Ship propulsion train efficiency sensing

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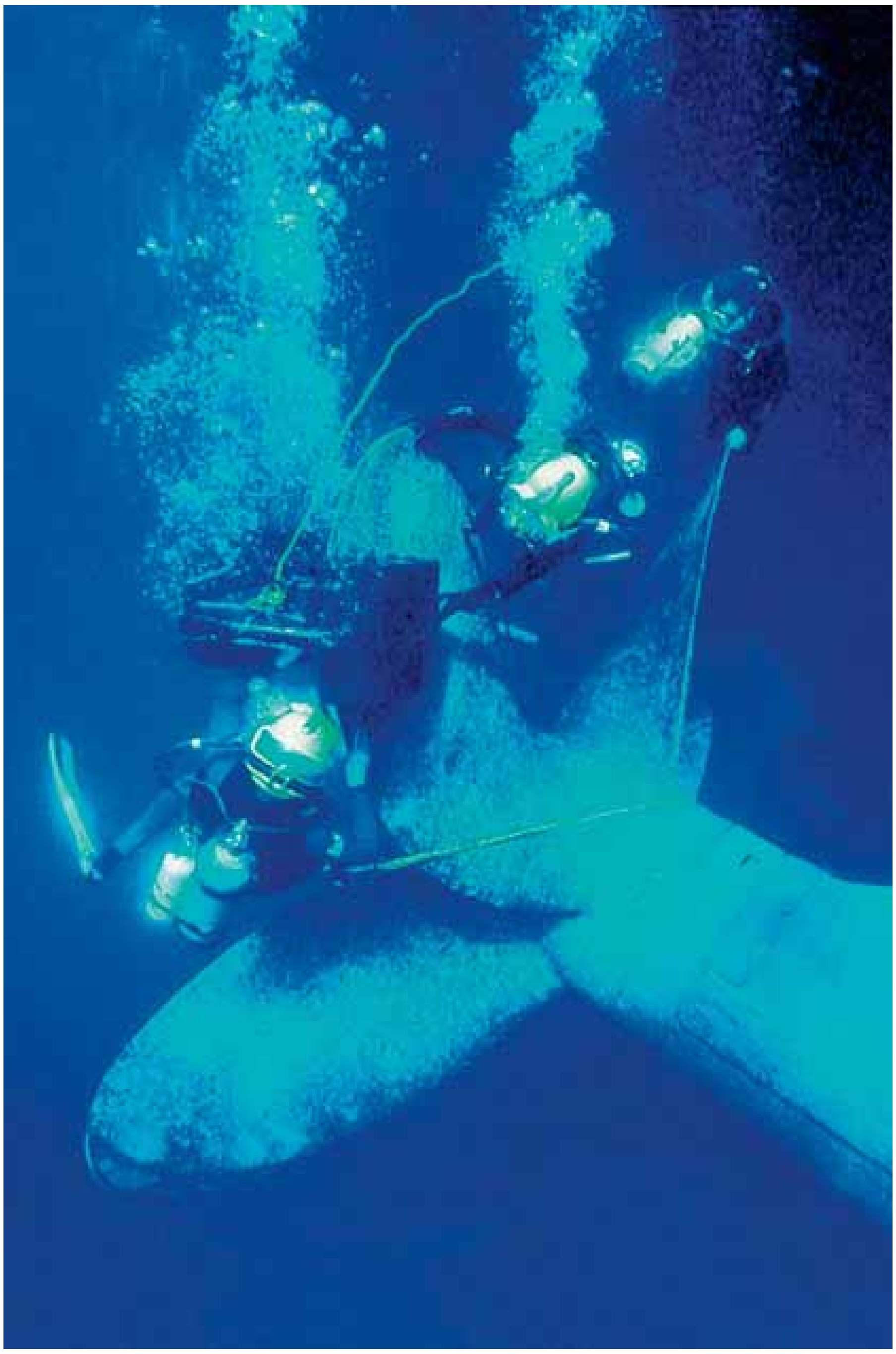

Fig. 1 – A Wärtsilä Services propeller polishing team at work.

Precise data is critical when making decisions that affect a ship's operations. This is especially true in matters relating to propulsion systems since docking may be required. For maximum efficiency, therefore, accurate sensing is essential.

When comparing the energy present in the fuel burnt in the diesel engine with the output energy of the ship itself, approximately 70% is lost. Heat losses in the diesel engine are the main contributors to these energy losses, but there are also losses due to fouling and the ship environment. In practice these losses vary during the operational period.

Propellers and ship hulls get fouled. The ship may be operated in adverse conditions with added resistance from waves and wind. The counteractions to minimize these non heat-related losses can be grouped into three categories:

- Ship route planning and navigation
- Ship and propeller cleaning scheduling
- Propulsion device setting optimization.

To make meaningful gains in efficiency, basically all three need optimization methods. For the first two, the operator has to make a trade-off between the costs of corrective actions against the cost of fuel. In the operational decision process, the owner needs precise information on the gains to be achieved by alternative routing or docking a ship in order to clean the hull or polish the propeller. The propulsion device setting optimization is an integrated part of the propulsion control. An automatic search is done for the optimal rotational speed and pitch in order to minimize fuel consumption, while keeping the ship's speed constant.

The precise information from which to make operational decisions requires accurate sensors, as well as adequate signal processing.

Contrary to the heat losses, the achievable gains are only in the magnitude of up to 5% of the energy in the fuel burnt by the diesel engine. This achievable gain sets high requirements for the accuracy of the sensors and the robustness of the signal processing. Many attempts have been made in the past to introduce performance monitoring systems. Lessons learnt from these former systems are:

- The sensors must be sufficiently accurate and reliable.
- There is a need to distinguish between propeller efficiency and hull efficiency.
- The human factor is very important; a performance system should not result in an extra workload, and the use of the system must be intuitive with high system integrity. For this, data reduction techniques are needed.

Precise information enables the owner, for instance, to optimize the ship's docking periods for hull cleaning and propeller polishing. Another possibility is to mobilize a Wärtsilä propeller polishing team, as shown in Figure 1.

Defining propulsion train efficiencies

In general terms, efficiency is defined as the ratio between something that you put in and something that you get out. In shipping terms, that something that you put in is the heat input and that something that you get out is the effective propulsive power.

In mathematical terms this ratio reads:

$$(1)\ \eta_{ship} = \frac{R(1+f)u}{W}$$

where, the term $R(1+f)$ represents the resistive force with f as the hull factor, u represents the speed-through-water (STW), and W represents the heat input.

Calculating (overall) ship efficiency with high accuracy represents a challenging task. For this purpose all three components, namely, resistance, speed-through-water, and heat input must be accurately measured. While accurate speed-through-water and accurate heat input estimations are achievable using the hardware and the knowledge already available, accurate resistance force is more difficult to measure. Given the accuracy levels, the resistive force has to incorporate the effects of the waves and wind. However, by monitoring the ship while sailing in the same wave and wind conditions, one can express overall ship efficiency independently of the resistive force.

Another way of estimating overall ship efficiency is by assessing the efficiencies of the components of the ship's propulsion train. In Figure 2 we depict in general terms the main components of the drive train, with the corresponding efficiencies. The ship's overall efficiency is the product of the block efficiencies, as per the following:

$$(2)\ \eta_{ship} = \eta_{eng} \cdot \eta_{transmission} \cdot \eta_{propeller} \cdot \eta_{hull}$$

The propeller efficiency is calculated by using the following formula:

$$(3)\ \eta_{prop} = \frac{Tu_a}{Qn}$$

where, T is thrust, u_a is advance velocity, Q is torque, and n is propeller angular velocity.

The advance velocity is proportional to the speed-through-water, as follows:

$$(4)\ u_a = (1-w)u$$

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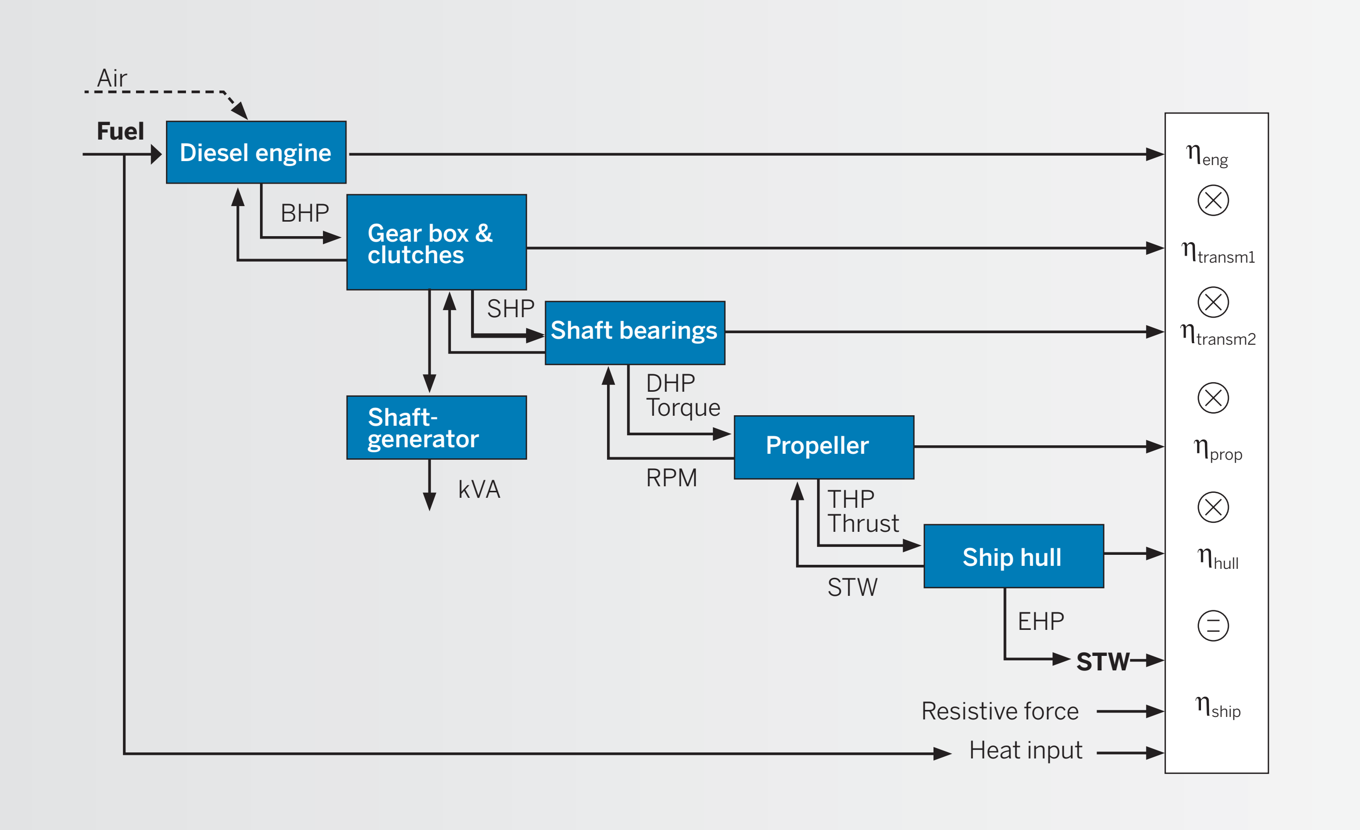


Fig. 2 – The main components of the propulsion drive train. The input and output of each of the components are indicated, as well as their corresponding efficiency.

by w denoting the wake fraction number.

The efficiency of the ship hull is calculated by the following formula:

$$(5)\ \eta_{hull} = \frac{(1-t)}{(1-w)}$$

Where t represents the thrust deduction number.

By combining the propeller efficiency and the hull efficiency, we can obtain the total propulsive efficiency, as follows:

$$(6)\ \eta_t = \frac{T_E u}{Qn}$$

Where T_E represents the effective thrust that is acting on the hull. The numerator is called the effective power and the denominator is called the delivered power.

When assessing propeller efficiency, direct measurements on the thrust, advance velocity, torque, and propeller angular velocity are needed. The first problem related to any propeller efficiency calculation is that the advance velocity, or the wake fraction number, can not be measured directly onboard ship. The second problem is that the thrust, torque and propeller angular velocity measurements have to be very accurate in order to fulfil the requirements specified earlier.

Sensors and signal processing

When considering an achievable efficiency gain in the order of 5%, it becomes clear that the accuracy requirements for the sensors and signal processing algorithms are demanding.

In this section we give a brief explanation of the sensors and what is required of them when making propeller and overall ship efficiency calculations. The means to estimate the accurate speed-through-water and the advance velocity, are also presented.

Thrust, torque, and rpm measurements

Thrust, torque and propeller angular velocity are the only ship variables involved in the efficiency formula that can be directly measured onboard the ship. However, the direct measurements are challenging due to the accuracy demands.

Propeller torque and angular velocity are the most facile variables to measure. Propeller torque has been measured for decades by using strain-gauge techniques. The strain-gauges are placed directly on the propeller shaft, and measure the shaft elongation due to forces and moments. The small deformation of the sensor is translated into voltage changes. The voltage changes are then amplified in special electronic circuitries and the micro-strain (elongation) is determined. The typical deformation of a propeller shaft due to torque is about 330 micro-strains. The strain-gauges, with current technologies, are able to measure deformations of 1.5 micro-strains, with long-term stability, resulting in 0.5% accuracy for propeller torque measurement.

The thrust produced by the propeller induces a deformation in the shaft of about 35 micro-strains. Measured by the strain-gauges, this means a 4% long-term accuracy. Given the achievable propeller efficiency gain, the accuracy of the thrust sensor is far from that needed. Alternatives to direct measurements by strain-gauges are needed. Wärtsilä's Propulsion Technology research group has two approaches in dealing with this problem:

- Use of light-based thrust sensor to measure the small elongation, see Figure 3.
- Use of indirect measurements by strain-gauging at the thrust bearing support combined with an appropriate signal processing method.

Fig. 3 – Thrust sensor on a calibration test bench.

Fuel flow sensor

When overall ship efficiency is being calculated, an accurate estimation of the heat input is needed. The heat input can be estimated based mainly on fuel (mass) flow measurements and fuel caloric values. Measuring the fuel mass flow for overall ship efficiency purposes requires very accurate sensors. Due to re-circulation, the sensors have to be mounted on both the supply line and the return line. Furthermore, the sensors must be able to measure accurately without being affected by the existing pressure pulses.

Speed-through-water sensor

Speed-through-water (ship speed) is measured onboard most of the ships in service nowadays by Doppler Logs. Nevertheless, research conducted in the Wärtsilä Propulsion Technology unit has indicated that the accuracy of the Doppler Logs is far from that indicated by the producers. From the analysis of direct measurements we concluded that speed-through-water and speed-over-ground by Doppler Log have inaccuracy levels as high as 0.65% on average, when compared with the data from the Differential GPS (DGPS), while the inaccuracy level given by the producers is about 0.2%. When analyzing the speed-through-water and -over-ground in transversal direction in a ship coordinate system, we get inaccuracies of up to 50%.

Wärtsilä's Propulsion Technology has developed a mathematical algorithm that fuses the data from the Doppler Log, DGPS, Gyrocompass, Echo-sounder, Anemometer, and Ship's Roll to obtain improved speed-through-water and speed-over-ground. The mathematical algorithm, together with the support hardware is called the speed-through-water virtual sensor. See Figure 4 for the general scheme of the algorithm.

In Figures 5 and 6 one example of an improved speed-through-water measurement in ship longitudinal and transversal direction is presented. The measurements were performed within the Ship Sense European Project onboard the SeaFrance Rodin Ro-Ro ferry. The differences between the measured STW by Doppler Log and estimated by Wärtsilä's virtual sensor are about 0.7% for the longitudinal component. In transversal direction the differences are usually about 40%, but higher differences are often encountered.

Virtual sensor technology for advance velocity

As mentioned earlier, the propeller advance velocity (or the wake fraction) cannot be measured directly onboard ship. The advance velocity is the velocity of water entering the propeller's plane.

Finding a way to estimate the advance velocity is not a new topic. There have previously been attempts to find methods to calculate advance velocity (see M. Schmiechen 1991), but the lack of accurate sensors and proper mathematical approach has left the problem unresolved.

In Wärtsilä's Propulsion Technology research department, a method to estimate the advance velocity based on thrust, propeller torque, propeller rpm and engine torque measurements have been developed and patented. The method is still in its development phase and measurements are currently performed for validation purposes.

The method is structured around the Ship Dynamics Model (SDM) that is a 1-D model describing the dynamics of the ship. The SDM is inspired by the three-state model developed by M. Blanke et al (2000). In Wärtsilä's model the ship dynamics are split into four main components, namely, engine dynamics, propeller shaft rotational dynamics, propeller dynamics, and hull dynamics. Each component is assigned with one equation, as per the following:

$$(7)\ \tau_g \frac{dQ_{eng}}{dt} = k_g(n_{set} - n) - Q_{eng}$$

$$(8)\ I_p \frac{dn}{dt} = Q_{eng} - Q_f - Q$$

$$(9)\ m_w \frac{du_p}{dt} = T - R_p(u_p, u_a)$$

$$(10)\ m_s \frac{du}{dt} = (1 - t)T - R_b(u)$$

The SDM is then used in a parameter identification algorithm to estimate the advance velocity. In Figure 7 we give the structure of the advance velocity virtual sensor indicating the main components. The theoretical results so far indicate that we can estimate the advance velocity with 1.5% inaccuracy. To decrease the inaccuracy level well below 1%, we fuse the advance velocity data with the improved speed-through-water measurements, making use of Formula (4). →

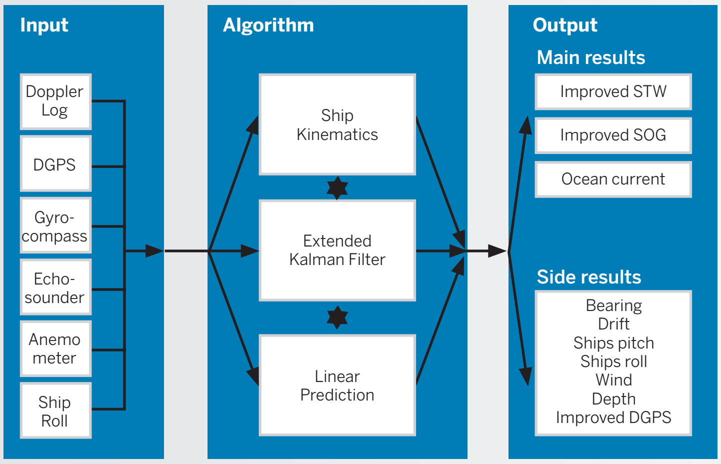


Fig. 4 – The general procedure for estimating the improved speed-through-water.

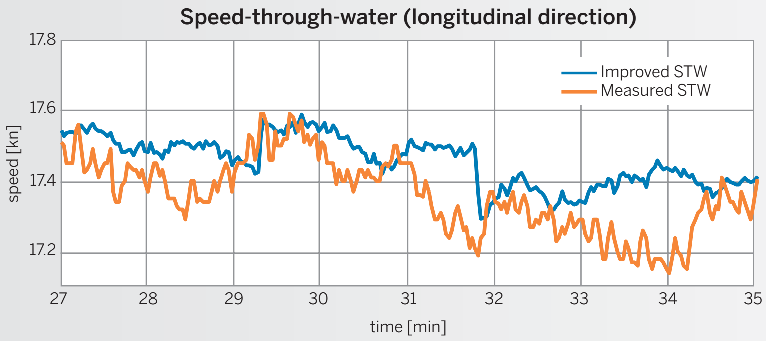


Fig. 5 – The improved speed-through-water in longitudinal direction.

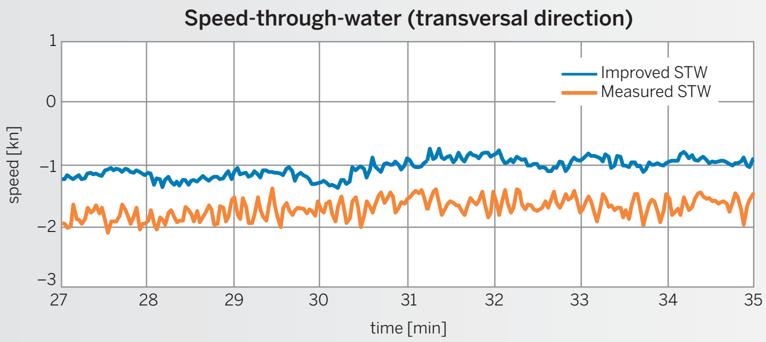


Fig. 6 – The improved speed-through-water in transversal direction.

The advance velocity virtual sensor is still in its development phase, and direct measurements of thrust, propeller torque, and propeller rpm are needed for verification of the SDM.

Outlook – fleet monitoring system

The technological developments presented in the previous section will result in advanced methods for a fleet monitoring system. The fleet monitoring system is fully integrated within Wärtsilä's engine and propulsion control systems. Figure 8 gives an overview of the measurement system.

The **overall ship efficiency** module represents the primordial monitoring system. This system also represents the most general index of fleet performance. The module combines accurate fuel consumption measurements with accurate speed-through-water estimations. For each ship in the fleet, measurements are performed at pre-established time intervals and stored in the system. The recorded measurements are used for trending overall ship efficiency in time as a function of weather conditions and operating regimes. Based on the overall ship efficiency trends, ship owners will be able to decide the exact time for overall ship inspections.

The **propeller efficiency module** represents an advanced propeller monitoring system. The module includes thrust, torque, and propeller rpm sensors, and accurate speed-through-water and advance velocity sub-modules. The most important feature of this module is that it estimates the propeller's efficiency onboard ship during regular operating time based on sequences of measurements of the aforementioned variables.

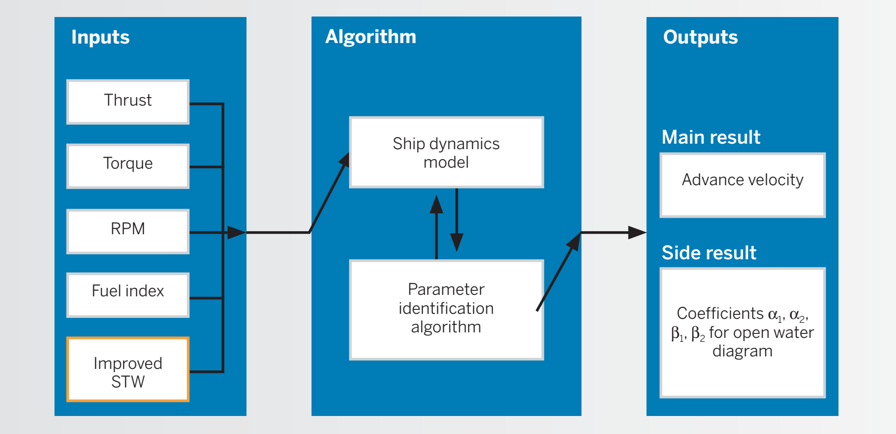
Knowing the ship's overall efficiency and the propeller efficiency, we can then estimate the hull efficiency by using the relation (2). This implies that the efficiency of the diesel engine and the efficiency of the mechanical transmission are known.

The fleet monitoring system is conceived as a modular system in which sensors, hardware modules and software modules are added, changed or updated in time. The system will have an onboard component and an offshore component. The communication between them is done using remote access technologies, such as GSM, ISDN, or GPRS.

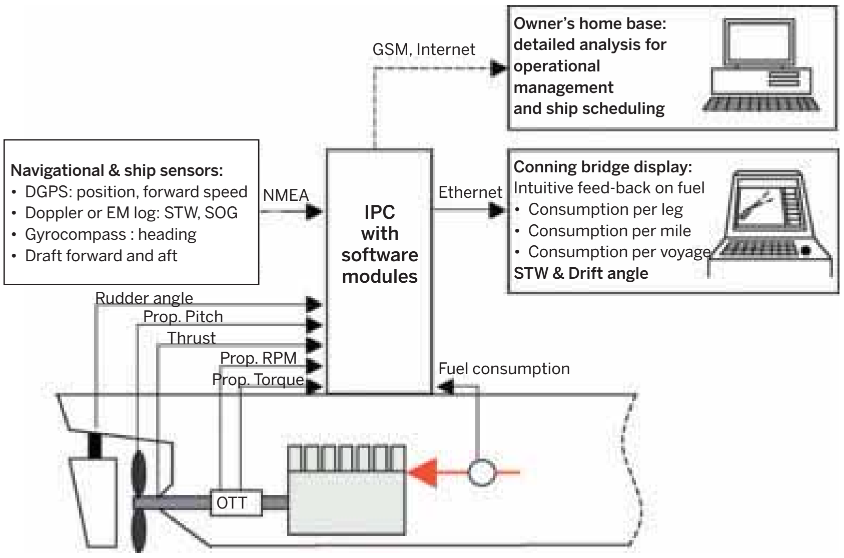
The onboard component of the fleet monitoring system will have a conning bridge display for the crew where information, such as consumption per leg, consumption per voyage, accurate speed-through-water, propeller efficiency and all navigation data, are indicated. A direct intuitive feed-back is given to the crew via the conning bridge display and the alarm and monitoring system. This will motivate the crew to operate the ship in a fuel-efficient way.

The offshore component is located at the owner's home office. This component will store the measured data for trending the ship's performance in time. The detailed data analysis for operational decisions, such as docking scheduling and mobilizing propeller polishing teams from Wärtsilä Services, are also performed here.

The fleet monitoring system is not conceived as an automatic system that performs tasks normally carried out by human operators. Rather, it is conceived as a tool that provides the ship's crew and owner with precise navigation and propulsion data that helps them in decision-making situations.



■ Fig. 7 – The main components of the advance velocity virtual sensor.



■ Fig. 8 – Propulsion performance monitoring system as part of the fleet monitoring system.

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