{opt} = \begin{bmatrix}
-1.91 & -0.41 & -1.0 \times 10^{-6} & -1.1 \times 10^{-6} \\
0.75 & 4.5 & -2.3 \times 10^{-6} & -2.4 \times 10^{-6} \\
0.078 & -0.11 & -2.1 \times 10^{-7} & -2.2 \times 10^{-7} \\
\end{bmatrix}.$$ 

The simulation results are shown in Figure 11.

Furthermore, to verify the effectiveness of the constructed LQR, another simulation using the original model and the constructed feedback law (33) was conducted. The simulation results are shown in Figure 12. The black line represents the simulation results of the original model, and the red line represents the simulation results of the proposed model.

5. Discussion

5.1. Construction of state-space model

In this paper, a method to construct a state-space model for an OTEC plant using the Rankine cycle is proposed. The state-space model was constructed by approximating the nonlinearity in the static calculation of a simple dynamic model. Because the simple dynamic model was constructed based on the physical laws and the calculation of linear approximation is not very complicated, various kinds of time-invariant state-space models corresponding to the physical parameters can be obtained easily by appropriately changing the ranges of the approximated data.

In the model construction, multiple flow rates of warm seawater, cold seawater, and working fluid were considered as the inputs. Therefore, the state-space model can be applied to the design of control systems based on the simultaneous manipulation of multiple flow rates. The model can also be applied to control system design with a single input by fixing some flow rates as constants.

In this study, the power output was selected as the output of the model to realize power generation control. However, suitable output equations can be obtained for other possible outputs (e.g. $Q_e$, $Q_c$).

In Section 3, an example of linear approximation was examined. Figures 2–4 show that the state-space model (19) can capture the behavior of the original model, as the calculation results are nearly the same. Indeed, the difference between the results using original model and approximated model is sufficiently small as verified from Table 2. Therefore, the model (19) is valid for the range considered in this paper. However, Figure 5 clarifies that the power output cannot be described appropriately by the output equation (22) owing to the nonlinearity between the power output and the temperatures of the warm and cold seawater at the outlet. Therefore, the ranges of the data to be
utilized should be carefully selected corresponding to the control purpose.

5.2. Simulation results

5.2.1. Step response

In Subsection 4.1, three simulation results for the step response are shown to check the behavior of the state-space model (19).

In Case S-1, three types of flow rates were changed in the ranges of 35–45 (kg/s) for warm and cold seawater and 0.1–0.5 (kg/s) for the working fluid (i.e. the range of linear approximation). Figure 6 shows that in Case S-1, the simulation results obtained with the proposed model were nearly the same as those obtained with the original model.

In Case S-2, the warm and cold seawater flow rates were set to values outside the range of 35–45 (kg/s). The difference in the range affected the simulation results, as shown in Figure 7. By comparing the simulation results of Cases S-1 and S-2, it is clear that the selection of the range of data to be used for the model construction is important.

In Case S-3, the warm and cold seawater flow rates were changed within the range of 35–45 (kg/s), but the working fluid flow rate was fixed at 0.35 (kg/s). Figure 8 shows the same tendency of the simulation results as Case S-1. Furthermore, by comparing the results of Case S-1 with those of Case S-3, we can verify the effect of the working fluid flow rate $m_{wf}(t)$ on the system dynamics. From Figures 6 and 8, it can be seen that the heat flow rates $Q_c(t)$ and $Q_s(t)$ were particularly affected by the change in the working fluid flow rate $m_{wf}(t)$.

Thus, the above arguments demonstrate not only the successful model construction but also the limitation of the constructed model.

5.2.2. Power generation control based on PI control

In Subsection 4.2, two kinds of control simulations were performed. In the first simulation, both the state-space model (19) and the output equation (22) obtained by linear approximation were used. Figure 9 indicates that the PI controller for the original model was valid for the power generation control of the proposed model. However, the results were very different. This difference came from the linear approximation. Indeed, we see from Figure 5 that the approximation results in the ranges of $T_{SS_{wso}} = 26.5 – 27.0 (^\circ C)$ and $T_{SS_{cso}} = 10.5 – 11.5 (^\circ C)$ were different with the results using original model. This affected the transient part at $t = 0 – 20 (s)$ of this simulation. Furthermore, the values of steady state were also affected by this effect. By determining the matrix $C$ appropriately (i.e. changing the linear approximation method), we may be able to improve the behavior of transient/steady-state mentioned above. However, perfect improvement is difficult because the original model shows the nonlinearity as seen in Figure 5. In the second simulation, only the state-space model (19) was used for the control simulation. Figure 10 shows the simulation results. This figure indicates that the results were almost the same in both cases. A comparison between Figures 9 and 10 shows that the controlling effect depends heavily on the nonlinearity of the power output $W(t)$.

Therefore, the influence of the nonlinearity of the power output should be appropriately considered when designing the control system. Because the PI parameters were selected by trial and error, a precise selection method should also be developed.

Here, it should be noted that decoupled models to ordinary PI control for single input single output systems are not easily constructed because the original model has nonlinearity in the output part.

5.2.3. Linear quadratic regulator

In Subsection 4.3, the LQR was designed using the proposed model. The simulation results shown in Figures 11 and 12 demonstrate that the LQR constructed using the state-space model (19) worked well in controlling not only the model (19) but also the original model. This result is based on the realization of feedback control through state feedback. Indeed, as verified in the above discussion, the state-space model (19) in the simulation in this study shows good fitting with that of the original model. Here, it should be noted that in Figure 12, the power output $W(t)$ shows an overshoot because it was not directly considered when constructing the LQR. However, the overshoot can be improved by appropriately adjusting the weighting matrices in (34).

6. Conclusion

In this study, a method to construct a time-invariant state-space model for an OTEC plant using a Rankine cycle with multiple flow rate inputs was established based on a simple dynamic model. Linear approximation was applied to construct the state-space model. The effectiveness and limitation of the linear approximation were confirmed numerically. Furthermore, to evaluate the constructed model, numerical simulations of the step response and power generation control based on PI control and LQR were conducted. It was verified from the simulations that reasonable results were obtained not only within the ranges of the data used for the model construction but also beyond them. Because the effectiveness of the proposed method has never been verified experimentally, the authors intend to develop an experimental environment to acquire the experimental results via the proposed control systems. Furthermore, the authors will construct state-space models for other types of OTEC plants.
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References
[1] THE 17 GOALS, Sustainable Development [accessed 2021 Sep 13]. Available at https://sdgs.un.org/goals.
[2] Khaligh A, Onar OC. Energy harvesting, solar, wind, and ocean energy conversion systems. Boca Raton (FL): CRC Press; 2010.
[3] Yang M, Yeh R. Analysis of optimization in an OTEC plant using organic Rankine cycle. Renew Energy. 2014;68:525–34.
[4] Wang M, Jing R, Zhang H, et al. An innovative organic Rankine cycle (OCR)-based ocean thermal energy conversion (OTEC) system with performance simulation and multi-objective optimization. Appl Therm Eng. 2018;145:743–754.
[5] Rajagopalan K, Nihous GC. Estimates of global ocean thermal energy conversion (OTEC) resources using an ocean general circulation model. Renew Energy. 2013;50:532–540.
[6] VanZwieten JH, Rauchenstein LT, Lee L. An assessment of Florida’s ocean thermal energy conversion (OTEC) resource. Renew Sustain Energy Rev. 2017;75:683–691.
[7] Syamsuddin ML, Attamimi A, Nugraha AP, et al. OTEC potential in the Indonesian seas. Energy Procedia. 2015;65:215–222.
[8] Goto S, Motoshima Y, Sugi T, et al. Construction of simulation model for OTEC plant using Uehara cycle. ELECTR ENG JPN. 2010;170(4):9–17.
[9] Matsuda Y, Urayoshi D, Goto S, et al. Seawater flow rate regulation of OTEC plant using Uehara cycle by considering warm seawater temperature variation. Int J Innov Comput Inf Control. 2017;13(6):2123–2131.
[10] Goto K, Goto S, Sugi T, et al. Construction of simple dynamic model for OTEC plant using Rankine cycle. Trans Inst Syst Control Inf Eng. 2016;29(1):40–50. (in Japanese)
[11] Ikekami Y, Yasunaga T, Morisaki T. Ocean thermal energy conversion using double-stage Rankine cycle. J Mar Sci Eng. 2018;6(1):21.
[12] Goto S, Matsuda Y, Sugi T, et al. Web application for OTEC simulator using double-stage Rankine cycle. IFAC PapersOnLine. 2017;50(1):121–128.
[13] Matsuda Y, Goto S, Sugi T, et al. Control of OTEC plant using double-stage Rankine cycle considering warm seawater temperature variation. IFAC PapersOnLine. 2017;50(1):135–140.
[14] Matsuda Y, Oouchida R, Sugi T, et al. Simultaneous regulation of multiple flow rates for power generation control of OTEC plant using double-stage Rankine cycle. Proceedings of SICE Annual Conference 2018; 2018 Sep 11–14; Nara, Japan:983–988.

[15] Matsuda Y, Oouchida R, Sugi T, et al. Power generation control of OTEC plant using double-stage Rankine cycle with target power output variation by simultaneous regulation of multiple flow rates. Proceedings of SICE Annual Conference 2019; 2019 Sep 10–13; Hiroshima, Japan:1412–1417.

[16] Matsuda Y, Suyama D, Sugi T, et al. Construction of a state space model for an OTEC plant using Rankine cycle with heat flow rate dynamics. IFAC PapersOnLine. 2020;53(2):13042–13047.

[17] Suyama D, Matsuda Y, Sugi T, et al. Construction of a state space model with cold seawater flow rate input for an OTEC plant using Rankine cycle. Proceedings of the 64th Annual Conference of the Institute of Systems, Control and Information Engineers; 2020 Mar 20–22; Online conference:356–360 (in Japanese).

[18] Matsuda Y, Suyama D, Sugi T, et al. Construction of a state space model with warm and cold seawater flow rate inputs for an OTEC plant using Rankine cycle. Proceedings of SICE Annual Conference 2020; 2020 Sep 23–26; Online conference:1856–1861.

[19] Matsuda Y, Suyama D, Sugi T, et al. Construction of a state space model with working fluid flow rate input for an OTEC plant using Rankine cycle. Proceedings of SICE Annual Conference 2021; 2021 Sep 8–11; Online conference:176–179.

[20] Xue D, Chen YM. Analysis and design of control systems in MATLAB and simulink. Singapore: World Scientific Publishing Co. Pte. Ltd.; 2015.