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SHIP PROPULSION SYSTEM AS A BENCHMARK FOR FAULT-TOLERANT CONTROL

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Abstract: Fault-tolerant control combines fault detection and isolation techniques with supervisory control to achieve autonomous accommodation of faults before they develop into failures. While fault detection and isolation (FDI) methods have matured during the past decade the extension to fault-tolerant control is a fairly new area. The paper presents a ship propulsion system as a benchmark that should be useful as a platform for development of new ideas and comparison of methods. The benchmark has two main elements. One is development of efficient FDI algorithms, the other is analysis and implementation of autonomous fault accommodation. A benchmark kit can be obtained from the authors.

Keywords: Fault-tolerant control, fault detection, fault handling, benchmark, autonomous supervisory control.

1 INTRODUCTION

Faults in ship propulsion systems are far from being unlikely events and many faults have resulted in events with severe damage and significant loss of capital investment. While safety and reliability are of paramount importance in marine automation, fail-operational systems are not employed. Instead, a safety system philosophy is applied, where individual machinery is shut down if local faults are detected. This strategy is only locally optimal and, as an example, a prime mover shut down has often left ships without ability to break, because a sensor fault occurred in its diesel maneuvering system. Overall optimization in the handling of faults would clearly be an attractive alternative in this field.

While interesting benchmark studies and industrial applications exist on fault detection and isolation (FDI) (Blanke and Patton (Dec. 1995), Isermann and Ballé (1997), Frank (1995), Bennet and Patton (1997)) publications about

autonomous fault-tolerant control have been sparse (Blanke *et al.* (May 1997), Patton (1997)). The present benchmark serves the purpose of of-

fering a realistic and challenging problem with high industrial relevance. The problem offers challenges in both FDI and autonomous supervisory control. Challenges in FDI include robustness to parameter uncertainty, and nonlinear characteristics for propeller and hull resistance. Challenges in the fault-tolerant control part include re-configuration of controllers to accommodate severe faults. The two parts of the benchmark could be studied individually. The benchmark is intended as a means to enhance theory and technology within fault-tolerant control and it is hoped that several groups will work together on both international publication of results and enhancement of the industrial state of the art. This paper describes the benchmark, the background of the problem, and suggests test sequences for uniform evaluation of results.

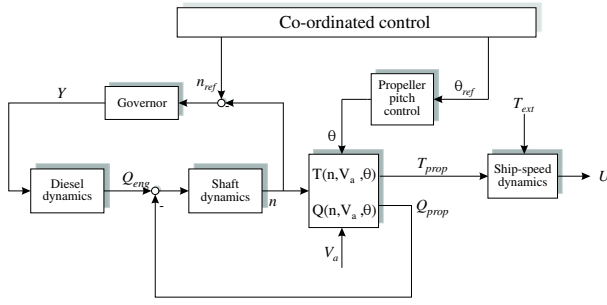


Fig. 1. Diagram of the ship speed propulsion system

2 SHIP PROPULSION SYSTEM

The example chosen for benchmark testing of various FDI methods is the propulsion system for a ferry. Appendix A contains main data for the ship. An outline of the propulsion system is shown in Fig. 1. The main components/subsystems are:

- Diesel dynamics: diesel engine that generates torque to drive the propeller shaft. The control input is fuel index Y .
- Shaft dynamics: shaft acceleration from difference between diesel and propeller torques.
- Propeller characteristics: shaft speed n , propeller pitch θ and water speed V_a determine propeller thrust and torque.
- Ship speed dynamics: Propeller thrust balanced by resistance from hull and external forces from wind and waves.
- Propeller pitch and shaft speed controllers determine propeller pitch and fuel index, respectively.
- Coordinated control level gives set-points to shaft speed and propeller pitch.

The coordinated control level is detailed in Fig. 2. The following functions are included:

- A combinator gives a set of command values: n_{com} and θ_{com} as function of command handle position.
- A module to optimize propulsion efficiency determines n_{com} and θ_{com} based on measured values of Y , n , θ and U .
- Ship speed control module to maintain a command value of ship speed U_{ref} using measured values of Y , n , θ , and U as input.
- An overload control changes n_{com} and θ_{com} to prohibit the prime mover to enter torque limits. The fuel index is used to determine an approaching overload condition.

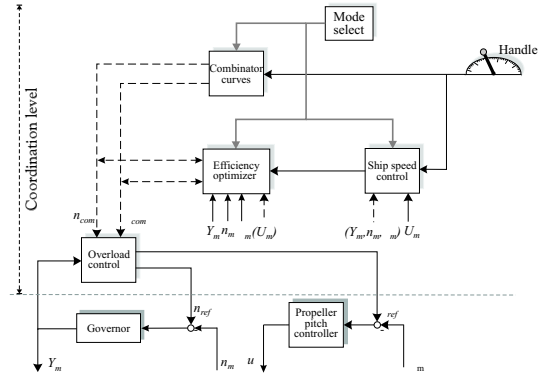


Fig. 2. Control hierarchy for the propulsion system. Lowest level comprises: governor, propeller pitch control. Co-ordination level comprises: combinator for shaft speed and propeller pitch, optimized shaft speed and pitch module, ship speed control, and pitch and diesel overload control.

2.1 Control hierarchy for the propulsion system

The objective for the propulsion system is to maintain the ship's ability to propel itself and to maneuver. This requires thrust ahead for propulsion and alternating ahead/astern for maneuvers. With positive shaft speed n , this can be obtained by appropriate change of propeller pitch θ . Propulsion efficiency can be optimized by varying shaft speed and propeller pitch in a coordinated manner. Fig. 2 illustrates following steps:

- Simple coordination of commands to n and θ . A lever position is converted to commands in n and θ by lookup in a fixed table.
- A second co-ordination block (efficiency optimizer) tunes the variables n and θ to achieve minimum power consumption for a given value of ship speed (handle position).
- An overload control block, which reduces propeller pitch if a diesel engine torque limit is reached, has final command of set-points n_{ref} and θ_{ref} to the lower level controls.
- The final step is to make closed loop control of ship speed for ocean passage.

2.1.1 Propeller pitch and shaft speed control

The propulsion system consists of two basic control loops, one for propeller pitch and one for shaft speed. A block diagram with more detailed architecture for the lower level is shown in Fig. 3. This includes the various saturation phenomena and limiter functions in the shaft speed and pitch control loops. Values of parameters are listed in

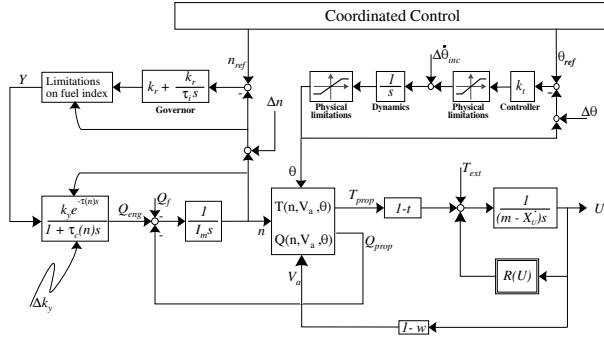


Fig. 3. Block diagram of the propulsion system with saturation phenomena shown for shaft speed and pitch controller. The generic faults of the benchmark are indicated.

appendix B. Inputs at the lower level controls are shaft speed set point n_{ref} and propeller pitch set point θ_{ref} . Unknown inputs are external force imposed on the ship speed T_{ext} and friction torque Q_f . Measured outputs are diesel engine shaft speed n_m , fuel index Y_m , propeller pitch position θ_m , and ship speed U_m .

3 FAULT SCENARIO

The occurrence of a generic fault can have several reasons. In the benchmark, we consider four generic faults resulting in six realistic events. The faults are listed in table 1 and are further explained below. They have different degree of severity. Some are very serious and need rapid fault detection and accommodation to avoid serious accidents if the component failure happens during a critical maneuver. Time to detect and re-configure is hence essential. Some of the faults are actual events that have caused serious damage due to lack of fault-tolerant features in existing propulsion control systems. Fig. 3 locates the generic faults of the benchmark in a system block diagram. The faults are

1. Faults related to the propeller pitch:

$\Delta\theta_{high}$: This fault can occur due to an electrical or mechanical defect in pitch sensor or its interface.

Fault	Sym.	Type
sensor faults	$\Delta\theta$	additive - abrupt
hydraulic leak	$\Delta\dot{\theta}_{inc}$	additive - incipient
sensor faults	Δn	additive - abrupt
diesel fault	Δk_y	multiplicative - abrupt

Table 1 Generic faults considered in the benchmark

Fault	Consequence	Severity
$\Delta\theta_{high}$	<i>deceleration</i> \Rightarrow <i>manoeuvring risk</i>	high
$\Delta\theta_{low}$	<i>acceleration</i> \Rightarrow <i>collision risk</i>	very high
$\Delta\dot{\theta}_{inc}$	<i>gradual speed change</i> \Rightarrow <i>cost increase</i>	medium
Δn_{high}	<i>deceleration</i> \Rightarrow <i>manoeuvring risk</i>	high
Δn_{low}	<i>acceleration</i> \Rightarrow <i>collision risk</i>	very high
Δk_y	<i>diesel overload</i> \Rightarrow <i>wear, slowdown</i>	medium

Table 2 Consequences and severity level for the benchmark faults

$\Delta\theta_{low}$: This fault can occur due to an electrical or mechanical fault in the pitch sensor or its interface.

$\Delta\dot{\theta}_{inc}$: A leakage can occur in the (hydraulic) actuation part of the control system. In practice, often in an overpressure valve.

2. Faults related to shaft speed measurement. A dual pulse pick-up is used for measuring the shaft speed. The followings are considered:

A maximum signal Δn_{high} (EMI disturbance on one pick-up) and

A minimum signal Δn_{low} (loss of both pick-up signals).

3. Fault related to the diesel engine (Δk_y). The generated shaft torque can be lower than expected due to the following causes: reduced air inlet, reduced fuel oil inlet or, a cylinder is not working.

To determine how faults affect the system operation the fault propagation analysis methodology (Blanke (1996)) is employed. This is a hierarchical bottom-up, inductive analysis method that shows end-effects, consequences, and the assessed severity level for each fault. The results are shown in table 2.

3.1 Requirements to FDI

The requirements to FDI design are the following where T_s is the sampling time in the particular control loop:

- *Time to detect* (T_d): Sensor feedback faults ($\Delta\theta_{low}$, $\Delta\theta_{high}$, Δn_{low} , and Δn_{high}): $T_d <$

$2T_s$. The incipient fault $\Delta\dot{\theta}_{\text{inc}} : T_d < 100 T_s$. The gain fault $\Delta k_y : T_d < 5T_s$.

- *Unknown input.* A time-varying external drag force from weather and shallow water, is a potential source of false detection. FDI should be insensitive to this.
- *False detection probability:* $P_f < 0.01$. Fault-free real data, including harbor maneuvers, are provided to make a realistic test of algorithms with respect to false detection.
- *Missed detection probability:* $P_m < 0.001$. Due to the high severity level of faults, which can result in endangering the ship (and its crew), the probability of not detecting them when they occur should be as low as possible.
- *Robust design:* Several sources of model uncertainty exist: slowly increasing hull resistance $R(U)$ due to growth (0 increasing to 20% of $R(U)$), varying external force from sea and wind ($\pm 10\%$ of $R(U)$). A-priori uncertainty in propeller thrust and torque ($\pm 10\%$) and engine friction (from 5 to 8%). General uncertainty on other physical parameters ($\pm 2\%$). FDI should be robust to these. Posteriori data for parameters may be identified and used for FDI. Measurement noise is specified in Appendix C.

3.2 Requirements to re-configuration

Fault handling should incorporate appropriate steps to accommodate the benchmark faults. The remedial actions should primarily use re-configuration at the coordination level to accommodate a fault. Performance in a re-configured mode can be lower than under no-fault conditions. Large transients should be avoided when changing to a re-configuration mode. Bump-less transfer is not required, but is a desired feature.

4 DYNAMIC MODEL

This section describes the dynamics of the physical system. The functional blocks are diesel engine, propeller and hull dynamics in forward motion.

4.1 Diesel engine dynamics

The diesel engine generates a torque Q_{eng} , controlled by its fuel index, Y , to drive the shaft. The diesel engine dynamics can be divided in two parts. The first part describes the relation between the generated torque and the fuel index. It is given by following transfer function (Blanke (1981), Blanke and Andersen (July 1984), and

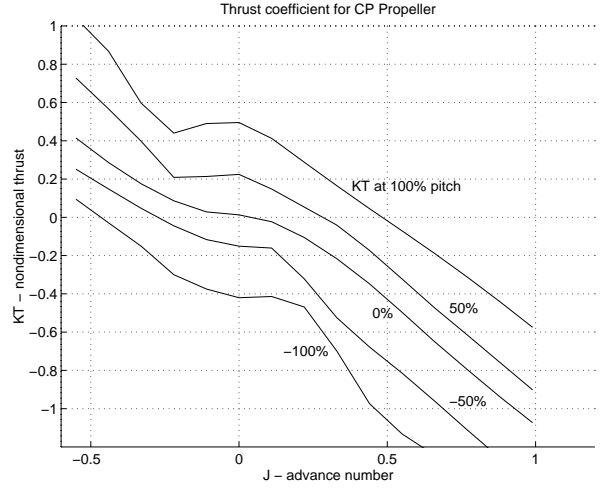


Fig. 4. Non-dimensional propeller thrust as function of advance number $J = 2\pi V_a/n$ for different values of pitch.

Fossen (1994, pp. 246-257)):

$$Q_{\text{eng}}(s) = \frac{(k_y + \Delta k_y) e^{-\tau s}}{1 + \tau_c s} Y(s) \quad (1)$$

where τ represents a time delay (half the period between consecutive cylinder firings), k_y is the gain constant and τ_c is the time constant corresponding to torque build-up from cylinder firings:

$$\tau_c \approx \frac{0.9[\text{rad}]}{n} \quad (2)$$

This model is valid for steady-state operation of two-stroke diesel engine, and the time-delay can be ignored in this context.

The second part express the torque balance of the shaft

$$I_m \dot{n} = Q_{\text{eng}} - Q_{\text{prop}} - Q_f \quad (3)$$

Q_{eng} is the torque developed by the diesel engine, Q_{prop} is the developed torque from propeller dynamics, and Q_f is the friction torque.

4.2 Propeller characteristics

A controllable pitch propeller (CP) has blades that can be turned by means of a hydraulic mechanism. Propeller pitch θ can be changed from 100% (full ahead) to -100% (full astern). The developed propeller thrust and torque are determined by following bilinear relations (Blanke (1981)):

$$\begin{aligned} T_{\text{prop}} &= T_{|n|n}(\theta)|n|n + T_{|n|V_a}(\theta)|n|V_a & (4) \\ Q_{\text{prop}} &= Q_0|n|n + Q_{|n|n}(\theta)|n|n + Q_{|n|V_a}(\theta)|n|V_a & (5) \end{aligned}$$

The term Q_0 describes the torque which is produced by the CP-propeller when the pitch is zero.

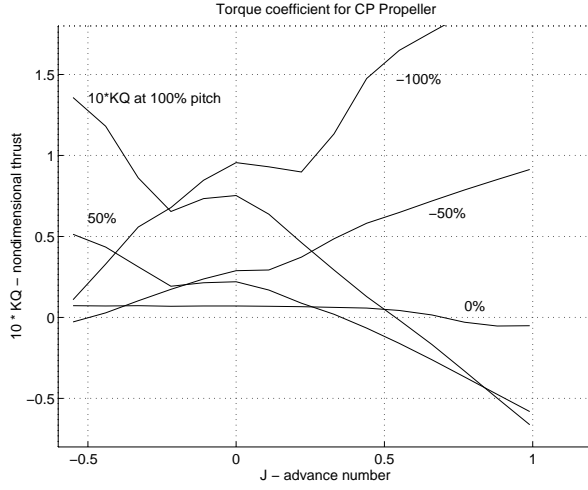


Fig. 5. Non-dimensional propeller shaft torque as function of advance number $J = 2\pi V_a/n$ for different values of pitch. Data from sea tests.

The value of Q_0 is normally 5% of propeller torque Q_{prop} at nominal operation. V_a is the velocity of water passing through the propeller disc:

$$V_a = (1 - w)U \quad (6)$$

U is the ship speed. w is a hull dependent parameter called the wake fraction. The coefficients $T_{|n|n}$, $T_{|n|V_a}$, $Q_{|n|n}$, and $Q_{|n|V_a}$ are complex functions of the pitch θ . In the benchmark, T_{prop} and Q_{prop} are calculated by interpolating between tables of data measured in model propeller tests. Figures 4 and 5 show graphically the dependency of T_{prop} and Q_{prop} on n and V_a for different values of the pitch. K_T and K_Q , in these figures, are non-dimensional thrust and torque coefficients:

$$\begin{aligned} T_{\text{prop}} &= K_T \rho D^4 |n|n \\ Q_{\text{prop}} &= K_Q \rho D^5 |n|n \end{aligned}$$

where D is the propeller diameter, and ρ is the mass density of water.

4.3 Ship speed dynamics

The following non-linear differential equation approximates the ship speed dynamics:

$$(m - X_{\dot{U}})\dot{U} = R(U) + (1 - t)T + T_{\text{ext}} \quad (7)$$

$$U_m = U + \nu_U \quad (8)$$

The term $R(U)$ describes the resistance of the ship in the water and is a negative quantity. Fig. 6 shows the hull resistance as function of the speed for two given load conditions. $X_{\dot{U}}$ represents the added mass in surge and is negative. Thrust deduction, t , represents lost net thrust, due to propeller generated flow at the ship's stern. T_{ext} is the external force from wind and waves. ν_U is measurement noise.

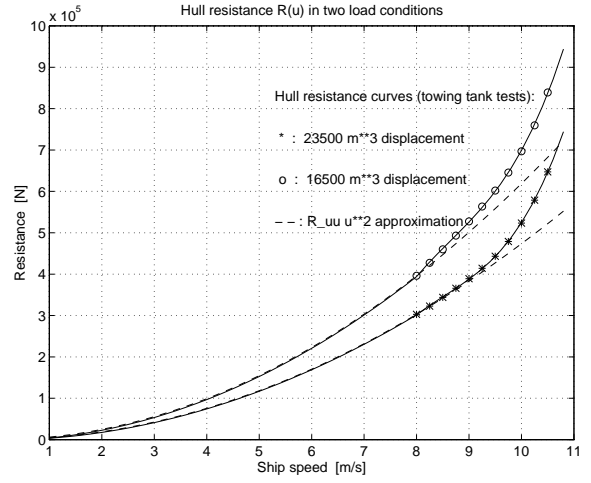


Fig. 6. The magnitude of hull resistant is dependent on ship speed and its loading conditions. The commonly adopted square law curve is not valid in the relevant range of operation, (8.5 to 10.5 m/s).

5 CONTROL SYSTEM HIERARCHY

The set-point for the propeller pitch θ_{ref} , and the shaft speed n_{ref} are calculated on the basis of the chosen mode. The following modes are defined (Izadi-Zamanabadi and Blanke (1998)):

1. Maneuvering mode (fixed breakpoint characteristics determine n and θ from handle position) is mainly used under the following conditions:
 - Approaching harbor or sailing out of it.
 - In confined areas.
 - When maximum maneuverability is needed.
2. Economy mode is used during long distance voyage, ocean cruising, and on deep water. Fixed breakpoint characteristics determine n_{com} and θ_{com} from handle position
3. Optimal efficiency control mode used during long distance voyage. The command signals n_{com} and θ_{com} are modified to optimize fuel efficiency at a given speed.
4. Speed control mode is used during an ocean passage to keep the sailing schedule within a certain limit.

The control hierarchy is treated as belonging to two levels, the lower and the upper. Re-configuration will usually take place at the upper level, although lower level controllers could also be modified to achieve fault-tolerance in some cases.

The following subsections detail the control algorithms used in the benchmark and lists the resources required to run each controller. This information is needed for the analysis of services that will be possible in case of faults. It is also used to determine which algorithms could be used as replacement of one that uses a particular signal, on which a fault has occurred.

5.1 Lower level controls

The lower level controls consist of shaft speed and propeller pitch controllers.

5.1.1 Propeller pitch control

The pitch control subsystem consists of a large hydraulic actuator turning the propeller blades, feedback from a sensor and associated controller and drive electronics. The controller is of proportional type in the benchmark. The pitch control system is described by the following equations:

$$\begin{aligned} \theta_m &= \theta + \nu_\theta + \Delta\theta \\ u_{\dot{\theta}} &= k_t (\theta_{\text{ref}} - \theta_m) \\ \dot{\theta} &= \max(\dot{\theta}_{\min}, \min(u_{\dot{\theta}}, \dot{\theta}_{\max})) + \Delta\dot{\theta}_{\text{inc}} \\ \theta &= \max(\theta_{\min}, \min(\theta, \theta_{\max})) \end{aligned} \quad (9)$$

where θ_m is the measured propeller pitch, $(\dot{\theta}_{\max}, \dot{\theta}_{\min})$ are rate limits set by hydraulic pump capacity and geometry and $(\theta_{\max}, \theta_{\min})$ are physical limits for propeller blade travel. ν_θ is the measurement noise. The leakage fault is $\Delta\dot{\theta}_{\text{inc}}$, and the pitch sensor fault is $\Delta\theta$. It is noted that the control signal is not measured.

Summary of signals to pitch control unit: input is $\theta_m, \theta_{\text{ref}}$; output is $-\theta$.

5.1.2 Shaft speed control

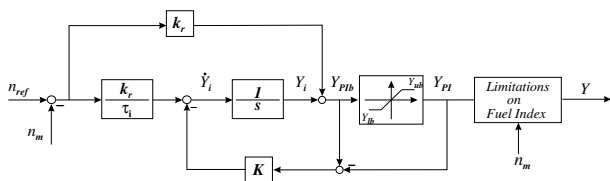


Fig. 7. The governor

Input to the shaft speed controller, the Governor in Fig. 7, is shaft speed reference n_{ref} and the measured shaft speed n_m . The output is the fuel index Y . In the benchmark, the governor is a PI controller. Anti-windup is part of the integrating action and K is the anti-windup gain. The con-

troller is:

$$\begin{aligned} n_m &= n + \nu_n + \Delta n \\ \dot{Y}_i &= \frac{k_r}{\tau_i} ((n_{\text{ref}} - n_m) - K(Y_{PIb} - Y_{PI})) \\ Y_{PIb} &= Y_i + k_r \cdot (n_{\text{ref}} - n_m) \end{aligned} \quad (10)$$

$$Y_{PI} = \min(\max(Y_{PIb}, Y_{lb}), Y_{ub})$$

Y_{lb} and Y_{ub} are the lower, respectively upper bounds for the integrator part of the governor and Δn the measurement fault. The governor comprises fuel index limits to keep diesel engine within its allowed envelope of operation.

Limits on fuel index Due to physical constraints on torque characteristics of diesel engines, the fuel index command from the governor is limited as a function of measured shaft speed relative to the maximum continuous rating for the engine. The benchmark assumes:

$$y_{\max} = \begin{cases} 0.4 & n_m \leq 40\% \text{ of } n_{\max,a} \\ 1 & n_m \geq 80\% \text{ of } n_{\max,a} \\ \frac{1.5n_m}{n_{\max,a}} - .2 & \text{otherwise} \end{cases}$$

$$Y = \max(0, \min(Y_{PI}, y_{\max})) \quad (11)$$

where $n_{\max,a}$ is the maximum allowed generated shaft speed, n_m is the measured shaft speed, y_{\max} is the hard limit specified for the engine, and Y denotes the command fuel index. The fuel index is non-negative.

In actual systems there is, furthermore, a limit associated with the scavenging air pressure. For reason of simplicity, this is disregarded in the benchmark.

Summary of signals: input is n_m, n_{ref} , output is Y .

5.2 Upper level control

The upper level of control comprises combinator curves for handle in two modes of operation (maneuvering and ocean passage), overload controller, efficiency optimizer and ship speed controller.

5.2.1 Handle characteristics

A command lever position constitutes the main man-machine interface (MMI) for speed command. The resulting signal, shown in Fig. 8 is the handle position h . Co-ordinated command in shaft speed and propeller pitch are obtained as

$$\begin{bmatrix} \theta_{\text{com}} \\ n_{\text{com}} \end{bmatrix} = g(h) \quad (12)$$

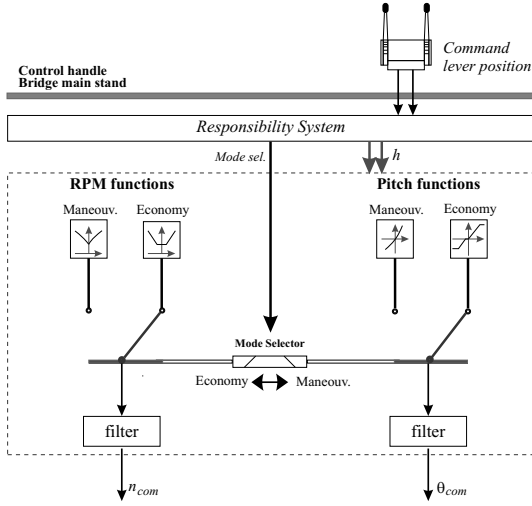


Fig. 8. Handle characteristics: the values for n_{com} and θ_{com} are dependent on the chosen mode and the handle position.

The function g has two instances. One for maneuvering, another for ocean passage (economy). Summary of signals: input is $h, (mode\ select)$, output is n_{com}, θ_{com} .

5.2.2 Diesel overload control

Diesel overload will occur if propeller torque is higher than the torque limit of the engine at a particular shaft speed. Overload is avoided by decreasing propeller load torque such that shaft speed can be increased, assuming maximum shaft speed is not yet reached. One algorithm is

$$\dot{\theta}_{corr} = \begin{cases} k_f \Delta Y & \text{if } \Delta Y \geq \epsilon, \\ \frac{k_f}{k_b} (\Delta Y - \theta_{corr}) & \text{if } \Delta Y < \epsilon \end{cases} \quad (13)$$

where $Y_m - Y_{lim}(n_m) = \Delta Y$. θ_{corr} is the correction value for propeller pitch set-point. $Y_{lim}(n_m)$ is a shaft speed dependent limit value. Values of the parameters k_f , k_b , and ϵ are given in app. B. The corrected set point for the propeller pitch is then:

$$\theta_{ref} = \theta_{com} + \theta_{corr} * \text{sign}(\theta_m)$$

Summary of signals used: input is $n_m, \theta_{com}, \theta_m, Y_m$, output is θ_{ref} .

5.2.3 Efficiency optimizer

The efficiency optimal determines the set of n and θ that achieves the desired ship speed $U_{ref} = f_{sc}(h)$ as determined by the handle position, without ship speed feedback.

Alternative 1 One controller consists of a search algorithm in n, θ minimizing the average shaft power while maintaining desired propeller thrust

$$\begin{bmatrix} \theta_{com} \\ n_{com} \end{bmatrix} = \min_{n, \theta} \{k_y Y_m n\} \quad (14)$$

with the constraints

$$T_{|n|n} \theta_{com} n_{com}^2 + T_{|n|V_a} n_{com} (1-w) U_{ref} = \frac{R(U_{ref})}{(1-t)}$$

$$n_{min} \leq n \leq n_{max} \quad \wedge \quad 0 < \theta \leq \theta_{max} \quad (15)$$

The second equation obtains constant propeller thrust, according to Eq. 7. The initial values of θ_{com} and n_{com} are taken as θ_m , respectively n_m .

Summary of signals: input is $f_{sc}(h)$ (from handle) or U_{ref} (from speed controller), Y_m, n_m , output is n_{com}, θ_{com} .

Upon failure in Y_m, n_m or θ_m measurement, the algorithm might use the command values Y, n_{com} , or θ_{com} given by $g(h)$, Eq. 12.

Alternative 2 Another solution could be to minimize the fuel index while maintaining the desired ship speed U_{ref} . The solution is found by using the steady state part of Eq. 1 and Eq. 3:

$$\min_{n, \theta} \{Y\} = \min_{n, \theta} \left\{ \frac{Q_{nn}(\theta) n^2 + Q_{nV_a}(\theta) n U_{ref} + Q_f}{k_y} \right\} \quad (16)$$

with the same constraints as before, Eq. 15.

Summary of signals: input is $f_{sc}(h)$ (from handle) or U_{ref} (from speed controller), θ_m, n_m , output is n_{com}, θ_{com} .

Alternative 3 Another approach could be to find a solution which results in the best achievable propeller efficiency η_{prop}

$$\max_{n, \theta} \{\eta_{prop}\} = \max_{n, \theta} \left\{ \frac{T_{prop}(\theta, n, U_{ref}) U_{ref}}{Q_{prop}(\theta, n, U_{ref}) n} \right\} \quad (17)$$

where the propeller trust and torque are given by Eq. 4 and Eq. 4. The constraints are, again given by Eq. 15.

Summary of signals: input is $f_{sc}(h)$ (from handle) or U_{ref} (from speed controller), θ_m, n_m , output is n_{com}, θ_{com} .

Note The three alternative algorithms above use assumed hull resistance $R(U)$ to calculate required thrust. In a real application, algorithms would estimate $R(U)$ and T_{ext} such that actual resistance was used in the optimization.

5.2.4 Ship speed control

Ship speed control aims at maintaining a set ship speed within a narrow margin of less than 0.1 kt. It is important that there is no overshoot in this controller. A simple control algorithm is employed for the benchmark:

$$\begin{aligned} U_{ref} &= f_{sc}(h) + k_U(f_{sc}(h) - U_m) + K_{IU}IU \\ \dot{I}_U &= (f_{sc}(h) - U_m)\delta_{IU} \\ \delta_{IU} &= \begin{cases} 1 & -0,5kt < f_{sc}(h) - U_m < 0,1kt \\ 0 & otherwise \end{cases} \end{aligned} \quad (18)$$

Summary of signals: input is U_m and h , output is U_{ref} .

6 A MODEL WITH TWO SHAFTS

The propulsion system, which is described in the previous sections, consists of one engine and one propeller on one shaft. The real ferry has two shafts, however. A model for this extended system is provided in (Izadi-Zamanabadi and Blanke (1998)). It has two identical engine-propeller sets, placed on starboard and port sides of the ship. The parameter modifications needed for achieving the same performance as the propulsion system with shaft is also shown in (Izadi-Zamanabadi and Blanke (1998)). The necessary modifications include change in propellers' diameter, engine gain, and nominal shaft speed. Due to extra coupling effect between propulsion sets, performing FDI and reconfiguration tasks becomes even more challenging.

7 BENCHMARK DEFINITION

7.1 Test sequence

The test sequences for the complex (and non-linear) system applied in the benchmark and time intervals for different fault events are shown in the following table. In addition the value of the measured signals in faulty situations is given in this table. The total simulation time is 3500 sec..

Event	Start time	End time
$\Delta\theta_{high}$	180s	210s
$\Delta\theta_{inc}$	800s	1700s
$\Delta\theta_{low}$	1890s	1920s
Δn_{high}	680s	710s
Δn_{low}	2640s	2670s
Δk_y	3000s	3500s

The fault Δk_y corresponds to 20% drop in the diesel engine gain k_y .

Test-sequences for the nonlinear case together with the imposed unknown inputs are shown in Fig. 9. Measured data from sea tests are shown in Fig. 10. The sea-tests do not comprise known faults.

7.2 Benchmark test

The main task is to design FDI algorithms that makes it possible to detect and isolate the faults mentioned. The algorithm should be robust to model uncertainty, load change, and external forces.

The known and measured variables are propeller pitch set-point θ_{ref} , propeller pitch measurement θ_m , shaft speed set-point n_{ref} , shaft speed measurement n_m , ship speed U_m , and the fuel index Y_m . Data is obtained by sampling every 1 sec. The additional variables provided in the data files of the benchmark are for intermediate analysis only.

7.2.1 Procedure

To make the benchmark test uniform, the following strategy is recommended.

1. Fault detection and isolation:
 - (a) Design FDI.
 - (b) Test with data set generated by non-linear model.
2. Re-configuration
 - (a) Design controller re-configurations for the different faults
 - (b) Design supervisor logics and implement a running system
3. Test and validation
 - (a) Test against supplied data from sea tests (without faults) to verify robustness
 - (b) Test against supplied data from the non-linear simulation

7.2.2 Reporting

Reporting should include objective measures of performance:

1. The FDI part of the benchmark

- (a) Time to detect a fault using simulated sequences
 - (b) False detection rate using sea test data
 - (c) Missed detection rate for simulated sequences (if any)
 - (d) Time to re-configure a controller after a fault is detected
 - (e) Performance characteristics of re-configured controls
 - (f) Computational complexity for methods
2. The re-configuration part
- (a) Investigate re-configuration possibilities for each fault
 - (b) Investigate re-configuration means:
 - i. estimate faulty signal from redundant information
 - ii. alternative control method to avoid use of faulty signal/part
 - iii. alternative control with reduced performance
 - iv. alter the services offered, e.g. by fall-back to lower level control
3. Design the logic and a software architecture to implement the fault-tolerant solution

Contributions to the benchmark could be limited to cover only the non-linear FDI part, the re-configuration part, or the software architecture.

The authors will be pleased to receive communication about results and will make a WWW page for interchange of results and contacts.

8 SUMMARY

A propulsion system consisting of two control loops is presented as a benchmark example. The system has a simple dynamics but has nonlinear characteristics. The control consists of coupled loops (shaft speed and propeller pitch) and coordinated control gives several possibilities for controller re-configuration when faults occur. These characteristics are very common in many industrial processes and the ship problem is interesting in its own right as an object for fault-tolerant control. Efficient accommodation of faults in this system could contribute to enhance maritime safety.

The paper provided a complete, nonlinear description of the system. It should therefore be possible to design and compare all elements of fault-tolerant control: from FDI design over controller re-configuration to state-event logics and implementation of supervisor functions.

The benchmark includes data sequences which enable comparison of different approaches.

Interested readers can down-load a benchmark kit consisting of:

- *A linear model for the propulsion system with one engine and one propeller written in SIMULINK®.*
- *Nonlinear models for the propulsion system with 1 engine + 1 propeller and correspondingly 2 engines + 2 propellers written in SIMULINK®.*
- *A set of simulated data sequences described above.*
- *Measured data from tests at sea.*

The kit can be acquired from the WWW address:

www.control.auc.dk/~blanke/FTC/home.html

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Appendix A. SHIP DATA

The benchmark in this paper is a model of the propulsion system (with one engine + one propeller) for a ferry with a length of 147.2 m and a displacement of 12.840 m³ (fully loaded) and the following data:

Par.	Value	Description	Unit
I_m	0.25·10 ⁶	inertia	kg m ²
m	13.282	weight (fully loaded)	tons
m	10.359	weight (unloaded)	tons
D	6.123	Propeller diameter	m
ρ	1025	Water density	kg/ m ³
N	6	Number of cylinder	-
k_t	0.15	pitch angle control gain	-
k_y	1.137·10 ⁶	engine gain	Nm
k_r	0.2211	governor gain	rad ⁻¹ s
K	226	Anti-Windup gain	-
τ_i	5	time cons. in the PI	s
U_{\max}	9.7	max. ship speed	m/s
n_{\max}	120	max. shaft speed	RPM
$V_{a,\max}$	8.54	max. advanced speed	m/s
$Q_{\text{eng},\max}$	1137	max. torque (motor)	kNm
$T_{\text{prop},\max}$	889.8	max. developed thrust	kN
$Q_{\text{prop},\max}$	1063	max. developed torque	kNm
$X_{\dot{U}}$	0	added mass in surge	kg

Appendix B. LIMITS IN VARIABLES

The values of parameters for saturation in the model are:

Par.	Value	Description	Unit
$\dot{\theta}_{\max}$	0.2	max limit on pitch rate	-
$\dot{\theta}_{\min}$	-0.2	min limit on pitch angle	-
θ_{\max}	1	max limit on pitch angle	-
θ_{\min}	-0.7	min limit on pitch angle	-
$n_{\max,a}$	120	max allowed shaft speed.	RPM
Y_{lb}	0	lower bound for fuel index	-
Y_{ub}	1	upper bound for fuel index	-
k_f	0.05	gain in overload controller	-
k_b	1	gain in overload controller	-
ϵ	0.05	threshold in overload contr.	-

Disturbances

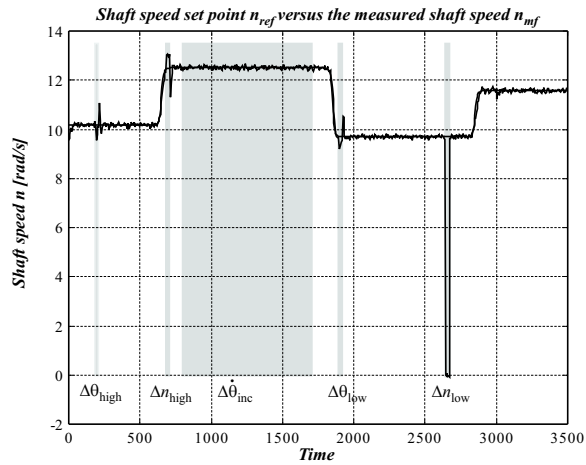
The following two disturbance sources are considered:

Source	Name	Value
Q_f	friction torque	0.05 * $Q_{\text{eng},\max}$
T_{ext}	external force	0.1 * T_{\max}

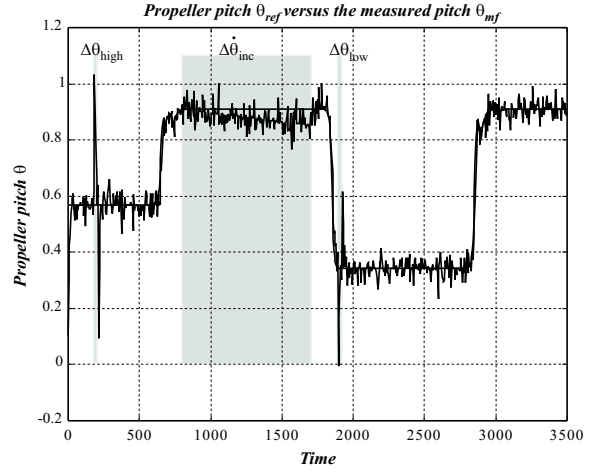
Noise

Measurement noise is considered to be Gaussian white noise with zero mean. The following table shows the signals with which the generated noise with given standard deviation are added:

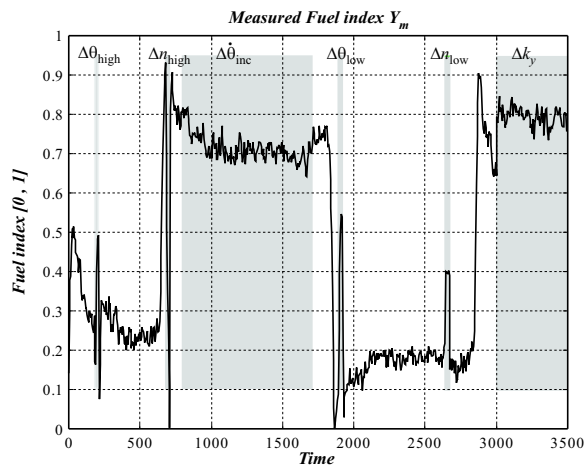
Signal	Name	Standard deviation
ν_U	ship speed	0.01 * U_{\max} (9.7m/s)
ν_n	shaft speed	0.005 * n_{\max} (124RPM)
ν_θ	propeller pitch	0.0425 * θ_{\max} (1)
ν_Y	fuel index	0.005 * Y_{\max} (1)



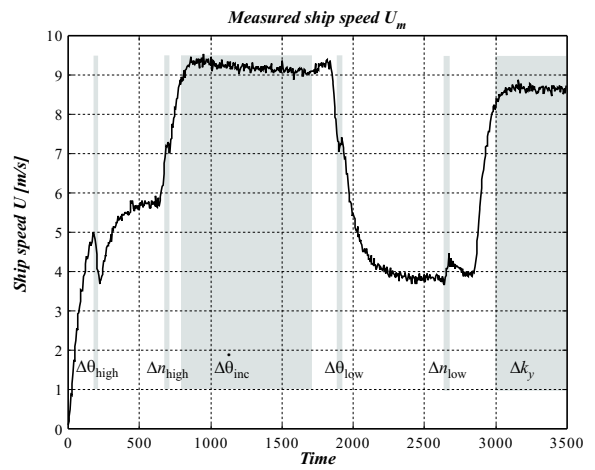
(a) Measured shaft speed n_m



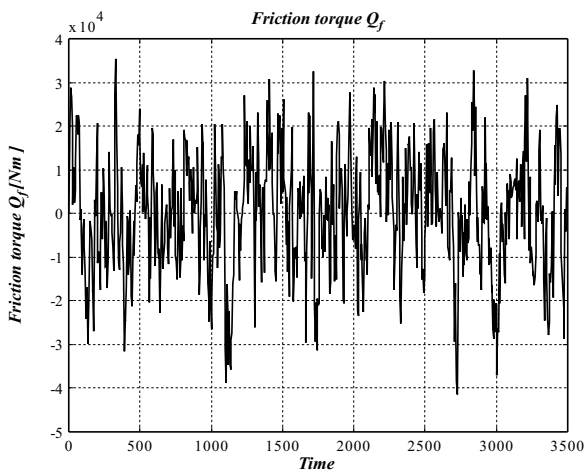
(b) Measured propeller pitch θ_m



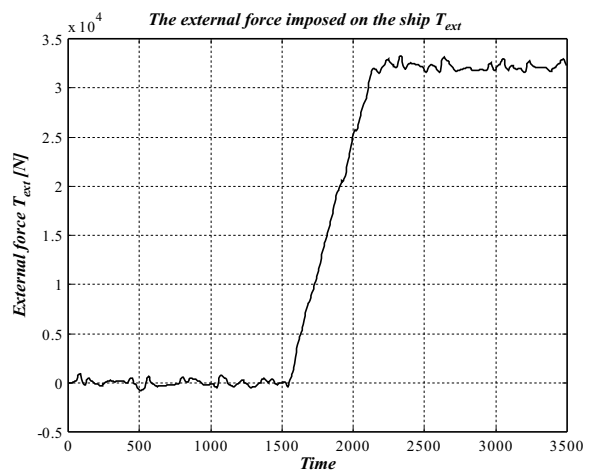
(c) Measured fuel index Y_m



(d) Measured ship speed U_m

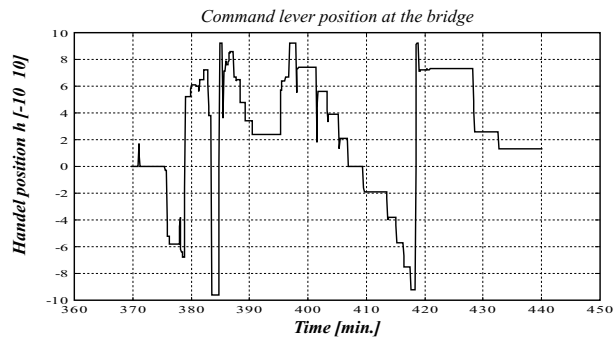


(e) Friction torque Q_f

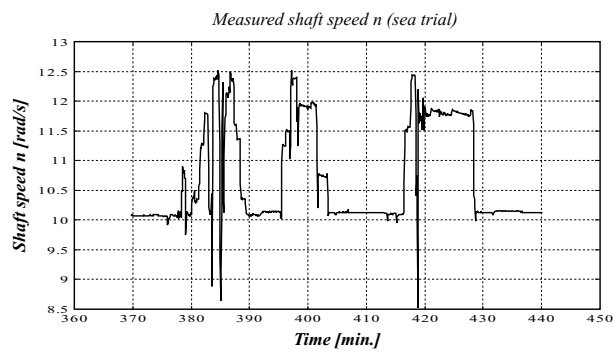


(f) External force T_{ext}

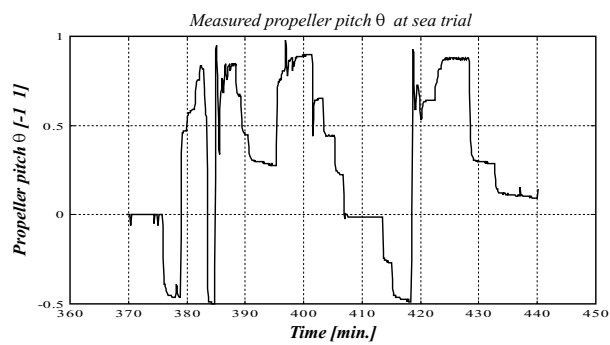
Fig. 9. Simulation data for the benchmark with faults as described in the fault scenario.



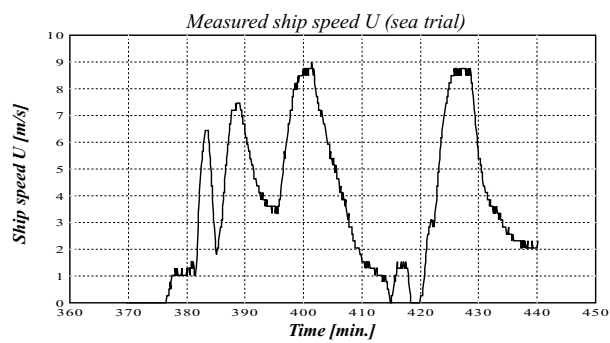
a) Handel position at the bridge (sea trial)



b) Measured shaft speed n_m (sea trial)



c) Measured propeller pitch θ_m (sea trial)



d) Measured ship speed U_m (sea trial)

Fig. 10. Data from sea trial without faults.