How an overall understanding of a ship's behaviour including its systems can be acquired in operation is described. The purpose presented is for identifying how fuel & emissions can be influenced by design choices and operating strategies. Through an energy simulation based method, performances and of ships in operation are described and analysed. The approach enables covering complete ship systems within their environmental influences, as illustrated in Fig 1. Demonstrating on a ferry case, this method is combined with an on-board monitoring system. Both off-line route analyses as well as real-time feedback on-board. It is shown that changes in conditions and operating points enable exposure of component characteristics that normally remain hidden within the overall system. Furthermore, verifications of how equipment components behave within a systems environment can be gained also. Here comparison with equipment product data and computational flow analyses (CFD RANS code) of full-scale controllable pitch propellers and ship hull are applied.

Fig.1: Combining worlds: monitoring, full-scale validation, CFD and Power-bond simulations

1. Introduction

There is an interest today in attaining highest Ship energy efficiency to reduce fuel cost and gaseous emissions. Challenging factor is to meet logistic targets under best possible operational conditions. This may deviate from where the ship is designed for. In general, the ship design targets deviate from the actual in-service conditions. Common practice is to specify a contractual maximum attainable speed and a maximum continuous speed. Here a general trend is that many ships sail less fast as designed for. Furthermore, environmental factors are not always properly accounted for, resulting into possible design-offsets. Given the fact that the design shows ideal sub-optimal matches with given operations and possible retrofitting makes it of interest to analyse total ship systems to negotiate their given operational demands. Possible redesigns with pay-back times between 1-3 years are interesting. In view of new-builds, better understanding the merits for optimal operations and generic solution models at an early concept design stage will enable better future designs for operations. Such models can also be utilised for quantifying impact on actual ships, for example after exhaust gas treatment
systems and propulsor conversions. In fact, by connecting this to actual monitoring data on-board, predictions can be verified afterwards.

The qualitative fuel consumption over speed is shown in Fig.2. The larger the ship speed, the higher the fuel consumption. The design speed typical per ship type is also shown. The black markers illustrate the design point on the blue curve. Due to the increased fuel consumption, ship speeds have reduced, indicated by the orange arrows. Because of deviating from the initial design point, there is a tendency of higher fuel consumption, moving towards an off-design point, illustrated by the green line dash-dot line. The ferry ship type is interesting for having the highest impact with respect to fuel consumption in terms of absolute numbers. Remark however is, there is a scale effect in the ship type. Targeting a ferry case for development has a favourable impact. Another benefit is that they are sailing on fixed routes, being easily accessible.

![Annual Fuel cost as function of speed](image)

Fig.2: Fuel consumption over speed at typical design points per ship type

2. **Objective**

Identifying how fuel and emissions can be influenced by design choices and operating strategies by acquiring an overall understanding of a ship’s behaviour including its systems in operation. In this context, the real time propulsion performance management approach has been limited to use for design purposes of total solutions. The part related to development of a real time advisory system on-board has been excluded from the scope.

3. **Approach**

A total ship system can be composed from the following elements:
- Ship hull
- Energy components
- Navigation and controls
- Environment
- Crew

Typical information that can be acquired involves:
- Design requirements
- System design and Component specifications
- Component performances (Engine FAT, Propeller OW efficiency, model basin tests)
- Key system performances are determined for contract purposes at trial conditions (speed/power, manoeuvres incl. turning circle, zig-zag and crash stop)
- On-board data, power management, AIS, navigation, manual logs (e.g. noon reports)

This information is insufficient to acquire proper understanding of in-service performance in view of ship design requirements. In order to meet our objective, a monitoring system and data processing by simulation based approach have been developed, shown in Fig. 3.

Fig.3: Flow scheme acquiring data and interfacing with the ship design simulation environment

The approach consists of the following key elements:
- Propulsion performance monitoring set-up
- Ship energy simulation model
- Interfaces for hard-ware in the loop
- Interfaces for design modifications and operating strategies

The monitoring set-up and simulation model are further explained in this paper.

3.1. Propulsion performance monitoring set-up

The propulsion performance can be monitored, using a set of sensors and data acquisition system. The monitoring system that has been designed for one of the cases involves a ROPAX Ferry, here the system acquires 101 signals, 10 Hz covering:

- Two drive-trains which includes engine, controllable pitch propeller and shafts
- Ship that contains the load controller, drafts, angels and motions, speed through water
- Navigation: GPS, Autopilot
- Other systems such as Hotel load and stabilisers.
The set-up of the data acquisition system is shown in Fig. 4. Here also the design simulator is connected to the monitoring grid, enabling real time design simulation experiments onboard and gain insights at real-time.

4. Ship energy simulation model

In order to analyse the ship propulsive performance a ship energy simulation model has been developed in GES. For comparison of results and modelling capabilities also Matlab-Simulink has been used. Also an interfacing between the two has been applied, benefiting from the pro-processing functions in Matlab.

The core simulations have been centralised in GES. Due to the code optimisation and fast solver techniques it was shown that GES is 100 times faster than real-time (using a quad core CPU at 2.7GHz). Large influencing factors however are smooth description of components in all operating domains and robust system controls.

4.1. Principles of the GES-model

The simulation concept is based on energy flow analysis, using the power-bond method. The basis for this is a scheme in which all relevant power sources, converters and consumers are represented by individual model elements called components. Typically components represent fuel tanks, engines, alternators, transformers, gearboxes, propellers and energy consumers such as heating, lighting or ship resistance. Each component contains either a system of lower level components or a mathematical description of the corresponding piece of equipment, right down to the underlying equations derived from elementary physics. This is what makes the simulation concept both robust and flexible. A component approach makes it possible to easily modify the behaviour of an arbitrary energy consumer or power source and new machinery can be defined to cope with new developments. Each component has input and output gates. If there is an energy flow from one component to another, the terminals of
these components are connected, thus enabling an energy transfer between the components. This leads to a simple representation of the interaction between systems.

### 4.2. Simulation levels

Four levels are introduced:

1. Operating scenario level
2. Ship level
3. Ship system level
4. Ship component level

Fig. 5 shows the levels including example input and output. The sub-systems, such as the diesel engines and propellers are characterised separately. Subsequently the sub-systems are connected on an energy flow level, defining systems. The combination of all energy related systems can be grouped into a ship. At scenario level, specifying the conditions and demands, the equilibrium can be calculated for each operational point. Finally the properties of various system designs and the effect of fine tuning on fuel consumption are determined.

The simulation tool for the power-management system models the power-distribution grid of the onboard system. It calculates the steady-state flow distribution of the grid and simulates the disturbance and the new load-flow situation after a disturbance.

![Fig. 5: Simulation levels](image)

In order to measure performance, several criteria can be defined. Some of these criteria are the ship’s maximum speed achievable after an event; the total power, etc. The performance level can be expressed in terms of fuel consumption, emissions, ship speed, availability, maintenance, costs and process conditions. In this scope fuel performance is the key parameter.
To get a better understanding of where the energy is consumed, the utilisation can be shown in a Sankey-diagram; an example of such diagram is shown in Fig. 6. In order to assess the impact of design and operating changes, this diagram has been parametric and connected to the simulator.

![Sankey-diagram example](image)

**Fig.6: Example of a Sankey-diagram for a general ferry case**

### 4.3. Ferry benchmark model

A Ferry, equipped with two CPP and four engines has been modelled in a power-bond model. The drive-train model in GES is shown in Fig. 7.

The benchmark model consists of two parts: the command system and the operational system. The command system contains the control, guidance and navigation systems. The operation system contains the actuators (controllable pitch propellers (CPP) and rudders), bearings, gearbox, the diesel-engines and the ship. The command system gives demands to the operation system, like fuel rack, propeller pitch, rudder angle and PTO power (i.e. transverse thrusters) The demands of the command system are set-points or our outputs of closed loop controllers. In the latter case the control loop is closed by feed-back signals from the operation system.

The control inputs to the command system are:

- Single lever settings, one for each CPP
- Steering wheel demands, one for each rudder
- Heading setting, in case of auto-pilot mode
- Track setting and ship speed setting in case of track control
- Load-limit or trim setting, one for each CPP load-control

The benchmark simulation model has been tuned (matched) by using the measurements onboard and by using design data. After verification and validation this model has been used to quantify the relative reductions of fuel and emissions, when both the benchmark model and the modified model are sailing the same route at the same speed through the water.
Fig. 7: Ferry Power-bond Simulation model in GES program
5. **Propulsor performance validation**

In order to validate the propulsor, a 3D-laser measurement has been applied to measure the geometry of the propeller blades as well as their position on the hub. The geometry has been transformed into a mesh to quantify the propulsor performance by means of Computational Fluid Dynamics (CFD) simulations.

![Fig. 8: Propeller open water performance of the actual blade geometry based on CFD (actual values are omitted)](image)

6. **Simulation results**

Simulation results have come available and are currently being analysed. For illustration purposes the following plots are shown in Fig. 9, measured versus simulated:

- Speed over time
- Propeller shaft speed
- Environmental factors Wind and Depth

7. **Conclusions**

A concept of combining measurements and a ship energy simulation model have been delivered. The possibility to verify the impact of equipment choices, design points and operations at an overall ship performance level has come available.

From 2 ferry evaluation cases, in-service potential performance improvements have been identified:

- Tuning of controls: 3%
- Energy audits and maintenance: 10%
- Improvement of operation at reduced operating speeds today: 2-5%
- Retrofitting of propulsors and engine tuning: 3-7%

The energy audits and maintenance results have been delivered and confirmed at one of our clients. Further processing of data and utilisation of results is needed.
Fig. 9: Time series of speed (top), propeller shaft speed (middle), wind and water depth (bottom)

References

