Ship energy efficiency in simulations and energy system analysis

Modelling and Optimization of Ship Energy Systems
October 23 - 25, 2017. EPFL Sion, Switzerland
Invited speaker
Assoc. Prof. Kari Tammi, Aalto University
Jari Vepsäläinen, Klaus Kivekas, Juuso Autiosalo, Guangrong Zou
2015: Le Bisse de Clavau
2004: L’Aiguillette d’Argentière
2000: Le Mont Blanc du Tacul
Content

Background

Previous examples

• HT water control
• Power turbine usage
• Shaft generator usage
• Power demand estimation

Current work on uncertainty in power system design

• Cycle uncertainty
• Robust design
• Digital twin

Future outlook
Background & team

Kari Tammi, Aalto University 2015-
Earlier Research Professor at VTT:
electric machines, energy efficiency,
electric vehicles, dynamics & control
At CERN 1997-2000 (LHC/CMS)
Teaching: Mechatronic machine
design (5 cr), Vehicle mechatronics
(5 cr), Design of electric vehicle
systems at IIT Guwahati, India 2016

Panu Sainio. Chief Engineer, expertise:
vehicle technology, hybridization, electric
powertrain

Shashank Arora. Post-doc, expertise:
batteries, mechanical modelling

Klaus Kivekäs. Electric powertrain
optimization with statistical methods

Jari Vepsäläinen. Multi-objective robust
design of electric powertrain

Juuso Autiosalo. Digital twin for industrial
products
Ship Energy Flow Modelling

Fuel

Marine Diesel Engine

Mechanical Power, 48%
Exhaust Gas, 25.5%
HT Water, 15%
LT Water, 11%
Heat Radiation, 0.5%

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**Motivation – Why Ship Energy Efficiency?!**

- 95% of worldwide transport of goods by ships
- Increasingly high fuel cost
- Accumulatively strict IMO rules

→ **GREEN SHIPPING!**

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*Fig. 1: An EEDI reference figure of new-building ships enforced by IMO.*

(Source: Lloyd’s Register, (2012), Implementing the Energy Efficiency Design Index)
Fuel costs as a percentage of total operational costs for different ship types

- Fuel cost for container ships is the highest among all the other ship types
- Many are struggling to balance their financial sheets
Motivation – How to Improve Ship Energy Efficiency?!

- Better planning
- Slow steaming
- Energy management
- Novel technology

Challenge
- How to evaluate the overall effectiveness of each solution?
- How to estimate the Return On Investment of each solution?
Multi-Domain Energy Flow Simulation in Brief

- Started in 2009

- Aim at a general tool for ship power plant simulation
  - To find **globally optimal** ways to improve ship overall energy efficiency
  - To be modelled at a **system level**, ONLY main sub-systems included

- Simulator modelling environment → **Matlab/Simulink/Simscape**
  - Different physical interactions are modelled in **DOMAINS** in Simscape
    - Available: Mechanical, Electrical, Thermal, pneumatic
    - Self-developed: Electrical AC, Thermalfluid, Steam
  - Component libraries for each domain using Simscape language
Multi-Domain Energy Flow Simulation – Example

- Helpful to thoroughly understand the energy distribution and consumption
- Potential to utilize the simulation method in different types of ships
Ship Energy Flow Simulator

- Sub systems
  - Electrical AC
  - 4 DG sets
  - HT/LT FWC
  - STEAM
  - Data I/O & processing, result display
Model validation results

- DG power output
  → mostly within [0.95 1]

- Ship fuel consumption
  → mostly within [0.95 1.15]

The energy flow simulator can accurately represent the energy flow distribution in the case ship.
HT water control example

- To test and verify different energy saving technologies and ideas

**QUESTION:** Can we harvest a part of the wasted heat energy by tuning the set-point of valve 4V02?
HT water control example

- To specify the set-point of valve 4V02 as a function of engine load

- To Check:
  - Working efficiency
  - WHR
  - Working safety
    - Constant set point
    - Variable set point
Power and steam turbine usage

- Shaft generator system (SG)
- Waste heat recovery system (WHR)
Shaft generator usage

- **Generator mode**
  - Harvest energy from ME shaft to generate electricity, less fuel consumption
  - More flexible energy utilization to achieve higher overall energy efficiency

- **Parallel generation**

- **Motor/booster mode**

(Source: Rolls-Royce, Hybrid shaft generator propulsion system upgrade)
Results

- Different energy saving solutions evaluated under operation cycles recoded on-board
- **Improved HT water temperature control** → ROI 1 year, annual fuel savings 50 kUSD (HT/LT 3-way valve), [1]
  - In collaboration with ABB & Deltamarin
- **Power turbine in waste heat recovery** → ROI 2 years, annual fuel savings 2 M€, [2-3]
  - In collaboration with ABB

How to Predict Ship energy Flows?
Energy flow prediction

- How to estimate energy flows within ship based on incomplete measurement information?
- How to predict / forecast the energy flows 6-32 hours ahead as accurately as possible?
- How to operate and control ship and ship systems as energy efficiently as possible?
Marine engine cooling water circuit

- Measured signals
- Observed signals
- Signals to predict

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>temperature</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>mass flow</td>
</tr>
<tr>
<td>$\dot{Q}$</td>
<td>heat</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>thermostat coefficient</td>
</tr>
</tbody>
</table>

Indices:
- $\text{in}$ - inlet
- $\text{out}$ - outlet
- $E$ - engine
- $BP$ - bypass
- $HE$ - heat exchanger
- $MIX$ - after mixer
- $\text{WHR}$ - waste heat recovery
- $H$ - heat from load
Signal estimation results (RLS)

- The "low variation" load profile has been used
- A constant set point for $T_{mix}$ has been used
- Details are presented in the attached, updated report
Uncertainty in machinery design
Cases electric vehicles
Driving cycle and passenger load uncertainty - approach

• How much do the variations in the driving cycle and passenger load on a single bus route affect the energy consumption?

• Create a method to generate varying synthetic cycles and passenger flows and then run them with a simulation model.

• Case example: Line 11 in Espoo, battery electric bus

• Note: “driving cycle” substantially more complicated in ships due to high auxiliary loads
Driving cycle and passenger load uncertainty - methods

- Divide route into segments between bus stops
- Create new cycles by randomly choosing respective segments from measured cycles
- Segments need to be connected
- The bus stops at which the vehicle stops are also randomized
- Cycle synthesis validated:
  - Passenger flow is sampled from a multivariate distribution
Driving cycle and passenger load uncertainty - results

- Energy consumption distribution acquired
  - Resembles normal distribution
  - Mean: 0.913 kWh/km, Range: 0.301 kWh/km
- Consumption correlates strongly with number of stops
  - Pearson coefficient: 0.778
- Lesser correlation with passenger load
Robust Design – Approach (1/2)

- **Noise factors** cause unwanted variation in vehicle performance
- **Robust design** = make the system insensitive to these variations
- Identify **noise factors** and their range of values
- Study **control factors** that reduce the effect of noise factor variation
Robust Design – Approach (2/2)

- Robustly optimize control factors to guarantee long lasting quality design, without unnecessary oversizing of components.

- Energy Generation & Control
- Energy Storages
- Propulsion
- Payload
- User Behavior
- Temperature
- Age & Wear
- Waves & Storms

Aalto University
Robust Design – Methods

Solution: Surrogate analytical model (PCE)

Challenge: Complex dynamic model

Sensitivity analysis: Impact of Noise Factors

Noise Factors

Control Factors
Robust Design – Results
Case: Electric City Bus
The consumption varied from \(0.4\) to \(2.3\) kWh/km in the selected route

- **Key noise factors**
  1. Ambient temperature
  2. Rolling resistance
  3. Mission
  4. Driver aggressiveness
  5. Traffic
  6. Payload
  7. Headwind
Digital Twin

Physical Twin

1. Can be inspected with all senses on location
2. Obeys laws of physics
3. Doesn’t have intelligence
4. Is constantly changing

Digital Twin

1. Can be inspected through a user interface from anywhere around the world
2. Laws of physics must be simulated
3. Can have artificial intelligence that can be used to control physical twin
4. Must be updated to match the physical twin

Knowledge

Data
Ship energy systems are constantly producing vast amount of data. This data could be utilized better with enhanced connectivity and data management. Currently, there is no standardized way of transferring and displaying data. Standardizing work is necessary, and good standards can only be achieved through experience. Functional demonstrators will crucial for creating the future standards.
Benefits of Digital Twin come from multiple factors:

1. Deeper knowledge of the energy process state
2. Centralized data interface
3. Deductions from comparing large populations with e.g. with artificial intelligence
4. Truly integrating connected products to each other with standardized data formats
   → Energy system optimisation
   → Operation optimisation
   → Fleet management
Future outlook
Technologies (to be) studied

IoT: automation systems provide with various measurements

Computer power enables on-line control and e.g.

- Uncertainty and sensitivity in design
- Tracking simulator approaches

Emerging technologies:

- Electrification (hybridization), DC grid, variable AC
- Energy storages, electric and thermal
- Waste Heat Recovery (ORC, connection to energy storages)
- Absorption chillers
- Power turbines and multi-stage turbo charging

SET final publication in VTT Technology series