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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 as large as 2%, MAN (2013). A proper service can reduce or eliminate this increments in SFOC. Moreover, when all factors that affect the fuel consumption are considered, the variations in SFOC between scheduled overhauls 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^{TM} 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.

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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

$$p = P_{avg}/P_{max} \tag{1}$$

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

$$f = F_{avg}/P_{avg} \tag{2}$$

where F_{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

$$f = cp^2 + bp + a \tag{3}$$

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.

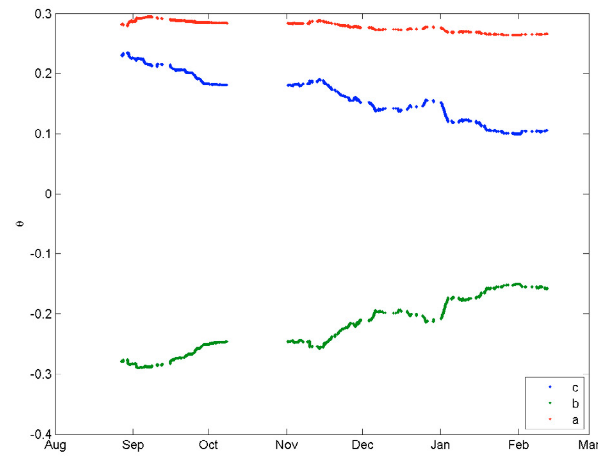

Fig. 1. Recursively estimated polynomial coefficients

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

$$\theta = \begin{pmatrix} c & b & a \end{pmatrix}^T \tag{4}$$

and the regression vector is

$$\varphi(t) = \begin{pmatrix} p^2(t) & p(t) & 1 \end{pmatrix}^T . \tag{5}$$

The recursive least squares algorithm is

$$\begin{aligned} e(t) &= f(t) - \varphi^T(t)\theta(t-1) \\ K(t) &= P(t-1)\varphi(t)/(\lambda + \varphi^T(t)P(t-1)\varphi(t)) \\ P(t) &= (I - K(t)\varphi^T(t))P(t-1)/\lambda \\ \theta(t) &= \theta(t-1) + K(t)e(t) \end{aligned} \tag{6}$$

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