A Method for Estimating the Fuel Consumption Characteristics of Small Boats Sailing in Medium to High-Speed Range

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This study aims to develop an application software to support energy-efficient operation for small boats of less than 20 tons. In order to develop this system, statistical surveys have been conducted on the relationship between ship speed, engine speed, and fuel consumption on a 19-ton small boat for several years. As a result, it was confirmed that fuel consumption does not necessarily increase monotonically with an increase in ship speed. Authors considered that this phenomenon can be utilised for saving fuel consumption in small boats effectively. In order to realise it, it is required to identify fuel consumption trends and compare the trends with the observed data. However, fuel consumption trends are affected by hull fouling, load weight and trim balance. For this reason, fuel consumption trend needs to be determined for each voyage. For the convenience of boat operators, it is desirable that fuel consumption trends are estimated by an easy, simple, and cost-effective method as soon as possible after leaving the port. The method proposed in the previous study was highly accurate, but it was not convenient due to two problems. This study proposes a new method for estimating fuel consumption trends that solves these issues. In order to develop a new estimation method, this study focuses on the hull frictional resistance. It was assumed that the effect of wave-making resistance on energy consumption in small boats saturates at medium to high speeds, and frictional resistance becomes the dominant factor. Thus, the fuel consumption trend of the boat was analysed on the assumption that it follows a fundamental physical law proportional to the cube of the ship's speed. Based on these assumptions, this study developed a new equation model that expresses the fuel consumption trend of small boats sailing in medium to high-speed range. The fuel consumption trend determined with the new model achieved proper performance. In addition, the method of estimating the fuel consumption trend using this model solves the two problems of the method of previous study.

KEYWORDS

~ Energy-efficient operation
~ Small boats
~ Fuel consumption trend
~ Statistical survey

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1. INTRODUCTION

Reducing fuel consumption has been an important issue for ships. Numerous technologies have been developed to approach this theme from various aspects, for instance, engine waste heat recovery [1], high-efficiency propellers [2], improved hull forms [3], low-friction paints [4], electronically controlled engines [5], and shaft generators [6] are typical efforts to reduce fuel consumption. However, these energy-saving technologies increase the cost of ship building. In the fishery industry in Japan, small business groups and self-employed contractors are the dominant players. Therefore, they do not have enough financial background to install expensive energy-saving equipment for their boats.

On the other hand, operational measures [7] have been emphasised to avoid installing expensive equipment for fuel economy. Operational measures include slow steaming, weather routing, and periodic hull and propeller cleaning. These methods do not raise a significant initial cost compared to installing energy-saving equipment. Therefore, fisheries can easily adopt these technologies using small boats less than 20 tons to adopt operational measures. Thus, this study proposes new operational measures as energy-saving technologies for small boats.

1.1. Typical operational measures (Slow steaming)

Slow steaming is one of the typical operational measures. The study [8] describes the effects of slow steaming on container ships to save fuel. According to this report, it could save 53% of fuel at the maximum by decreasing the ship speed from 24 knots to 19 knots. The energy-saving effects of slow steaming can also be achieved in small boats. Figure 1.1 shows an example of observed data relating to ship speed and BHP on a small boat. Decreasing ship speed by 10% results in a 27% reduction of BHP. Considering that navigation time becomes long due to the slowdown, total energy would be saved by about 19%.

1.2. The Fluctuation Phenomenon in Fuel Consumption

Fishing boats often go at medium to high speeds. Therefore, this research has examined the fuel consumption characteristics of small boats in the medium to high-speed range. Figure 1.2 shows some examples of measured values regarding the ship speed *V* and the fuel oil consumption (*FOC)* of a small boat. The figure shows that *FOC* tends to increase as *V* increases. Generally, skippers know and accept this trend. However, looking at these data in detail, this trend of increasing *FOC* with increasing *V* is not necessarily monotonic. *FOC* increases more than expected at some *V,* while it decreases or does not increase more than expected at other *V*.

As will be mentioned later, these observed data represent averaged values of the flow meters which measure fuel oil from tank to engine and fuel oil returning from engine to deaeration tank, including variation. However, these fluctuations exceed a guaranteed range of the flow meter's maker. Additionally, this paper has observed similar phenomena in every experimental voyage to a greater or smaller degree. In this paper, this phenomenon is temporarily called "FOC Fluctuation." Therefore, it may not be concluded that these variations are not measurement error, which means that there may be a reason to take it seriously into consideration.

1.3. Utilisation of FOC Fluctuation Phenomenon

This study does not aim to elucidate the mechanism of FOC fluctuation phenomenon. Instead, this study proposes a new operational measure to support the efficient operation of small boats by taking advantage of FOC Fluctuation Phenomenon. The approximate line in Figure 1.3 has been derived based on the measured speed and fuel consumption data. This approximate curve is the fuel consumption trend that boat operators must accept. In other words, the boat operator assumes the trend in advance. Similarly, if the fuel consumption is less than the expectation based on the FOC trend, it can be said that the boat sails on a better fuel efficiency. For example, in Figure 1.3, *FOC* at about 8 m/s is less than the approximate curve. It can be said that *FOC* is less than skipper's expectation in this case. Therefore, its navigation state can be judged as good. Similarly, if this FOC fluctuation phenomenon is effectively used, the navigation state can be judged as good/bad by comparing the fuel consumption trend during the voyage with the actual measured values of ship speed and fuel consumption. However, observing the trend in detail for several years, the trend differs from voyage to voyage depending on the load weight, trim balance, environmental conditions, and hull fouling. In other words, it is difficult to determine the fuel consumption trend in advance, and it is necessary to identify a new trend for each voyage. However, from a practical standpoint, it is unreal to request boat operators to take detailed data on each voyage to identify a new trend. Estimating the trend by measuring as few data sets as possible is desirable. Therefore, this paper develops a method to estimate the fuel consumption trend of small boats in the medium to high-speed range using a trend based on previously observed data and some measured data.

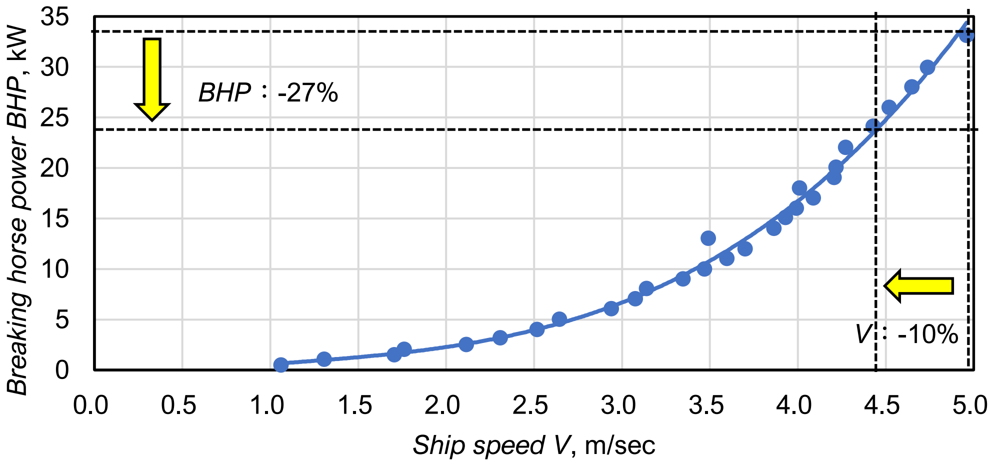

Figure 1.1. Observed data of ship speed and BHP on a small boat

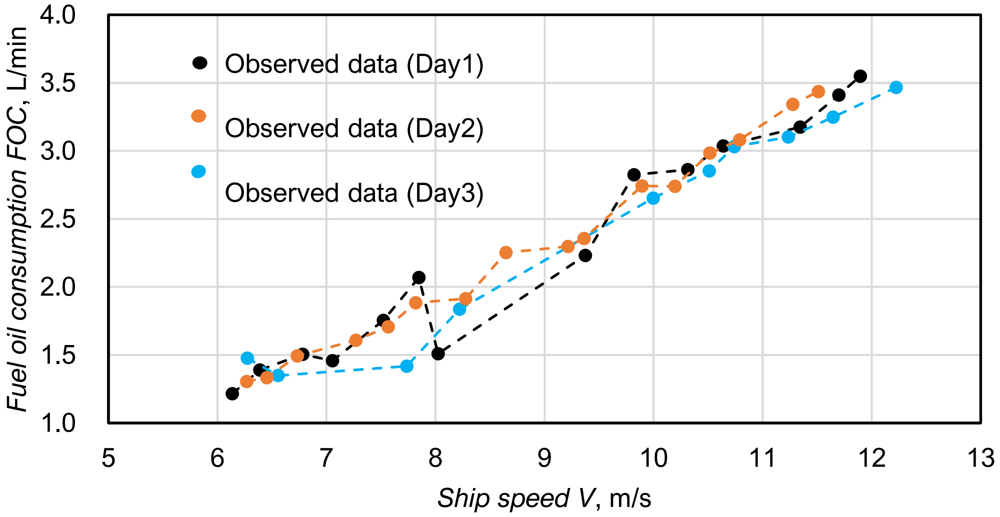

Figure 1.2. Observed FOC Fluctuation Phenomenon

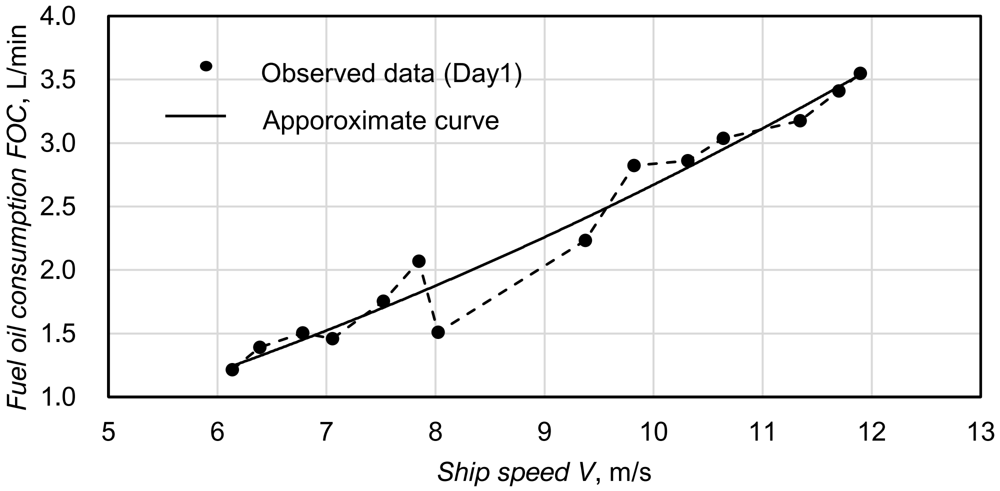

Figure 1.3. Comparison of approximate curves and observed data

2. A METHOD FOR ESTIMATING FOC TREND

2.1. Review of previous work

Previous research [9] developed a method for estimating FOC trend. The results of the method were highly consistent with actual voyage data. However, the method does not seem to resolve the two problems as follows.

Problem 1: It is required to obtain the measured data of ship speed and fuel consumption in detail, in advance, and at multiple times.

Problem 2: Additionally, the data must be measured at the maximum ship speed at each voyage.

These problems make it difficult to use the estimation method of FOC trends in previous work. This paper proposes a new method that successfully deals with these issues.

2.2. Reducing the number of measuring in advance

In order to figure out fuel consumption trend, the approach established in previous research needs to have detailed multiple measurements. Therefore, skippers must spend considerable time for preparing this method beforehand. To simplify this method, it is desirable to reduce the number of previous measurements to determine FOC trend as much as possible. This study focuses on the frictional resistance of hull. To reduce the number of previous measurements, this study minimises the parameters which are required to derive the FOC trend by using a characteristic of the frictional resistance in the hull.

2.2.1. Influence of hull fouling on FOC trend

This study assumes that total hull resistance is primarily influenced by frictional resistance. Since the small boat that this study focuses on is used for fisheries surveys, it does not carry heavy cargo. Therefore, its draft does not change significantly. On the other hand, hull fouling cannot be ignored in this case because its anchorage time is long, which may influence the hull resistance.

Air resistance has a same equation structure as water frictional resistance. It cannot be distinguished in practice from the experimental point of view in actual sea condition. In this paper, for simplicity, water frictional resistance represents air resistance, too.

The frictional resistance R_f is expressed as follows:

$$R_f = \frac{1}{2}\rho C_f S V_s^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

where ρ: density of water, S: water contact area, C_f: frictional resistance coefficient, V_s: ship speed. Even if the hull is fouled with marine life, it is assumed that the water contact area S remains unchanged, but the frictional resistance coefficient C_f varies. In this study, it has been assumed that the frictional resistance coefficient could be expressed as kC_f (k: constant), which is the frictional resistance coefficient when hull is fouled.

Thus, when the hull is fouled, frictional resistance R_f is rewritten as follows:

$$R_f = k\left(\frac{1}{2}\rho C_f S\right) V_s^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

Generally, the effective horsepower EHP of a ship can be expressed as follows:

$$EHP = R_T V_s \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3)$$

where R_T: total hull resistance.

Small boats typically sail within a medium to high-speed range beyond the last hump where wave-making resistance is at its peak. It is known that wave-making resistance is saturated when ship speeds beyond the last hump. Therefore, the influence of wave-making resistance on propulsion energy consumption is assumed to be limited. Additionally, since this study is not a tank test, it is not possible to classify the resistance components in detail.

For this reason, it is assumed that the following equation is obtained:

$$R_T \propto R_f \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (4)$$

EHP required to keep ship speed is strongly correlated with fuel consumption. Therefore, for simplicity, the following equation is defined:

$$FOC \propto EHP \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (5)$$

Thus, when the hull is fouled, *FOC* is expressed as follows:

$$FOC \propto EHP = R_T V_s \propto R_f V_s = k\left(\frac{1}{2}\rho C_f S\right) V_s^3 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (6)$$

Here the ship speed *Vs* is the log speed, but it is difficult to measure it for a typical fishing boat. On the other hand, it is easy to grasp the speed over the ground which can be calculated from GPS position information. However, the speed over the ground is strongly affected by the tide and sea current.

Therefore, if the FOC trend is a function of the speed over the ground, it may be influenced by the tide current during the voyage. Therefore it is desirable to use another factor instead of the ship speed *Vs*. From long-term observation, this study considers that the engine speed is proportional to the ship speed in the medium to high-speed range. Hence, the following equation is defined:

$$V_s \propto N \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (7)$$

From equations (6) and (7), the following equation is obtained.

$$FOC(N) \propto k\left(\frac{1}{2}\rho C_f S\right) N^3 = k\left(\frac{1}{2}\rho C_f S N^3\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (8)$$

Therefore, FOC trend in a fouled hull condition can be expressed by constant *k* times that in a clean hull condition.

2.2.2. Previous measurement

To identify the FOC trend, it is necessary to conduct a detailed observation of the engine speed and fuel consumption beforehand. For several years, this study has conducted a statistical survey on the relationship between ship speed, engine speed, and fuel consumption, which Kanagawa Prefectural Fisheries Technology Center, Sagami Bay Experiment Station, had supported. The fisheries research vessel “Hojo” (Fig. 2.1), with an overall length of 19.8 m and a gross tonnage of 19 tons, was the test subject. Sixteen experimental voyages were conducted from October 2022 to March 2024.

On the experimental voyages, the engine speed was increased by 50 min^{-1} from 450 min^{-1} to 1950 min^{-1}, as shown in Figure 2.2. Ship speed, engine speed, and fuel consumption were measured at each speed for over 60 seconds. The actual measurements of these data were carried out without changing the vessel's heading and steering angle as much as possible. Immediately after the engine speed increases, the ship speed and fuel consumption are transient. It is not appropriate to use them as data to identify FOC trends. The last 30 seconds of data measured at each engine speed were averaged to analyse steady-state data. This study used data from a day out of 16 statistical surveys for "Previous Measurements" to identify the FOC trend.

From equation (8), this study regards *FOC(N)* as a function proportional to the cube of the engine speed *N*. Therefore, the data on this day's engine speed and fuel consumption were approximated as follows:

$$FOC(N) = aN^3 + b \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (9)$$

As mentioned before, FOC is supposed to increase monotonically with respect to increasing engine speed in general. It is desirable that FOC trend obtained in this study follow the skipper's expectation. It should be avoided to use approximation in which FOC trend has poles relative to the engine speed. This study has applied an approximate equation which shows FOC to increase monotonically in the range of engine speed hereby covered.

Figure 2.1. Outlook of Fishery research vessel “Hojo"

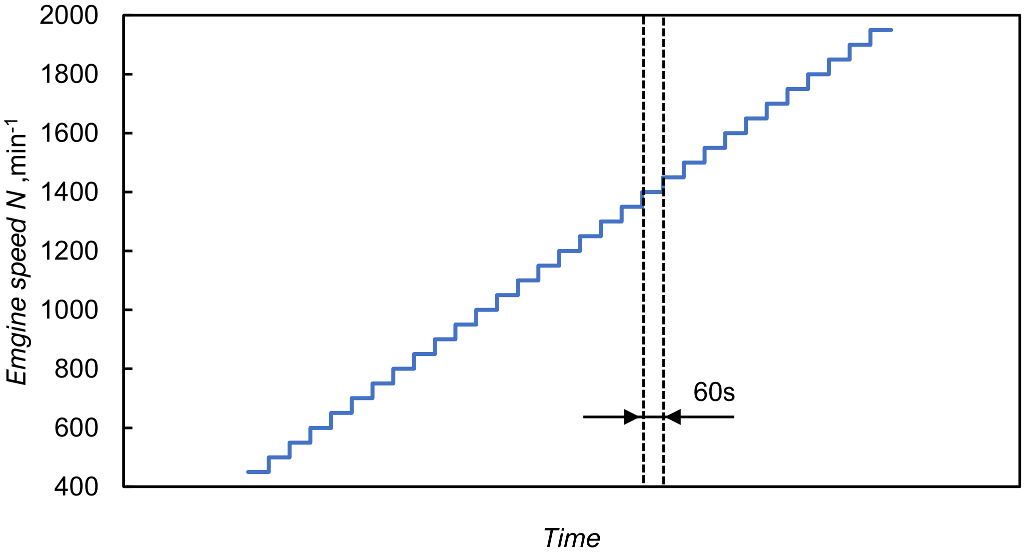

Figure 2.2. FOC measuring sequence in experimental voyage

2.2.3. Determining FOC trend based on previous measurement

As noted in Chapter 2.2.1, the FOC trend in a fouled hull can be represented as constant *k* times that in a clean hull. However, it is not always possible to conduct previous measurements in a clean hull condition. On the other hand, the FOC trends in a further fouled or clean hull state can be expressed as coefficient *k′* times based on the FOC trend in a fouled hull state. All factors except *k* in equation (8) are replaced by the trend observed in previous measurements expressed by an equation (9).

Thus, by replacing *k* in equation (8) with *k′*, the approximation equation for the FOC trend is rewritten as follows:

$$FOC(N) = k'(aN^3 + b) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (10)$$

Here the coefficients *a* and *b* are values directly obtained from previous measurements. The parameters required to determine the FOC trend can be confined to only the constant *k′* by expressing the trends as equation (10). Here the averaged data for 30 seconds in each engine speed in statistical survey are expressed as Figure 2.3.

If equation (10) is adjusted to the measured data of engine speed and fuel consumption, the constant *k′* can be expressed as follows:

$$k' = \frac{\sum_{i=1}^{n} FOC_i}{\sum_{i=1}^{n}\left(aN_i^3 + b\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (11)$$

N_i: Averaged engine speed for 30 s

FOC_i: Averaged fuel oil consumption for 30 s

Thus the equation (10) can be rewritten as follows.

$$FOC(N) = k'(aN^3 + b) = \frac{\sum_{i=1}^{n} FOC_i}{\sum_{i=1}^{n}(aN_i^3 + b)}(aN^3 + b) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . (12)$$

2.2.4. Verifying the proposed method

To verify the approximate equation (12), the data measured on a day, excluding previous measurements, has been applied to equation (12). Figure 2.4 shows these samples. In this figure, the black dots indicate the measured values of engine speed and fuel consumption from the previous measurement, and the black curve indicates the approximation curve obtained by the equation (9). Parameters *a* and *b* have been obtained by deriving the black curve. The blue dots indicate the measured values of engine speed and fuel consumption on Day 4, and the blue curve indicates the approximation curve obtained by the equation (12). The coefficient of determination of the blue approximation curve for the measured data (blue dots) was 0.992. The blue approximation curve shows high agreement with the measurement data, although the curve has been derived by the equation (12), using parameters *a* and *b* specifically on the data previously observed.

Similarly, data for all other measurement dates have been applied to equation (12). The coefficient *k′* ranges from 1.00 to 1.26. The coefficient of determination has also been obtained for all other measurement dates. As a result, the coefficient of determination was at least 0.949, which means that the approximate equation (12) explains the FOC trend with respect to engine speed. In other words, any FOC trend can be expressed as a coefficient *k'* times based on the FOC trend in a fouled hull state. The proposed method does not require detailed measurement multiple times, although the method proposed in the previous work requires lots of detailed measured data. Consequently, Problem 1, mentioned in Chapter 2.1, can be solved.

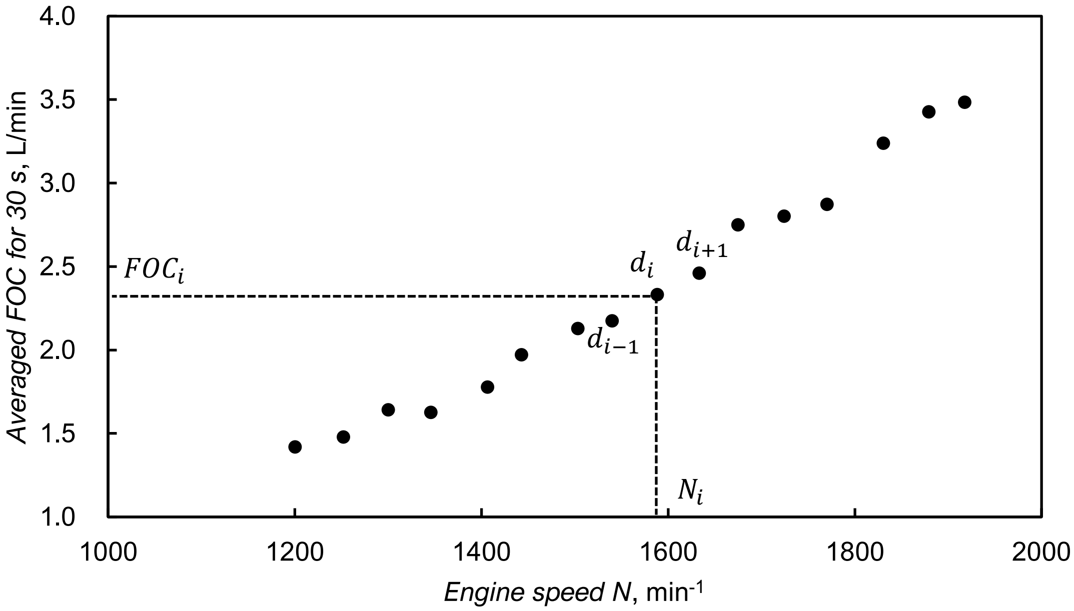

Figure 2.3. An example of averaged *FOC* for 30 s at each engine speed

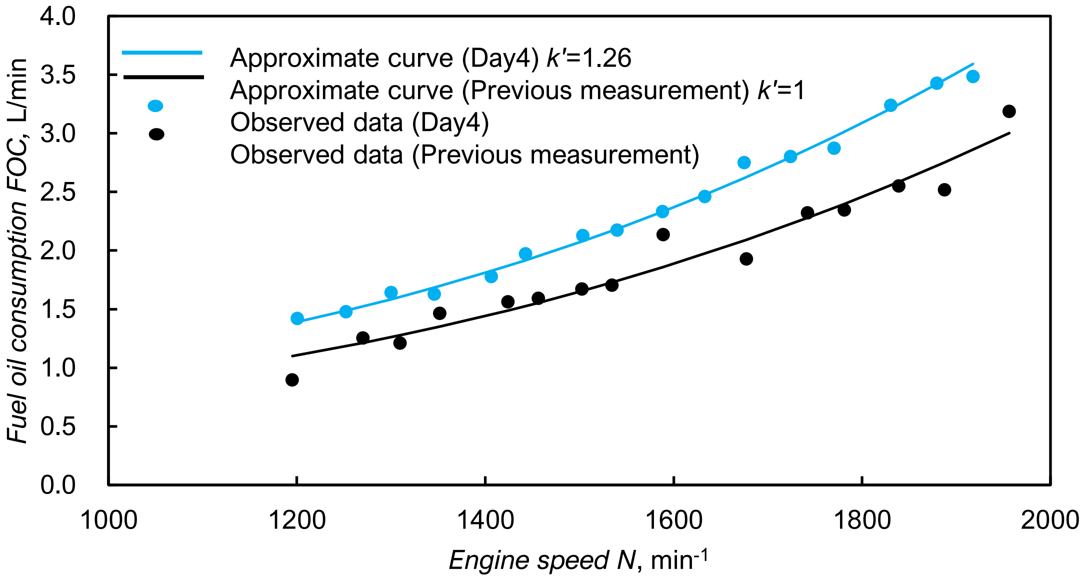

Figure 2.4. Approximate curves derived based on a previous measurement

2.3. Estimation of FOC trend from measurement data in the medium speed range

It was necessary to measure data at the maximum ship speed for every voyage in the previously proposed method [9], which made it impossible to obtain the FOC trend until the ship reached its maximum speed. From the perspective of engine maintenance, it is not advisable to operate the engine at maximum speed immediately after departing from port. Additionally, the higher the engine speed, the higher the fuel consumption in general. Skippers are temporarily forced to operate in a state where fuel consumption is very high if the previous work is applied. It is desirable to specify the FOC trend with measurement data taken at a low-medium speed range after leaving the port.

On the other hand, the only unknown parameter k' in the FOC trend can be derived by inputting observation data during the voyage into an equation (10). Generally speaking, it is expected that the more data input the more accurate result, which is close to approximation, is achieved. However, considering the users' convenience, it is desirable that coefficient k' is identified from as little observed data as possible. Additionally, it is preferable that those observed data are acquired in low or medium speed range which is over the last hump condition. An investigation was conducted into a relation between the number of input data and the accuracy of parameter identification for k'. Coefficient k' was determined under the following three conditions for data from all measurement days.

α: determining from only one observed data at about 1200 min^{-1}
β: determining from several observed data at about 1200 to 1400 min^{-1}
γ: determining from all observed data at about 1200 to 1950 min^{-1}

Using the calculated k' under these three conditions, the fuel consumption trends have been estimated. To evaluate the agreement of the estimated trend and over all observed data in medium to high-speed range, coefficient of determination has been computed for each measurement day. Fig. 2.5 shows the variation of the coefficient of determination. In Fig 2.5, if the variation in accuracy is small and the overall values are high, it means that the FOC trends are appropriately estimated in the data for all measurement days. Conversely, if the variation in accuracy is large, it means that the FOC trends are not properly estimated in the data on some measurement dates. In condition α, the median value of the coefficient of determination exceeds 0.91, but nearly half of the results have a coefficient of determination below 0.9. Therefore, it is difficult to say that the accuracy under condition α is sufficient. In condition β, FOC trends can be derived with several data for each voyage, and their lowest coefficient of determination is about 0.902. The coefficient of determination is lower than in condition γ, but the number of input data is about one-third of that. Additionally, condition β does not require observed data in high speed condition, while condition γ does. Considering the balance between convenience and accuracy, it can be concluded that determining coefficient k' under condition β is proper.

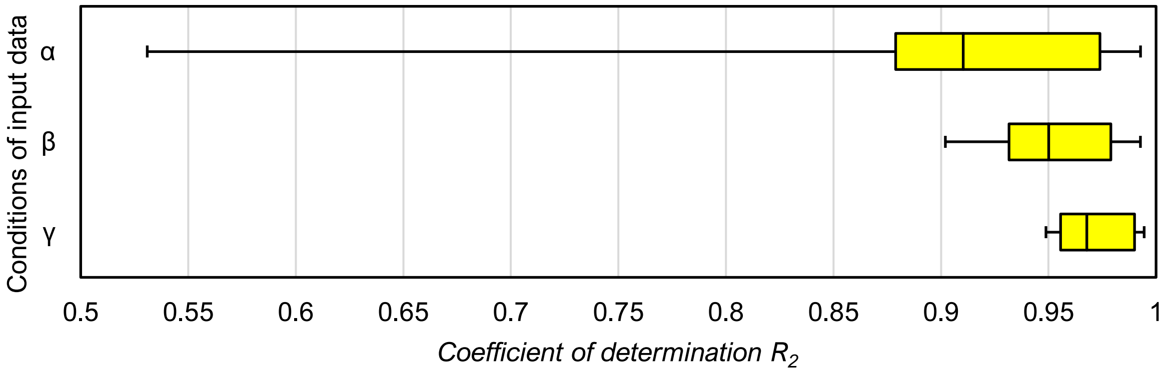

Figure 2.5. Difference in coefficient of determination depending on input data

3. CONCLUSION

This study has proposed a new method for estimating FOC trends that is required to utilise the fluctuation phenomenon. Similar research has not been found as far as far as the authors' research goes, except for previous research [9]. The method proposed in the previous work has problem 1 and problem 2, as noted in Chapter 2.1. This study has approached these issues by developing a new model equation which explains the FOC trend. As a result, FOC trends are expressed by the equation (12). Problem 1 can be solved because the proposed method does not require measurement data in advance multiple times. To approach problem 2, this study investigates the possibility of determining k' in equation (12) by inputting some data in the medium speed range is over the last hump condition. Coefficient k' has been obtained by inputting the measurement data into the equation (12) under the three conditions. As a result, it is considered that the more data input, the higher the accuracy of estimating the FOC trends. Considering the balance between convenience and accuracy, it can be assumed that determining coefficient k' under condition β noted in Chapter 2.3 is proper.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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