Data-driven Pump Performance Analysis Using Online Monitoring Data Accumulated with Supervisory Control and Data Acquisition System

Ryo Namba[1], Hiroyuki Hokari[2], and Hideaki Komine[3]

[1,2,3] *Toshiba Infrastructure Systems & Solutions Corporation, Kawasaki, Kanagawa, Japan*
ryo.namba@toshiba.co.jp
hiroyuki.hokari@toshiba.co.jp
hideaki.komine@toshiba.co.jp

ABSTRACT

Pump degradation has significant impacts on the operation of water treatment plants since pumps are widely used as basic facilities to supply and distribute water. The authors develop a method for quantifying pump performance to monitor pump degradation by using online monitoring data accumulated with a supervisory control and data acquisition (SCADA) system. The developed method estimates the performance of each pump from the measured values at the confluence of pipes with the least-squares method and respective on-off signals. From the viewpoint of practicality, the usefulness of the developed method was evaluated.

1. INTRODUCTION

Pumps are widely used in various fields such as energy, industry, agriculture, tap water supply, and sewage. Since the degradation of pump performance due to failures and abnormalities has a significant impact on the operations of these facilities, it is widely practiced that maintenance personnel periodically inspect and maintain the performance by checking records such as visual, noise, and tactile sensations. These current inspections that rely on the five human senses, such as sight, hearing, and touch, take a lot of time and effort, and inspection results that rely on the human senses tend to be individualized (Haddad, 2020). It is expected to develop the diagnostic techniques possible to make the inspections of the pump more efficient and quantifiable for tap water supply and sewerage facilities where the number of skilled engineers has been declining.

To diagnose pump failures or their signs of degradation, the techniques for analysis focusing on items such as vibration, sound, and lubricating oil have been actively researched (Raymond, 2004). Especially, vibration analysis is standardized by ISO-10816-3 (ISO, 2009) because the correspondence between failure modes and their causes is well recognized. On the other hand, from a practical point of view, Xue, Li, Wang, and Chen (2014) points out that it is difficult to identify early signs of degradation using amplitude-based criteria and to distinguish when multiple failure modes occur at the same time.

Other methods such as detecting vibrations of the degraded pump from an acoustic sensor indirectly (AlShorman et al., 2021) and diagnosing the pump conditions from information on metal wear particles in the lubricating oil (Raymond, 2004) have also been developed. Although these diagnostic technologies have the potential to quantitatively diagnose conditions and determine the causes of failures, they require the addition of new measurement sensors and investigation tasks.

The diagnostic technique without adding new measurement sensors and investigation using monitoring data accumulated in monitoring and control systems have been developed (Kallesøe, 2005). These techniques are utilizing machine learning technology because improvements in the performance of computers have made it possible to handle vast amounts of information. These technologies learn the normal state from multiple signal data accumulated in the SCADA system and detect anomalies using support vector machine (Xue et al., 2014) or deep learning (Fausing Olesen & Shaker, 2020) techniques. While these technologies can be applied not only to pumps but also to other facilities, they are characterized by the difficulty in determining the causes of the anomalies and interpreting countermeasures based on the diagnostic results.

Against the development of various diagnostic techniques described above, some techniques to diagnose the pumps as the target have also been developed by focusing on the performance values of pumps. The thermometric method (Foord, 1964) is one of these techniques and uses thermodynamic relationships to estimate flow rate and efficiency from measurements of temperature, head, and power. Since actual facilities may not have flow meters to measure the discharge flow rate of each pump, the thermometric method has a great advantage in that it is possible to estimate the performance of each pump without flow meters of each pump. However, it is not easy to introduce the thermometer to tap water supply and sewerage facilities from the viewpoint of cost-effectiveness since the thermometric method requires a crystal thermometer with high resolution.

The authors developed a diagnostic technique to estimate the performance values of pumps using monitoring data accumulated in the SCADA system in tap water supply and sewerage facilities (Namba, Hokari, & Komine, 2022). The feature of the developed method is that it is possible to estimate the performance values of pumps without adding new measurement sensors and investigation using only monitoring data commonly measured in tap water supply and sewerage facilities as input. The developed method can apply to the typical configuration of tap water supply and sewerage facilities in which multiple pumps are installed in parallel and a flow meter is installed at the junction. The problem of not being able to determine the discharge flow rate of each pump was solved by using an on–off signal for each pump and the least-squares method. This paper evaluates the usefulness of the developed method using actual monitoring data collected from tap water supply and sewerage facilities.

The structure of this paper is explained below. First, section 2 explains the target process to estimate the performances of pumps and the equipment configuration and the estimation procedure of the developed method. After that, the usefulness of the developed method is evaluated based on the results of actual monitoring data over a long period, finally, section 4 summarizes the conclusions and prospects for the future.

2. METHODS

2.1. Target Process

Figure 1 shows the tap water supply process related to the development method. For tap water supply facilities, the *Water Supply Facility Design Guideline* (2012) states that 3 to 5 pumps should be installed parallel including standby pumps to reduce the impact of their failures or inspections. The parallel pumping process such as shown in Figure 1 is commonly used actually.

Regarding the sensors installed in the above process, it is common to install only the necessary and sufficient sensors for monitoring and control from a viewpoint of installation and maintenance costs. Consequently, a flow meter and a pressure gauge are rarely installed for each pump.

The signals measured by these sensors are accumulated with the SCADA system as monitoring data. Among these signals, the signals used in the developed method are listed as follows:

1. flowrate Q $(\mathrm{m^3/min})$,
2. head H (mAq),
3. power P (kW), and
4. on-off D $(-)$.

Of the above signals, flow rate, head, and power are measured for the entire process at confluences, and in other words, are not measured for each pump. It is noted that only the on-off signal is measured for each pump. Hereinafter, each signal will be explained in detail.

The total flow rate $Q(t) = \sum Q_i(t)$ is measured according to time t, but each flow rate $Q_i(t)$ of No. i pump is not measured. It is necessary to obtain the estimated flow rate $\hat{Q}_i(t)$ to estimate the performance of each pump.

Regarding the head, it can be assumed that the measured value $H(t)$ is equivalent to each discharge head $H_i(t)$ of No. i pump ($H(t) = H_i(t)$) if the distance from the pump outlet to the position of the pressure gauge is short and the friction loss of the piping is close to zero. If a pressure gauge is not installed and measured, the difference in water level between the source and destination of the water reservoir can be used as an alternative signal to the head signal. This paper uses the difference in water level between the source and destination of the water reservoir for evaluation.

The total power $P(t) = \sum P_i(t)$ of installed pumps is measured. The alternative signal to total power can be collected if the SCADA system monitors not the total power but the total current because the current signal can be converted into a power signal with the received voltage.

The on-off signal $D_i(t)$ is measured for each pump and valued as shown in

$$D_i(t) = \begin{cases} 1 & \text{(in operating)}, \\ 0 & \text{(stopped)} \end{cases} . \tag{1}$$

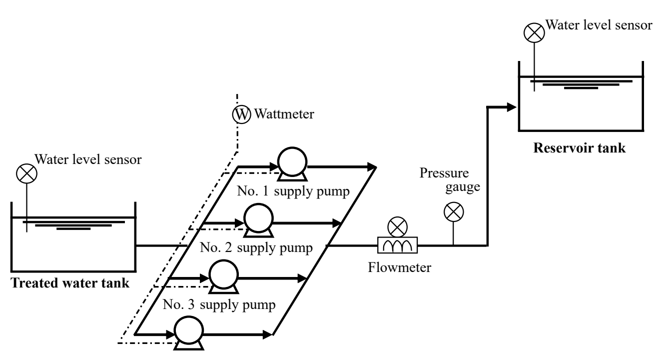

Figure 1. Target process for the developed method.

The developed method estimates the flow rate $\hat{Q}_i(t)$ of each pump by using the measured total flow rate signal $Q(t)$ and each on-off signal $D_i(t)$ without measuring the flow rate $Q_i(t)$ of each pump.

2.2. Developed Method

Since the estimated performance values such as head, power, and efficiency are determined according to the flow rate, they are generally given in the form of performance curves shown as:

$$H_i(t) = \alpha_i Q_i(t)^2 + \beta_i Q_i(t) + \gamma_i = H(t), \tag{2}$$

$$P_i(t) = \delta_i Q_i(t)^3 + \epsilon_i Q_i(t)^2 + \lambda_i Q_i(t) + \mu_i, \tag{3}$$

$$\eta_i(t) = \frac{9.8}{60} \cdot \frac{Q_i(t) \cdot H_i(t)}{P_i(t)} \tag{4}$$

where $Q_i(t)$, $H_i(t)$, $P_i(t)$, and $\eta_i(t)$ means flow rate ($\mathrm{m^3/min}$), head (mAq), power (kW), and efficiency (%) of each pump, respectively.

Figure 2 shows an example of a performance curve (Q-H curve) plotting Eq. (2) with $Q_i(t)$ on the horizontal axis and $H_i(t)$ on the vertical axis. In this example, the operating range is 5.8-11.0 $\mathrm{m^3/min}$, and the rated (maximum efficiency) flow rate is 8.8 $\mathrm{m^3/min}$. The purpose of the developed method is to estimate the coefficients $\alpha_i, \beta_i, \cdots, \mu_i$ in the Eqs. (2)-(4) using accumulated monitoring data.

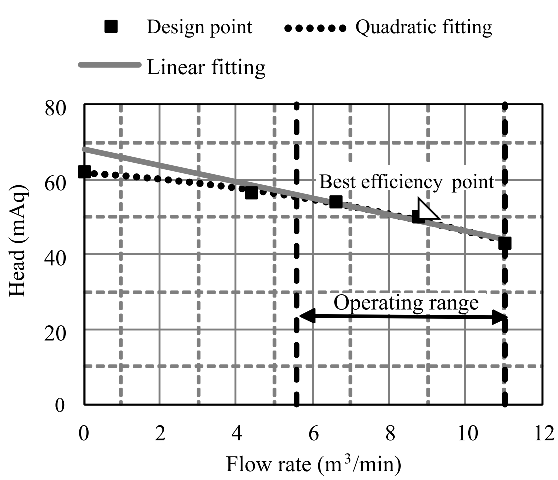

Figure 2. Example of Q-H performance curve.

If $H_i(t)$ and $Q_i(t)$ in Eq. (2) are measured, it is possible to directly obtain the coefficients α_i, β_i, and γ_i; however, $H_i(t)$ and $Q_i(t)$ are unmeasured as described above. Even if the assumption $H_i(t) = H(t)$ is applied, the coefficients α_i, β_i, and γ_i cannot be obtained directly unless $Q_i(t)$ is given in some way. From another point of view, if the data for a single pump operation is accumulated among the data for multiple pump operations, the coefficients α_i, β_i, and γ_i may be obtained. In fact, however, there may be no data for single-pump operation since multiple pumps are always in operation, otherwise, there may be little data for single-pump operation. Therefore, the coefficients can not be always obtained directly using the Eqs. (2)-(4).

The basic idea of the developed method is to approximate the relationship between head and flow rate shown in Eq. (2) with the following linear relation (Namba et al., 2022):

$$\hat{Q}_i(t) = a_i H_i(t) + b_i. \tag{5}$$

By using the linear approximation of Eq. (5), the developed method makes it possible to estimate the coefficients of each pump even if the data for a single pump were not available. Introducing the linear approximation of Eq. (5), the estimation problem for the coefficients is reduced to a problem that can be easily solved by the least-squares method. The development method exploits the fact that the performance curve is close to a straight line in the operating range in Figure 2.

Specifically, with the squared error between the total flow rate $Q(t)$ and the total estimated flow rate $\hat{Q}(t)$ adjusted by on-off signals $D_i(t)$ shown in below:

$$\begin{aligned} J &= \sum_{\tau=0}^{t} \Big(Q(\tau) - \hat{Q}(\tau) \Big)^2 \\ &= \sum_{\tau=0}^{t} \left(Q(\tau) - \sum_{i=1}^{N} \hat{Q}_i(\tau) \right)^2 \\ &= \sum_{\tau=0}^{t} \left(Q(\tau) - \sum_{i=1}^{N} \Big(a_i H_i(t) + b_i \Big) \cdot D(t) \right)^2 \end{aligned} \tag{6}$$

as the cost function, the developed method uses the least-squares method and obtains the regression parameters a_i and b_i in Eq. (5) as following equations:

$$\boldsymbol{\theta} = (\boldsymbol{X}^T \boldsymbol{X})^{-1} \boldsymbol{X}^T \boldsymbol{Y}, \tag{7}$$

$$\boldsymbol{\theta} = \begin{bmatrix} a_1 \cdots a_N \; b_1 \cdots b_N \end{bmatrix}^T, \tag{8}$$

$$\boldsymbol{X} = \begin{bmatrix} D_1(0)H(0) & \cdots & D_N(0)H(0) & D_1(0) & \cdots & D_N(0) \\ D_1(1)H(1) & \cdots & D_N(1)H(1) & D_1(1) & \cdots & D_N(1) \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ D_1(t)H(t) & \cdots & D_N(t)H(t) & D_1(t) & \cdots & D_N(t) \end{bmatrix}, \tag{9}$$

$$\boldsymbol{Y} = \begin{bmatrix} Q(0) \; Q(1) \cdots Q(t) \end{bmatrix}^T. \tag{10}$$

The developed method obtains the estimated flow rate $\hat{Q}(t)$ of each pump by substituting the calculated regression parameters a_i and b_i into Eq. (5). Moreover, considering the Q-P performance curve in Eq. (3) is close to a straight line in the operating range, the estimated power $\hat{P}_i(t)$ for each pump can be derived by a linear approximation. Finally, the developed method obtains the estimated efficiency $\hat{\eta}_i$ of each pump by substituting the measured head $H(t)$, the estimated flow rate $\hat{Q}_i(t)$, and the estimated power $\hat{P}_i(t)$ into Eq. (4).

2.3. Evaluation Methodology

The target process is a tap water supply process in which $N = 4$ pumps are installed in parallel to supply water treated at a water purification plant from the source reservoir to the destination reservoir as shown in Figure 1. Purified water is distributed to consumers from the distribution reservoir. All installed pumps have the same specifications and are operated at fixed full speed. In the matter of the operation of the pumps, the start and stop of installed pumps are manipulated by operators through the SCADA system according to the water level of the source and destination reservoir. The number of pumps in operation is not kept constant because the water demand of the destination reservoir fluctuates throughout the day. The number of pumps in operation fluctuates between 1 and 2 to remain the water level of the destination reservoir within a certain range. The combination of operating pumps is changed to equalize the accumulated running time which is recorded for each pump on the SCADA system. The monitoring data are measured and recorded every minute and this paper used the data for the period of 3 years and 6 months from March 2017 to August 2020. It was noted that the difference in water level between the source and destination of the water reservoir was used as an alternative signal to the head signal since the pressure gauge was not installed on the target process.

Assuming that the developed method is used as an alternative to the monthly inspections which are applied with the diagnostic method described in section 1, this paper evaluates the usefulness of the developed method. First, the 3 years and 6 months of monitoring data were divided into one-monthly period data, and then the developed method was applied for each one month data as input data. Consequently, the estimated performance such as head, power, and efficiency for the specific flow rate (rated flow rate 7.0 $\mathrm{m^3/min}$) were obtained and their time-series changes were checked to make it easier to evaluate the estimation results for each month. During the evaluation period, the No. 4 pump was out of operation for about one year from January 2018 to March 2019 for preparation for renewal. Since the renewal of the No. 4 pump was carried out in March 2019, the performance change of the No. 4 water pump before and after renewal was observingly evaluated.

3. Results & Discussion

Figure 3 shows long-term changes in estimated performance (head, power, efficiency) corresponding to the rated flow rate of 7.0 $\mathrm{m^3/min}$, and Table 1 summarizes the means and standard deviations for Figure 3 (Statistical values for No. 4 pump renewed in March 2019 were calculated for the period up to December 2017).

From the results in Table 1, the relative standard deviation (the ratio of the standard deviation to the mean) for head, power, and efficiency ranged from about 2.7 to 4.1%, 1.6 to 2.2%, and 4.2 to 5.8%, respectively. Assuming that the true values of these performances have remained constant over the 3 years and 6 months, it is considered that the performance values estimated by the developed method produce errors within the range of 5.8% or less. Although Yamaura, Watanabe, Nakajima, and Sakamoto (2014) shows an example of a 10% decrease in pump efficiency over 13 years, there is little information about changes in pump performance over the long term. Moreover, it is difficult to determine whether the true values remained constant or changed. If the true values of head, power, and efficiency remained constant, the evaluation results correspond to the fact that the developed method cannot detect performance changes of 5.8% or less while the developed method would have the usefulness of not requiring new sensors or inspection tasks. In other words, performance changes of at least about 4.1% in head, 2.2% in power, and 5.8% in efficiency are required for the developed method to conclude that the performance has changed obviously. It is noted that these requirements are derived from the most unfavorable assumptions for the development method. The detectable performance change would be smaller if the true value has changed.

Table 1. Statistical measurements of the estimated values

Pump No.	Head (mAq)		Power (kW)		Efficiency (%)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
No. 1	51.1	1.39	112	2.45	52.1	4.5
No. 2	46.0	1.87	115	2.47	45.5	5.8
No. 3	49.2	1.51	109	1.70	51.6	4.5
No. 4	49.5	1.39	110	1.74	51.4	4.2

Figure 3 implies that the estimated performances such as head and efficiency have seasonal variations, with higher values in winter and lower values in summer. If the true values of head, power, and efficiency remained constant, the obtained seasonal changes could be due to changes in the physical properties of water such as viscosity and temperature, or efficiency of the electric motor, or external effects of the measurement system for sensors; therefore, the detectable performance may be smaller if these factors and influences are clarified and the developed method is improved with them.

Next, let us review the comparison of long-term changes in estimated performance among 4 pumps. In Figure 3, the performance values of the No. 2 pump have relatively large differences compared to the other pumps. Specifically, for example, the estimated power of the No. 2 pump is about 4% higher than that of the other pumps. Since the developed method supports quantifying the performance of pumps and their operational cost, it is possible to estimate the specific cost-effectiveness for the renewal or repair of the target pump. This support for quantifying the pump performance is an advantage of the development method.

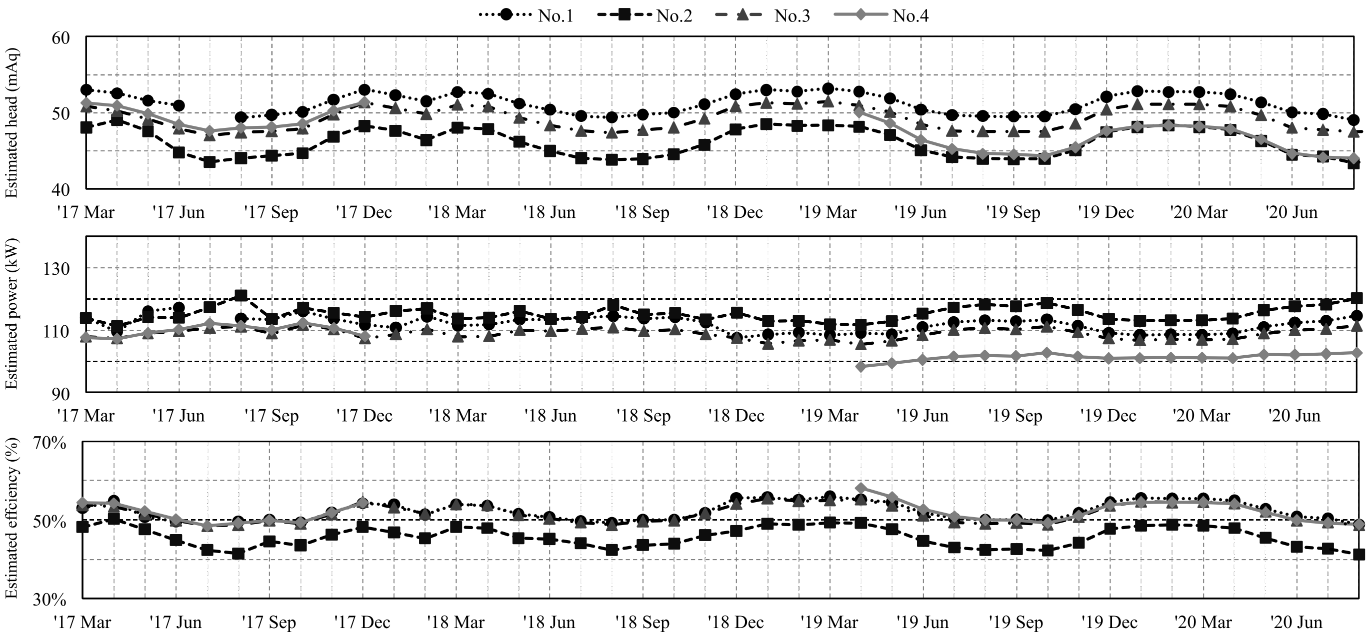

Figure 3. Trend of the estimated values for the developed method at rated flow

Finally, the estimated performance values of the No. 4 pump renewed after about one year of inactivity are evaluated. The performance values before the renewal fluctuated within the ranges of head 49.5 ± 0.9 mAq, power 110 ± 2.5 kW, and efficiency $51.4 \pm 3.0\%$ and it is unreadable degradation of performance within the data collection period before the renewal in Figure 3. On the other hand, it is confirmed that the No. 4 pump was operated with approximately 10% less power than the other pumps and contributed to energy saving while the efficiency of the No. 4 pump shows no significant change before and after renewal by comparing the periodic averages of pump performance values. The developed method can quantitatively show the actual effectiveness of renewal for the No. 4 pump and is expected to be useful for operational improvements and reviews of renewal plans.

4. Conclusion

This paper evaluated the results of the pump diagnosis technique which estimated pump performance values using actual monitoring data for the tap water supply process. The developed method can estimate performance values such as flow rate, head, power, and efficiency by utilizing monitoring data accumulated with the SCADA system and the least-squares method without installing new sensors or additional inspection tasks. From the results of a long-term evaluation, it was confirmed that the developed method is practically capable of identifying changes in pump performance values. In addition, from the case study of the renewal of the No. 4 pump, it was confirmed that the effectiveness of the actual pump renewal can be derived; then, the developed method is expected to be useful for operational improvements and reviews of renewal plans. Since the accumulation of data and case studies are important for the technology of facility diagnosis, the authors will continue to improve the developed method and will study the feasibility of estimating anomaly factors and remaining service life.

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