Estimation and Optimization of Vessel Fuel Consumption

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Abstract: Vessels with diesel-electric power generation enable efficient and flexible operation of the power plant. In order to make sure that the power plant runs at the optimum operation point at all times, this paper proposes a method for on-line estimation of the specific fuel consumption of individual generators to enable tracking the true efficiency of each power generation unit, and a method for on-line optimization of the power plant using the estimated specific fuel consumption. Based on the results calculated using measured operation profiles from a large cruise ship, fuel savings of 4-6% can be achieved.

Keywords: Marine, Ship, Estimation, Optimization, Power management, Load dispatch

1. INTRODUCTION

Diesel electric power generation in large vessels allows a flexible and efficient utilization of the fuel. The produced power can be distributed between several units for generation of electric power. Efficient operation implies that the use of fuel is minimized.

An important performance parameter for a diesel generator is the specific fuel oil consumption (SFOC) which describes how much fuel that is needed to produce 1 kWh of electric energy, and is normally depending of the actual power. The specific fuel consumption may differ significantly between similar diesel generator.

The SFOC changes over the running time of the engines. Increments in SFOC between service intervals is caused by various factors, for instance, dirty intake air filters, turbocharger partly blocked or dirty nozzle ring, partly blocked charged air coolers, worn injection pump elements, and worn injection nozzles. Also, continuous variations in SFOC is produced by other factors, for example quality variations in the fuel specifications (e.g. fuel water content, low fuel heat value, fuel Sulfur content, fuel ash content). The SFOC increments between service intervals as a function of operating hours can be up to 6%, Wärtsilä (2015). All above mentioned factors affecting the SFOC point to the necessity of using on-line SFOC estimation algorithms. Moreover, real-life large ships have a set of engines (e.g. 4, 6, 8), where each engine has different number of operating hours and in some cases with different power capacity. Therefore, using the ideal SFOC that is provided by the engine manufacturer may lead to a suboptimal solution in the decision of which engines to use and how the load should be shared between them to fulfill the current power production requirement.

This report proposes a new approach for minimization of the fuel consumption of diesel electric marine vessels. This involves a new method for on-line estimation of the actual specific fuel consumption and a related optimization method. The proposed approach has several benefit:

• It can be used to advice which diesel engines to run, which ones to have as stand by, and which ones not to use. This will typically vary over time since the ones that are used usually deteriorate when being used.
• Power optimization to determine how to distribute the load over the available diesel engines will provide more accurate results when the input data are more trustworthy.

It is assumed that sensors for measuring fuel consumption and generated power are calibrated regularly and are working as intended, and that they are supervised such that failures would be detected and reported. Other approaches for load dispatching between diesel generators for fuel saving are presented in Frisk (2015), Hansen (2000), and Radan (2008).

This results in this study are based on data recorded in the ABB EMMA™ ABB (2016) system during seven months from a large cruise ship that is equipped with four similar diesel generators. The data has been used for simulation and evaluation. It is sampled with one minute sampling interval, where one sample represents an average over one minute of faster sampling.
2. TRACKING OF SPECIFIC FUEL OIL CONSUMPTION

To operate a set of diesel generators optimally it is needed to have a good knowledge of their specific fuel oil consumption. The actual SFOC has been shown to vary with operating hours of a diesel generator, see MAN (2013) and Wärtsilä (2015), and further there may be a variation between apparent equal units.

The specific fuel consumption will be estimated recursively from measured data. Two approaches will be taken here:

- It could be approximated by a polynomial function.
- It could be approximated by a set of values, where each value is assumed to be constant in a narrow interval of the diesel generator power.

Data for this is available from the ABB EMMA™ system for each diesel engine.

2.1 Selection of Data for Recursive Estimation

Since SFOC relates to operation under constant load, we will first propose a method to determine when an engine is operating in almost stationarity. Data from such periods will then be used for the recursive estimations.

The model will consider the relative power, which is defined as

\[ p = \frac{P_{\text{avg}}}{P_{\text{max}}} \]  \hspace{1cm} (1)

where \( P_{\text{avg}} \) is the minute average power and \( P_{\text{max}} \) is the maximal power for a diesel generator. Further, the specific fuel oil consumption is calculated as

\[ f = \frac{F_{\text{avg}}}{P_{\text{avg}}} \]  \hspace{1cm} (2)

where \( F_{\text{avg}} \) is the minute average fuel consumption for a diesel generator.

To identify periods without transients the signals \( p \) and \( f \) are both filtered through band-pass filters. The output from such a filter will approach zero when the input is constant, and it will be non-zero when the input signal changes. The diesel generator is considered to run in stationarity when all of the following conditions are satisfied:

1. The fuel flow \( f \) is larger than zero.
2. The relative power \( p \) is larger than zero.
3. The band-pass filtered \( f \) is smaller than a threshold.
4. The band-pass filtered \( p \) is smaller than a threshold.
5. The data sample is not tagged invalid by the data producer.

The following subsections will describe two different recursive estimation procedures.

2.2 Recursive Estimation of second Order Polynomial

The specific fuel consumption is here described by a second order polynomial

\[ f = cp^2 + bp + a \]  \hspace{1cm} (3)

where \( f \) and \( p \) were defined in (1) and (2). A recursive algorithm will estimate the coefficients \( a, b, \) and \( c \) to always have an actual estimate how the specific fuel consumption depends on the actual power. Higher order polynomials are avoided since it would then be harder to obtain accurate SFOC estimates.

A straight forward text book recursive estimator with exponential forgetting is used here. The estimated parameter vector is

\[ \theta = (c \ b \ a)^T \]  \hspace{1cm} (4)

and the regression vector is

\[ \varphi(t) = \begin{pmatrix} p^2(t) \ p(t) \ 1 \end{pmatrix}^T. \]  \hspace{1cm} (5)

The recursive least squares algorithm is

\[ e(t) = f(t) - \varphi^T(t)\theta(t-1) \]
\[ K(t) = P(t-1)\varphi(t)/\lambda + \varphi^T(t)P(t-1)\varphi(t) \]
\[ P(t) = (I - K(t)\varphi(t))P(t-1)/\lambda \]
\[ \theta(t) = \theta(t-1) + K(t)e(t) \]  \hspace{1cm} (6)

It provides a new estimate of the coefficients each time it is executed. The forgetting factor was \( \lambda = 0.99998 \) which can be interpreted as data is forgotten in approximately one month.

The recursive estimator has the ability to follow the time varying SFOC. Figure 1 shows the variation of the estimated polynomial coefficients during the operation from August to February. The gaps in the curve relate to periods when this particular diesel generator was not in operation. The unused samples with non-stationary operation are too short to see in Figure 1.

Recursive identification of a polynomial approximation of the specific fuel consumption is straightforward to use. However, the polynomial function may become peculiar if excitation is concentrated to a narrow power interval. This is often the case for the power in a diesel generator. The estimated SFOC curve may then be misleading for powers far away from the ones used for estimation and will then be less useful for optimization.

2.3 Estimation using Intervals for Different Power

The specific fuel consumption is in this section instead described as a number of values of the SFOC, each one representing a narrow interval of the diesel generator...
power \( p \). Here the power range is divided into \( n \) intervals, where each interval has its unique value for the SFOC. To estimate these values, \( n \) different recursive estimators are used to capture the variation over time. For each interval, \( i \), the recursive estimator is

\[
e(t) = f(t) - \theta_i(t - 1) \\
K_i(t) = P_i(t - 1)/(\lambda + P_i(t - 1)) \\
P_i(t) = (1 - K_i(t)P_i(t - 1))/\lambda \\
\theta_i(t) = \theta_i(t - 1) + K_i(t)e(t)
\]

and there is one estimate of the SFOC, \( \theta_i(t) \), for each interval. There is also one covariance matrix \( P_i(t) \) for each interval. Depending on the actual power, the specific recursive estimator for the related interval is chosen. Samples for estimation are only considered during stationarity. These are selected as outlined in Section 2.1.

Figure 2 (top) shows the obtained specific fuel consumption for \( n = 20 \) different intervals for the power of a diesel generator. The choice of \( n \) is a trade-off between accuracy and computational effort. For some power intervals there are no data, hence no estimates. The histogram below shows the distribution of the power for different intervals in the data. An interesting observation here is that the specific fuel consumption seems to have two local minima.

Figure 3 shows the specific fuel consumption estimates for the interval estimation. The estimates are shown for four dates. The figure shows that this method also provides estimates of the specific fuel consumption that increases with operating hours.

Figure 4 shows comparisons the specific fuel consumption between diesel generators at a specific date. DG3 seems to have the highest specific fuel consumption of all the diesel generators. This can be an indicator of required maintenance. From these variations it can be seen that it is beneficial to estimate the momentary specific fuel consumption and to use it for load distribution among the four generators.

3. OPTIMIZATION

The estimated SFOC will be used to determine the optimal load distribution between the different diesel generators in the ship. The format of the estimated SFOC as a set of values for each diesel generator is not well-suited for continuous optimization. The format can however be used in a binary optimization problem which is used to find the optimal power distribution.

Consider the \( n \) power intervals that were used to describe the SFOC above. Each engine can operate in any of these \( n \) intervals and it could be turned off. Assume that the engine is restricted to operate at powers that are in the middle of the intervals. Hence, each engine can have \( n + 1 \) operating points. With four engines we define a binary decision vector \( x \) with \( 4 \times (n + 1) \) elements that are either 1 or 0. Constraints and objective function will now be defined for a binary optimization problem.

Each engine can operate in only one point simultaneously, which can be expressed by the equality constraint

\[
\begin{bmatrix}
[1 \cdots 1] \\
[1 \cdots 1] \\
[1 \cdots 1] \\
[1 \cdots 1]
\end{bmatrix} x = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}
\]

or

\[
A_{on} \cdot x = B_{on}
\]

where all off diagonal block matrices are zero.
The provided power should be at least as high as the required power $B_{\text{pow}}$
\[
\begin{bmatrix}
0 & p_{c1} & 0 & p_{c2} & 0 & p_{c3} & 0 & p_{c4}
\end{bmatrix} x \geq B_{\text{pow}}
\] (10)
or
\[
A_{\text{pow}} \cdot x \geq B_{\text{pow}}
\] (11)
where $p_{cij}$ are arrays with the centers of the power intervals. Here, with $n = 20$ it is $[0.025, 0.075, \ldots, 0.975]$, corresponding the largest diesel generator. The array will be different depending on size of the diesel generators, e.g. a diesel generator with half the power of the largest one will have its maximum interval center slightly below 0.5.

Define the objective function to minimize
\[
\begin{bmatrix}
0 & f_1 & 0 & f_2 & 0 & f_3 & 0 & f_4
\end{bmatrix} x
\] (12)
or $C^T x$ where $f_i$ is an array for the fuel consumption for engine $i$. Each component $f_{ij}$ is given by the product of the power for the middle of the interval, $p_{cij}$, and the estimated specific fuel consumption for that interval, $\theta_{ij}$, i.e. $f_{ij} = \theta_{ij} p_{cij}$ A binary optimization problem can now be defined as
\[
\begin{align*}
\text{minimize} & \quad C^T x \\
\text{subject to} & \quad A_{\text{on}}x = B_{\text{on}} \\
& \quad A_{\text{pow}}x \geq B_{\text{pow}}
\end{align*}
\] (13)

### 3.1 Cost for Engine Start

The binary optimization as formulated above does not penalize start of engines. Solutions at subsequent samples may therefore lead to many stops and starts of engines which, of course, is not desirable. To address this problem an addition is done to the penalty function. The addition is formulated from the state at the previous sample. Define
\[
C_s = \begin{bmatrix}
0 & e_1 & 0 & e_2 & 0 & e_3 & 0 & e_4
\end{bmatrix}^T
\] (14)
where $e_i$ is an array with $n$ equal elements. If engine $i$ was running at the previous sample, $e_i$ is populated with zeros, otherwise it is populated with the cost of starting an engine, $Q$. The loss function of the optimization problem (13) is now modified to
\[
\begin{align*}
\text{minimize} & \quad (C^T + C_s^T) x \\
\text{subject to} & \quad A_{\text{on}}x = B_{\text{on}} \\
& \quad A_{\text{pow}}x \geq B_{\text{pow}}
\end{align*}
\] (15)

In this problem there is no cost to continue operating the engines that are in operation but there is a cost for starting a new one. The cost for starting a new engine has been discussed in Frisk (2015), where it is proposed that the cost is set to be equal to running the engine at 100% for two minutes. This would correspond to $Q = 0.44$ which has been used here.

### 3.2 Spinning Reserve

At each moment the power consumed by the load must be equal to the power generated. Spinning reserve is the amount of additional generation capacity that without delay can be used to produce power. Typically there is also spinning reserve requirements related to minimum number of online generators. This comes from the requirement for single point failures and classification society rules. In coastal areas, single failure cannot lead to more than 50% loss of propulsion power. So tripping of one diesel generator cannot lead to larger drop in propulsion power than 50%, DNV (2011). There are also other types of requirements but in general the user defines the minimum number of generators for different operating conditions. The proposed solution permits that different kind of reserves can be intrinsically considered as part of the approach. Thus, reserve limits are included as a new constraint set of the optimization problem.

The binary optimization problem in (13) can easily be modified to include that there shall be a certain spinning reserve available. This is done by adding the following constraint to the optimization problem
\[
\begin{bmatrix}
0 & p_{\max1} & 0 & p_{\max2} & 0 & p_{\max3} & 0 & p_{\max4}
\end{bmatrix} x \geq B_{sr}
\] (16)
or
\[
A_{sr}x \geq B_{sr}
\] (17)
where $p_{\max i}$ is the maximal power for diesel engine $i$ and $B_{sr}$ is the required spinning power, i.e. the actual required power plus the spinning reserve.

### 3.3 Power Change Limitation

A diesel generator is only allowed to change its power within defined limits. This must also be included in the optimization problem. This can be obtained with the constraint
\[
L \leq \begin{bmatrix}
0 & p_{c1} & 0 & p_{c2} & 0 & p_{c3} & 0 & p_{c4}
\end{bmatrix} (x - x_0) \leq H
\] (18)

or
\[
L \leq A_d(x - x_0) \leq H
\] (19)
where $x_0$ is the binary vector from the previous sample, $L$ is an array with limits for power decrease, and $H$ is an array with limits for power increase. Both $L$ and $H$ depend on the actual power for each diesel generator.

### 3.4 Complete Binary Optimization Problem

With the additions from (15), (17), and (19) the optimization problem (13) can now be extended as
\[
\begin{align*}
\text{minimize} & \quad (C^T + C_s^T) x \\
\text{subject to} & \quad A_{\text{on}}x = B_{\text{on}} \\
& \quad A_{\text{pow}}x \geq B_{\text{pow}} \\
& \quad A_{sr}x \geq B_{sr} \\
& \quad L \leq A_d(x - x_0) \leq H
\end{align*}
\] (20)

The binary optimization problem (20) can also be solved using a brute force method.

### 3.5 Refinement of Solution from Binary Optimization

The binary optimization (20) selects one operating interval for each generator. It provides a power distribution that is slightly too high. It is assumed that this optimization is close to the true minimum fuel consumption. The individual generator powers are adjusted down to refine the solution from the binary optimization to decrease the power to the required level in the following way:
(1) Sort the diesel generators in decreasing order with respect to the fuel consumption for the actual operating intervals.

(2) For each generator in the order given in the first step, decrease the power until either the required power is reached, or the end of the interval is reached. Stop if the required power is reached, otherwise continue with the next generator. Make sure that generators on low power are not switched off.

3.6 Continuous Optimization

As an alternative to the above described binary optimization it is also possible to formulate the fuel optimization problem as a continuous optimization where the power of each diesel generator is a continuous variable. To do this the specific fuel consumption will be tracked using recursive estimation of a second order polynomial for each diesel generator as described in Section 2.2. The actual fuel consumption for diesel generator \(i\) is given by the product of the polynomial approximation of the specific fuel consumption and the actual power \(p\):

\[
F_i(p) = (c p^2 + b p + a)p. \tag{21}
\]

This setup will be used for comparison with the binary approach.

To include the start-up cost for a not running diesel generator and to include spinning reserve in the optimization, additional non-convex constraints are needed. This leads to an optimization problem that is much more complicated to solve.

4. SIMULATION RESULTS

The proposed concept was evaluated using ship data from seven months of operation. Simulations were done where the original diesel generator load distribution was compared with the ones from the approaches proposed in this paper. The fuel consumption was calculated for the new engine utilization. In the simulation the same total power and the same number of running diesel generators were used.

At each sampling interval during the simulation the following actions were taken:

(1) The required power each sample was taken from the data.

(2) The spinning reserve was determined from number of running diesel generators in the data, such that the new load distribution at each sample uses the same number of diesel generators as in the data.

(3) Detect if operation is sufficiently stationary for each engine using the band-pass filtering based procedure in Section 2.1. If so, run the recursive estimator for the specific fuel consumption for that engine.

(4) Solve optimization problem to distribute the needed total power over the available engines.

The following sections describe the different simulation scenarios.

4.1 Binary optimization

The first simulation uses the interval based recursive estimation method in Section 2.3 followed by the complete binary optimization problem in Section 3.4. The load distribution from the binary optimization each sample was finally adjusted as shown in Section 3.5 to match the required power.

Figure 5 shows the optimized power distribution (blue) and the original power distribution (red) for the four engines. A main difference compared with the original power distribution is that diesel generator 3 is not utilized at all here. The reason is that its specific fuel consumption is higher than for the other three engines, see Figure 3. The total produced power each minute (sample) is equal for the original case and for the optimized case.

The total fuel saving was 4.7% with the new approach for power distribution compared with the fuel consumption for the power distribution in the data.

4.2 Brute force optimization

The simulation here resembles the one in Section 4.1. It also uses the interval based recursive estimation method in Section 2.3. The difference is that here a brute force solution method is used for the binary optimization. The final adjustment step in Section 3.5 is also used here.

The total fuel saving was 6.0% compared with the fuel consumption for the power distribution in the data. The improved fuel efficiency of the approach here is that the full search is better to find the global minimum of the non-convex objective function.

4.3 Continuous optimization

For comparison also a continuous approach for power distribution was simulated. A second order polynomial function was recursively estimated for the specific fuel consumption for each diesel generator as shown in Section 2.2. The optimal load distribution was obtained using the method in Section 3.6. A solution using Matlab’s fmincon consumed about ten times more CPU time than the binary methods although neither start-up cost nor constraints for spinning reserve were used. This gave a total fuel saving of 4.2%. However, the approach is less useful in its current form, without start-up cost diesel generators are frequently started and stopped here.

4.4 Discussion

The result of this simulation indicates that a substantial amount of fuel can be saved if the power is optimally distributed over the engines. Some remarks needs to be made:

- Engine 3 performs worse than the other three engines. This has of course a large impact on the result. But it is important that poorly performing engines are identified.
- For the optimal load dispatch, the engines are operated differently than in the original case. Since the estimation of specific fuel consumption was based on
the original operation, the aging of engines were not accounted for in a correct way.

5. CONCLUSION

Methods for on-line estimation of the specific fuel consumption have been applied on data from a cruise ship. This has revealed that the fuel consumption between different diesel generators may differ significantly. There is also a variation over time depending on operating hours. Accounting for the variation in specific fuel consumption have been shown to be beneficial for finding the optimal load distribution between the diesel generators on the ship.

An interval based recursive estimator for SFOC has been proposed. It is accompanied by a binary optimization problem formulation to determine the optimal load distribution between the available diesel generators on a ship. The proposed methods have been compared with a more complex continuous optimization problem formulation.

The proposed methods can be used for either an automated optimizer for distribution of the power between the diesel generators or as an adviser for the on-board staff which engines to run and at what power.

REFERENCES


