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Marine Performance Surveillance with a Personal Computer

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1 Introduction

A good insight of the ship’s captain into the behaviour and the performance of his ship is necessary to improve fuel economy. A system is described here to give him an insight into this performance and to assist him when making operational decisions with regard to fuel consumption. A real-time monitoring device presents information on actual time-averaged performance data, such as propeller pitch and rpm, ship speed, delivered engine power and fuel consumption. For this, reliable sensors are necessary.

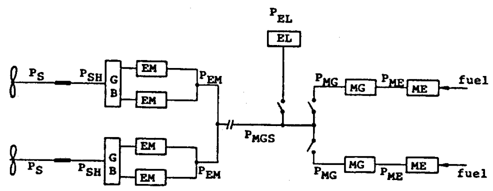
A mathematical model has been designed to predict the ship's performance on a personal computer. The model has calculation and plot modules for a given ship status and environment. In addition there is a voyage-planning module, which takes into account the different expected environmental conditions during a voyage. Trim, heading and speed can be changed to find an optimal performance with regard to fuel consumption.

The coefficients in the mathematical model are derived from external computer programs, model experiments and statistical information. Monitored data will be used to adjust some coefficients. Together with the monitoring device fouling of the ship’s hull and the propellers can be guarded too.

This system was originally designed for and placed on a Dutch container vessel, a project financed by the Foundation for Co-ordination of Maritime Research in the Netherlands, see Journée (1984). Because of very poor qualities for this purpose of the ship's sensors, the capability of the system could not be proven.

Nevertheless Wijsmuller Engineering believed in the possibilities of the system. They paid a lot of attention to the requirements of the different sensors and a new system was designed, see Verleg (1986). Wijsmuller Engineering made MV

MIGHTY SERVANT 3 available to test the capabilities of the new system during comprehensive trials, see Figure 1.



GB gear box.
EM electro motor.
EL electric system of ship.
MG main generator.
ME main engine.
nme number of main engines in use.

P_S mechanical power at the propeller.
P_{SH} mechanical power at the propellershaft.
P_{EM} electric power input to electro motors.
P_{MGS} electric power output of main generators for propulsion.
P_{EL} electric power output of main generators for electric system.
P_{MG} electric power output of main generator.
P_{ME} mechanical power output of main engine

Figure 1 Scheme of Propulsion Plant

Now, the sensors fulfil the requirements. The results of the calculation module are very accurate, at least in calm to moderate weather. In more severe weather the accuracy of the predictions can be influenced by the reliability of the observed or forecasted weather data.

This performance surveillance system, called PERSUS, can be used in every IBM-compatible personal computer with a mathematical coprocessor and a monochrome screen. The calculation module (288 Kbytes of memory), with plot and voyage planning facilities, can also be used on-shore.

This paper describes the system and the mathematical model. Results of full-scale trials and owner’s conclusions about the system are given too.

2 Performance Surveillance System

The fuel consumption per sailed mile is used as a performance index: ltr/wnm (liter per water nautical mile) or ltr/gnm (liter per ground nautical mile).

Besides by wind, waves and currents this performance index is influenced by trim, heading, and speed of the ship, pitch and rpm of propellers, the delivered power and fuel consumption of the main engines and the condition of hull and propellers.

In a seaway these phenomena vary with the time. Short and long periodic fluctuations can be distinguished. Short periodic fluctuations are caused by the dynamic behaviour of wind and waves. The changing average environment on the ship’s route and new settings of the ship, propeller or engine causes long periodic fluctuations. To get a good insight into the ship’s performance these phenomena should be presented on a time-base without the short periodic fluctuations. Average values during for instance 20 minutes have to be monitored.

With such a real-time monitoring device one can get insight into the effect of changing speed, heading, trim, etc. on fuel consumption. However, a disadvantage is that first action should be taken and after at least one time interval the effect can be judged. It is obvious that a reliable prediction, before any action has been taken, will be preferred.

For this purpose a calculation module has been designed. The mathematical model and its physical background are based on advanced hydrodynamic knowledge. Allowance is made for using monitored data to determine and adjust some coefficients in the mathematical model. This results into a module that translates as good as possible all environmental information into data related to fuel consumption and economics of the ship.

This accurate "predictive" calculation module can be used to give insight into the performance of the ship by means of graphs, trim optimisations, voyage planning, etc. Together with the monitoring module it can be used to judge fouling of the ship's hull and propellers.

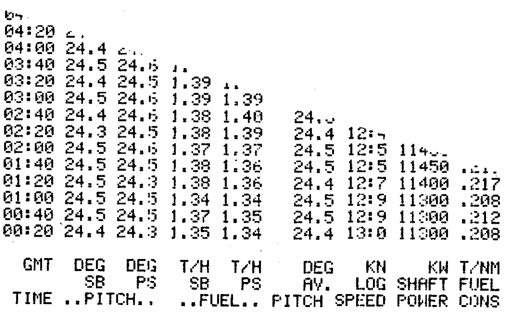
2.1 Monitoring Module

The sensor package for real time monitoring requires at least:

- propeller pitch meter(s), if Controllable Pitch Propeller (C.P.P.),
- rpm meter(s) at the propeller shaft(s),
- E.M. speed log (water speed),
- torque meter(s) at the propeller shaft(s) and
- fuel consumption meter(s) at the main engine(s).

This sensor package is determined by the fact that the system uses sophisticated methods for calculations, tuning after installation and surveillance of the condition of hull, propellers, engines and quality of fuel.

It may be clear that high demands are made on the reliability of these sensors. In particular the reproducibility of the sensors under all circumstances with respect to temperature, humidity, dirt and vibrations is very important. The repeatability should be better than 99%. A constant deviation can be corrected when calibrating the signals in the monitoring module. The calculation module will be tuned a short time after installation. Later decline of the signals will be translated into a changed performance of the ship.



GMT TIME	DEG SB ..PITCH..	DEG PS	T/H SB ..FUEL..	T/H PS	DEG AV. PITCH	KN LOG SPEED	KW SHAFT POWER	T/NM FUEL CONS
[illegible]								
04:20	[illegible]							
04:00	24.4	[illegible]						
03:40	24.5	24.6	[illegible]					
03:20	24.4	24.5	1.39	[illegible]				
03:00	24.5	24.6	1.39	1.39				
02:40	24.4	24.6	1.38	1.40	[illegible]			
02:20	24.3	24.5	1.38	1.39	24.4	[illegible]		
02:00	24.5	24.6	1.37	1.37	24.5	12:5	[illegible]	
01:40	24.5	24.5	1.38	1.36	24.5	12:5	11450	[illegible]
01:20	24.5	24.3	1.38	1.36	24.4	12:7	11400	.217
01:00	24.5	24.5	1.34	1.34	24.5	12:9	11300	.208
00:40	24.5	24.5	1.37	1.35	24.5	12:9	11300	.212
00:20	24.4	24.3	1.35	1.34	24.4	13:0	11300	.208

Figure 2 Registration Output

The following values are presented, optional on screen or paper-tape (reference to example in Figure 2):

- rpm, if F.P.P. (Fixed Pitch Propeller),
- pitch (degrees), if C.P.P. (Controllable Pitch Propeller),
- water speed (knots),
- power (kW),
- fuel consumption (m^3/hour),
- specific fuel consumption (ltr/kWh) and
- performance index (ltr/mile).

In case of one or two propellers or one or two engines the presentation of the separate and/or total values to match are optional.

2.2 Calculation Module

A calculation module has been designed to simulate the performance of the ship as accurate as possible. Required input data are:

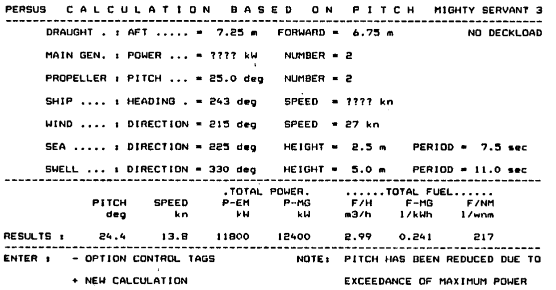
- ship's loading, defined by draft aft and forward,
- number of active main generators or engines,
- number of active propellers,
- ship's heading
- true wind, defined by direction and speed and
- sea and swell, each defined by main direction, significant wave height and average wave period.

With an input of the pitch of the propellers) this module calculates:

- a maximum acceptable pitch, if the maximum power will be exceeded,
- the ship's speed,
- the mechanical power at the propeller shaft(s),
- the (electric) power output of the main generator(s) or engine(s),
- the fuel consumption per hour of the main engine(s),
- the specific fuel consumption of the engine-generator system and

- the performance index of the ship: fuel consumption per mile through the water.

An example of a display view is given in Figure 3.


PERSUS   C A L C U L A T I O N   B A S E D   O N   P I T C H   MIGHTY SERVANT 3

DRAUGHT . : AFT ..... = 7.25 m   FORWARD = 6.75 m   NO DECKLOAD

MAIN GEN. : POWER ... = ???? kW   NUMBER = 2

PROPELLER : PITCH ... = 25.0 deg   NUMBER = 2

SHIP .... : HEADING . = 243 deg   SPEED = ???? kn

WIND .... : DIRECTION = 215 deg   SPEED = 27 kn

SEA ..... : DIRECTION = 225 deg   HEIGHT = 2.5 m   PERIOD = 7.5 sec

SWELL ... : DIRECTION = 330 deg   HEIGHT = 5.0 m   PERIOD = 11.0 sec

	PITCH deg	SPEED kn	.TOTAL POWER. P-EM kW	P-MG kW	......TOTAL FUEL...... F/H m3/h	F-MG l/kWh	F/NM l/wnm
RESULTS :	24.4	13.8	11800	12400	2.99	0.241	217

ENTER : - OPTION CONTROL TAGS   NOTE: PITCH HAS BEEN REDUCED DUE TO

+ NEW CALCULATION   EXCEEDANCE OF MAXIMUM POWER

Figure 3 Calculation Based on Pitch

It is also possible to perform these calculations based on the ship's speed or on the electric power output of the main generator(s).

The theoretical background is described in appendix I. To get accurate predictions, trial results were used to adjust some coefficients in the mathematical module. This is described in appendix II. Fouling of the ship's hull and propellers, changed quality of fuel and additional wind resistance of the deck load can also be taken into account, see appendix III.

2.3 Other Facilities

The calculation module gives insight into the performance of the ship by means of graphic displays. Also it is possible to make a voyage planning based on weather forecasts, climatological weather information and current information.

Performance Based on Speed

Speed has a large influence on the fuel consumption performance of a ship. An example is given in Figure 4.

The figure shows that too low speeds result in a bad performance. In this example minimum fuel consumption is found at about 60% of the service speed.

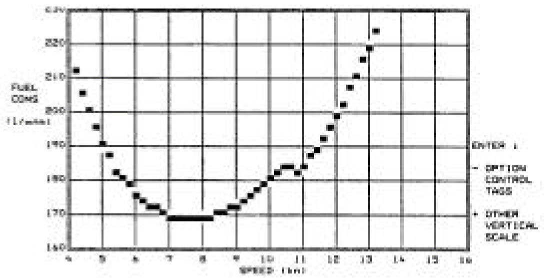


Figure 4 Fuel Consumption Based on Speed

Accounting for the electric - from the main generators for the electric system of the ship at lower power outputs of the main engines - power causes the jump in the figure. Also the figure shows that a constant speed at these environmental conditions will give a better performance than sailing partly with a low speed and partly with a high speed.

Performance Based on Heading

A change of heading will change the directions of wind, sea and swell, relative to the ship. An example of a display output is given in Figure 5.

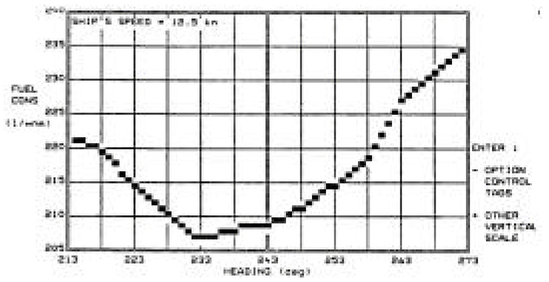


Figure 5 Fuel Consumption Based on Heading

Performance Based on Trim

Trim can have a large influence on the fuel consumption performance of the ship. An optimum trim saves fuel without any additional costs. An example of a display output is given in Figure 6.

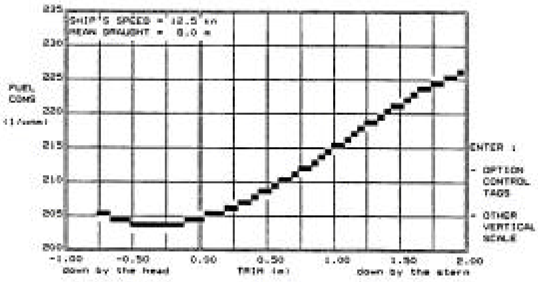


Figure 6 Fuel Consumption Based on Trim

Effect of Fouling

During the life time of the ship fouling of the hull and propeller, expressed in coefficients, will increase the performance index. This can be displayed as a function of the ship's speed, see Figure 7.

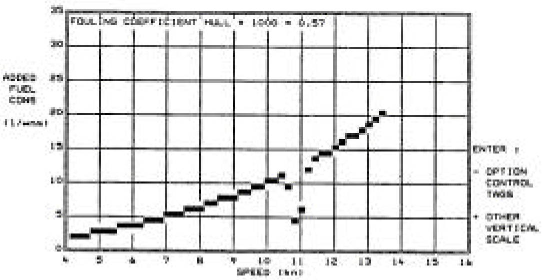


Figure 7 Added Fuel Consumption due to Fouling

The dip in the curve vis caused by the calculated power delivered to the ship's electric system.

Voyage Planning

The calculation module is used for making voyage planning too. Five voyages can be studied simultaneously. Each route can be divided into tracks between start and destination. This can be done manually or automatically for great circle or rhumb line navigation.

On each track manual input is required of:

- current: direction and speed,
- wind: direction and speed,
- sea: direction, height and period and
- swell: direction, height and period.

These data are assumed to be constant on each track and can be updated during the voyage.

Two different types of calculation are possible:

- calculation of an estimated time of arrival with a given constant pitch, speed or power and
- calculation of a constant pitch, speed or power with a required time of arrival.

At each track the program shows:

- date and time at the end of the track,
- distance, course and speed over ground,
- course and speed through the water,
- pitch of the propellers,
- electric power output of the main generators and
- performance index and fuel consumption.

Overall values are presented of:

- the total distance to sail
- the average ground speed and water speed
- the average performance index
- the total fuel consumption.

NR	..LAT..	..LONG..	CURRENT deg	CURRENT kn	.WIND. deg	.WIND. kn	.....SEA..... deg	.....SEA..... m	.....SEA..... sec	....SWELL.... deg	....SWELL.... m	....SWELL.... sec
01	50°00'N	005°40'W										
			070	2.0	270	15	280	2.5	6.5	320	2.0	9.0
02	48°32'N	011°03'W										
			100	2.0	260	17	270	3.0	7.0	330	2.0	9.0
03	46°51'N	016°07'W										
			110	1.5	260	21	260	3.0	7.0	340	2.5	10.0
04	44°56'N	020°51'W										
			120	1.5	250	25	255	3.5	8.0	340	3.0	11.0
05	42°51'N	025°16'W										
			130	1.5	250	27	250	4.0	8.0	350	3.0	11.0
06	40°37'N	029°23'W										
			140	1.5	240	30	250	4.0	8.0	350	3.0	11.0
07	38°14'N	033°13'W										
			150	1.0	240	35	250	5.0	9.0	000	2.5	10.0
08	35°44'N	036°48'W										
			160	1.0	240	35	240	5.0	9.0	000	2.5	10.0
09	33°08'N	040°11'W										
			170	1.0	250	25	250	3.5	8.0	010	2.0	9.0
10	30°27'N	043°21'W										
			180	1.0	260	20	260	3.0	7.0	010	2.0	9.0

NR	..LAT..	..LONG..	CURRENT deg	CURRENT kn	.WIND. deg	.WIND. kn	.....SEA..... deg	.....SEA..... m	.....SEA..... sec	....SWELL.... deg	....SWELL.... m	....SWELL.... sec
11	27°42'N	046°21'W										
			190	1.5	270	20	260	3.0	7.0	020	2.0	9.0
12	24°52'N	049°12'W										
			200	1.5	280	15	270	2.5	6.0	020	2.0	9.0
13	22°00'N	051°55'W										
			210	1.5	290	15	280	2.5	6.0	030	1.0	7.0
14	19°06'N	054°32'W										
			220	1.5	300	15	300	2.0	5.0	030	1.0	7.0
15	16°09'N	057°03'W										
			230	2.0	310	15	310	2.0	5.0	040	1.0	7.0
16	13°10'N	059°30'W										
17	° 'N	° 'E										
18	° 'N	° 'E										
19	° 'N	° 'E										
20	° 'N	° 'E										

Input data of tracks

NR	..DATE.. gmt	TIME gmt	.....GROUND..... DIST gnm	CRS deg	SPEED kn	..WATER.. CRS deg	SPEED kn	...TOTAL PROPULSION... PITCH deg	P-MG kW	FUEL l/gnm	FUEL m3
01	12-05-87	17:00									
			228	247	11.8	251	13.7	24.0	11700	239	55
02	13-05-87	12:21									
			228	244	11.6	249	13.3	24.0	11800	245	56
03	14-05-87	07:59									
			229	240	12.1	245	13.1	24.0	11850	236	54
04	15-05-87	02:50									
			228	237	11.8	243	12.5	24.0	12050	246	56
05	15-05-87	22:12									
			228	234	11.6	241	12.1	24.0	12200	252	57
06	16-05-87	17:45									
			228	231	11.6	239	11.7	24.0	12300	255	58
07	17-05-87	13:23									
			228	229	11.0	234	10.9	23.9	12400	271	62
08	18-05-87	10:06									
			229	227	11.2	232	10.8	23.9	12400	266	61
09	19-05-87	06:32									
			228	225	13.2	229	12.7	24.0	12000	218	50
10	19-05-87	23:46									
			228	224	14.0	227	13.3	24.0	11800	204	46

NR	..DATE.. gmt	TIME gmt	.....GROUND..... DIST gnm	CRS deg	SPEED kn	..WATER.. CRS deg	SPEED kn	...TOTAL PROPULSION... PITCH deg	P-MG kW	FUEL l/gnm	FUEL m3
11	20-05-87	16:05									
			229	222	14.5	225	13.3	24.0	11800	196	45
12	21-05-87	07:51									
			228	221	15.3	223	13.9	24.0	11600	183	42
13	21-05-87	22:46									
			228	220	15.5	221	14.0	24.0	11550	180	41
14	22-05-87	13:28									
			228	219	15.7	219	14.2	24.0	11500	176	40
15	23-05-87	03:57									
			229	218	16.3	217	14.4	24.0	11450	169	39
16	23-05-87	17:57									
	total/average:		3423		12.9		12.8			222	762

Calculation of E.T.A. with a constant pitch (24^{o})

NR	..DATE.. gmt	TIME gmt	.....GROUND..... DIST gnm	CRS deg	SPEED kn	..WATER.. CRS deg	SPEED kn	...TOTAL PROPULSION... PITCH deg	P-MG kW	FUEL l/gnm	FUEL m3
01	12-05-87	17:00									
			228	247	11.0	251	12.9	22.5	10000	221	50
02	13-05-87	13:46									
			228	244	10.8	249	12.4	22.5	10150	228	52
03	14-05-87	10:58									
			229	240	11.3	245	12.3	22.5	10200	219	50
04	15-05-87	07:16									
			228	237	10.9	243	11.7	22.5	10350	230	52
05	16-05-87	04:10									
			228	234	10.7	241	11.2	22.5	10500	236	54
06	17-05-87	01:22									
			228	231	10.7	239	10.8	22.5	10600	239	55
07	17-05-87	22:42									
			228	229	10.1	235	10.0	22.5	10800	258	59
08	18-05-87	21:14									
			229	227	10.3	232	10.0	22.5	10800	253	58
09	19-05-87	19:25									
			228	225	12.4	229	11.8	22.5	10300	202	46
10	20-05-87	13:50									
			228	224	13.1	227	12.4	22.5	10150	187	43

NR	..DATE.. gmt	TIME gmt	.....GROUND..... DIST gnm	CRS deg	SPEED kn	..WATER.. CRS deg	SPEED kn	...TOTAL PROPULSION... PITCH deg	P-MG kW	FUEL l/gnm	FUEL m3
11	21-05-87	07:12									
			229	222	13.7	226	12.4	22.5	10150	180	41
12	21-05-87	23:57									
			228	221	14.5	223	13.1	22.5	9950	166	38
13	22-05-87	15:41									
			228	220	14.7	221	13.2	22.5	9900	163	37
14	23-05-87	07:09									
			228	219	15.0	219	13.5	22.5	9800	159	36
15	23-05-87	22:21									
			229	218	15.6	217	13.7	22.5	9750	152	35
16	24-05-87	13:00									
	total/average:		3423		12.1		12.0			206	706

Calculation of constant pitch with a required time of arrival (13.00)

Figure 8 Voyage Planning from Land's End to Barbados

Figure 8 gives voyage planning with a constant pitch and a required time of arrival. The calculations show, among others, the influence of the sailing time on the fuel consumption

3 Full Scale Trials with MV MIGHTY SERVANT 3

Comprehensive trials have been carried out with MV MIGHTY SERVANT 3. All sensors have been tested and calibrated without problems. The ship was unloaded and 16 draft-trim combinations with a range of speeds in calm beam to following seas could be sailed. About 150 runs were used to check and to improve the mathematical model and to determine coefficients. Theseresult in a calculation module that fits all measured data during the trials within the accuracy of the measurements itself. An example is given in Figure 9. From these experiments was concluded that on another ship far less trials are necessary to determine all coefficients accurately.

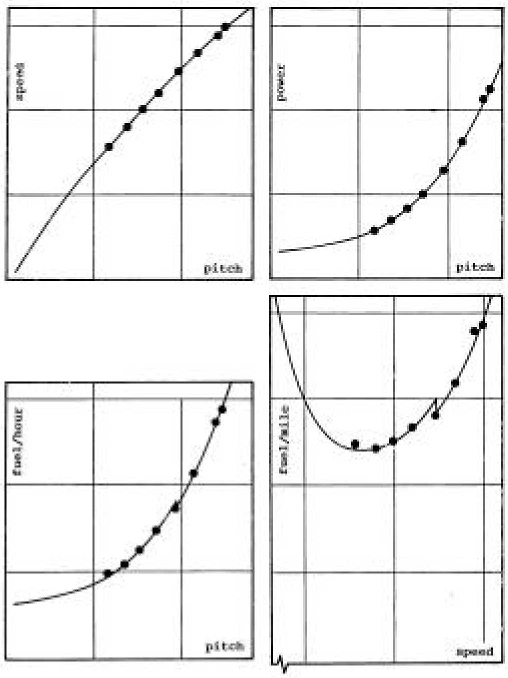


Figure 9 Measured and Calculated Data of MV MIGHTY SERVANT 3 in Calm Water

Two remarkable results of the trials are shown here.
Figure 10 shows a composed display of the effect of draft and trim on fuel consumption. The remarkable effect of the

draft aft is caused by the shape of the aft body of the ship.

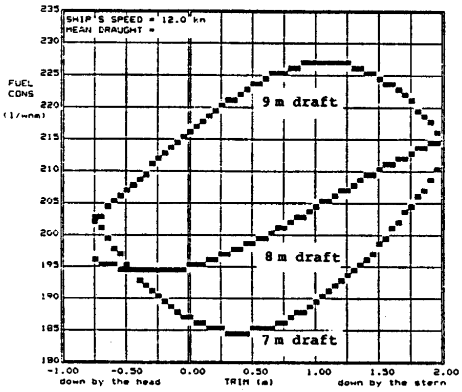


Figure 10 Fuel Consumption Based on Displacement

Figure 11 shows a composed display of an accurate hind-cast of sailed trials with one and two active propellers in oblique calm to moderate waves.

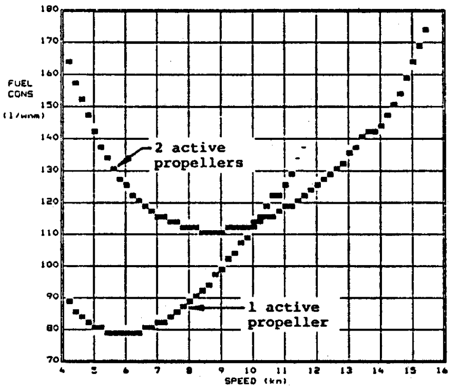


Figure 11 Fuel Consumption with 1 and 2 Active Propellers

At low speeds much lower fuel consumption can be achieved with one active propeller. In spite of a higher resistance caused by the free-running propeller (about 40% of the still water resistance) and a lower relative rotative efficiency of the active propeller (about 5%), the higher pitch of the active propeller results in a much better propulsion efficiency at lower speeds. A free running propeller is possible in case of a diesel electric power plant. At higher readings of the propellers in head waves this effect will decrease.

Only one experiment could he carried out in higher confused head waves of about 5 meters, with a measured ship speed of 4.1 knots. The hind-casted speed dropped from 10.2 knots in still water to 3.7 knots in these estimated wave conditions. A fuel consumption of 1.34 m3/h was measured while 1.16 m3/h was calculated, caused by too low a calculated power in the low speed ratio of the propellers. This aspect needs further investigations.

4 Conclusion of Ship's Owner

The ship's owner, from on-board operational experience with PERSUS, concluded the following:

- The sensors and data acquisition system produce good and reliable mean values, suitable for processing and to judge and improve the performance of the ship.
- The calculation module proved to be very useful on-board, for voyage planning but also for post- processing.
- Pay back periods of such a system is expected to be about one year but will depend on actual efficiency of the operations.
- In off-design conditions up to 50% reduced fuel consumption was found. For an average on long-term up to 15% reduction (reference to Figure 11) can be claimed.
- The management on-board gets better insight into the performance of the ship and the actual efficiency of the operations.
- It is essential to carefully introduce this type of systems: arrange training, supply documentation, clearly indicate possibilities and constraints.

For future work is recommended:

- Development of routines to estimate wind resistance of deck-cargo (initi-ated).

- Development of routines for data storage and automatic voyage post-processing (initiated).
- Implementation in on-board management assisting systems (initiated).
- Further investigations on overloaded C.P.P.'s and behaviour in severe weather.
- Research on variable rpm, C.P.P. or F.P.P., voluntary speed reduction, motions.
- Research on data banks for climatological data and a coupling of this information to the system (initiated).
- Research on coupling with navigation systems (initiated).
- Research on better observation techniques for environmental conditions.
- Further research in recently developed sensors (continuous).

The ship's owner hopes to continue further developments with the Delft University of Technology and with Wärsilä Information Systems, Turku. There is a wide field for applications of expert systems in marine environment.

5 References

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APPENDIX I: Mathematical Model

At a given pitch and rpm of the propellers, loading of the ship, wind and waves, the speed of the ship can be derived from the following equation of equilibrium:

$$R_{ship}(V) = R_{prop}(V)$$

in which R_{ship} is total resistance of the ship, R_{prop} is the resistance that can be gained by the thrust of the propellers and V is the ship's speed through the water.
The total resistance can be split into:

- the still water resistance R_{sw} ,
- the wind resistance R_w and
- the added resistance caused by the irregular waves, split into two ideal systems: R_z (sea) and R_d (swell).

Other contributions, for instance due to rudder motions, are assumed to be relatively small and consequently ignored.

The resistance that can be gained by the propellers follows from pitch, rpm, thrust characteristics of the propellers and the wake behind the ship.

Still Water Resistance

The still water resistance is expressed in a resistance coefficient:

$$C_{sw} = \frac{R_{sw}}{\frac{1}{2} r \cdot V^2 \cdot S}$$

with R_{sw} is still water resistance, r is density of sea water and S is wetted surface of the hull.

The wetted surface as a function of the amidships draft T_m of the ship is given by:

$$S = s_0 + s_1 \cdot T_m + s_2 \cdot T_m^{\ 2}$$

The coefficients have to be derived in the normal draft range of the ship. The effect of trim is ignored.

The still water resistance coefficient consists of three parts:

$$C_{sw} = C_f + \Delta C_f + C_r$$

in which C_f is the frictional resistance coefficient, ΔC_f is the fouling coefficient and C_r is the residuary resistance coefficient.

The frictional resistance coefficient is defined according to the I.T.T.C. formulation:

$$C_f = \frac{0.075}{\left({}^{10}\log(Rn) - 2\right)^2} \quad \text{with: } Rn = \frac{V \cdot L}{n}$$

where Rn is Reynolds number, L is ship's length and n is kinematic viscosity of sea water.

The determination of the fouling coefficient of the hull ΔC_f will be explained in appendix III and is assumed to be zero here in this "new" condition of the ship.

The residuary resistance coefficient C_r is depending on the amidships draft, the trim and the speed.

A third degree polynomial expression is used:

$$\begin{aligned} C_r = {} & r_{000} + r_{111} \cdot T_m \cdot tr \cdot V + \\ & r_{100} \cdot T_m + r_{200} \cdot T_m^{\ 2} + r_{300} \cdot T_m^{\ 2} + \\ & r_{010} \cdot tr + r_{020} \cdot tr^2 + r_{030} \cdot tr^3 + \\ & r_{001} \cdot V + r_{002} \cdot V^2 + r_{003} \cdot V^3 + \\ & r_{110} \cdot T_m \cdot tr + r_{210} \cdot T_m^{\ 2} \cdot tr + r_{120} \cdot T_m \cdot tr^2 + \\ & r_{101} \cdot T_m \cdot V + r_{201} \cdot T_m^{\ 2} \cdot V + r_{102} \cdot T_m \cdot V^2 + \\ & r_{011} \cdot tr \cdot V + r_{021} \cdot tr^2 \cdot V + r_{012} \cdot tr \cdot V^2 \end{aligned}$$

The coefficients can be derived from information such as empirical methods, model experiments or full-scale trials, by means of a least squares method. Appendix II describes the determination of these coefficients from full-scale trials.

Wind Resistance

$$R_w = C_w \cdot \frac{1}{2} r_{air} \cdot V_R^{\ 2} \cdot A_t$$

where C_w is wind resistance coefficient, r_{air} is density of air, V_R is relative wind speed and A_t is transverse projected wind area.

If no interaction is assumed between ship (index s) and deck load (index l), it can be written:

$$C_w \cdot A_t = C_{ws} \cdot A_{ts} + C_{wl} \cdot A_{tl}$$

The transverse projected area of the deck load A_{tl} is a constant value and the transverse projected wind area of the ship is approximated by:

$$A_{ts} = a_0 + a_1 \cdot T_m$$

The wind resistance coefficients are depending on the angle of attack a_r of the relative wind, derived from heading and speed of ship and true wind.

For a ship without deck load the relation between C_{ws} and a_r can be derived for an average draft from empirical methods like for instance given by Isherwood (1973). This relation can be approximated fairly by seven discrete points and a linear interpolation. For the variable deck load in general no experimental information is available. Standard methods (e.g. from Classification Authorities) for estimations can be used.

Added Resistance due to Waves

Ship motions in waves lead to a transport of energy from the ship to the surrounding water and an added resistance has to be gained to maintain the ship's speed. Based on hydrodynamic knowledge it is assumed that in practice only vertical ship motions have to be considered. The time-averaged added resistance in irregular waves follows from the transfer function of the added resistance and the energy density function of the irregular waves.

Here the transfer function of the added resistance will be calculated by the radiated energy method of Gerritsma and Beukelman (1972) for head to beam waves and the integrated pressure method of Boese (1970) for beam to following waves. A combination of these two methods leads to fair good results.

The irregular waves are supposed to consist of two separate ideal systems:

- a sea, defined by a Bretschneider frequency distribution of the energy of the waves with a cosine-squared directional spreading (index z) and
- a swell, defined by a Bretschneider frequency distribution of the energy of the uni-directional waves (index d).

With these two wave systems the added resistance due to a sea (R_z) and due to a swell (R_d) can be calculated for each loading, speed and heading of the ship. The wave systems are defined by a main wave direction (m_z resp. m_d), a significant wave height (H_z resp. H_d) and an average wave period (T_z resp. T_d).

Because these calculations take too much on-line computing time, they will be performed by a separate computer program, named ADDRES as given by Journée (1984), and the results will be implemented in an added resistance calculation routine.

For an amidships draft T_m, zero trim $tr = 0$, speed V and main wave direction m_z and/or m_d, ADDRES calculates:

- $R_z / H_z{}^2$ as a function of T_z
- $R_d / H_d{}^2$ as a function of T_d

To minimise the amount of data, these functions are approximated by:

$$R_{z,d} / H_{z,d}{}^2 = \max\left\{0, \min\begin{pmatrix} a_{z,d} + b_{z,d} \cdot T_{z,d} \\ c_{z,d} + d_{z,d} \cdot T_{z,d} \end{pmatrix}\right\}$$

The coefficients are calculated for a range of magnitudes; for instance 3 amidships drafts with even keel, 4 speeds and 10 mean wave directions.

In this way the added resistance due to sea and swell is, together with an interpolation method, known by only 960 values.

Thrust

The resistance that can be gained by the thrust of the propellers is given by:

$$R_{prop} = z \cdot T \cdot (1 - t)$$

in which z is number of propellers, T is thrust of one propeller and t is thrust deduction fraction.

Thrust T follows from the thrust coefficient K_T:

$$T = K_T \cdot r \cdot D^4 \cdot n^2$$

in which D is diameter of propeller and n is rps of propeller.

The thrust coefficient of a controllable pitch propeller is depending on the pitch p and the speed J, defined by:

$$J = \frac{V \cdot (1 - w)}{n \cdot D}$$

in which w is effective wake fraction.

Generally, the manufacturer of the propeller provides the thrust characteristics. If they are not available a fair good estimation can often be made with characteristics of systematic series of propellers, as found in literature.

With this information in the practical working area of the propeller, a least squares method delivers the coefficients of a third degree polynominal to describe thrust characteristics:

$$\begin{aligned} K_T = {} & ct_{00} + \\ & ct_{10} \cdot J + ct_{20} \cdot J^2 + ct_{30} \cdot J^3 + \\ & ct_{01} \cdot p + ct_{02} \cdot p^2 + ct_{03} \cdot p^3 + \\ & ct_{11} \cdot J \cdot p + ct_{12} \cdot J \cdot p^2 + ct_{21} \cdot J^2 \cdot p \end{aligned}$$

When fixed-pitch propellers are used all coefficients related to the pitch p are zero here.

Effective Wake Fraction

Generally the effective wake fraction is only slightly depending on the ship's speed and strongly depending on the under water hull geometry. Because of large scale effects, model experiments deliver only poor information on full-scale wake.

Also empirical methods to determine the wake fraction can be found in literature. A much better full-scale "torque-identity" method is described in appendix II.

Neglecting speed effect, the effective wake fraction is approximated by a second-degree polynomial, depending on the hull geometry:

$$\begin{aligned} w = {} & w_{00} + w_{10} \cdot T_m + w_{20} \cdot T_m^{\ 2} + \\ & w_{01} \cdot tr + w_{02} \cdot tr^2 + w_{11} \cdot T_m \cdot tr \end{aligned}$$

A least-squares method can be used to determine the coefficients from the available information.

Thrust Deduction Fraction

The thrust deduction fraction is scarcely influenced by scale effects, so results of model experiments can be used. Empirical methods are generally less reliable. The available information is valid for still water conditions and not for a ship with an overloaded propeller. In general trim information is not available and the speed effect is neglectable. So for still water, the thrust deduction fraction can be expressed as a function of the amidships draft.

$$t_0 = t_{00} + t_{10} \cdot T_m + t_{20} \cdot T_m^{\ 2}$$

At an increased loading and a constant pitch and rpm of the propeller, the thrust deduction fraction will decrease from t_0 at the still water loading until t_1 in the bollard condition. Based on model experiments a parabolic decrease is assumed at a constant pitch and rpm:

$$t = t_1 + (t_0 - t_1) \cdot \left(\frac{V}{V_0} \right)^2$$

in which t_1 is the thrust deduction fraction at the bollard condition (approx. 0.04) and V_0 is speed in still water. A disadvantage of this method is that always a calculation of the speed in still water at this pitch and rpm of the propellers is required.

Speed Calculation

The foregoing describes the calculation of R_{ship} and R_{prop} as a function of the speed at a given pitch and rpm of the propellers, a loading of the ship and the environmental conditions. A numerical method, for instance the “Regula Falsi” method, can be used to find the equilibrium velocity V.

Torque and Power of the Propeller

The torque of a free-running propeller in a homogeneous flow follows from:

$$Q = K_Q \cdot r \cdot D^5 \cdot n^2$$

in which K_Q is the open water torque coefficient.

Just like for thrust, the torque characteristics are normally provided by the manufacturer of the propeller or by literature, which results into:

$$\begin{aligned} K_Q = cq_{00} + \\ & cq_{10} \cdot J + cq_{20} \cdot J^2 + cq_{30} \cdot J^3 + \\ & cq_{01} \cdot p + cq_{02} \cdot p^2 + cq_{03} \cdot p^3 + \\ & cq_{11} \cdot J \cdot p + cq_{12} \cdot J \cdot p^2 + cq_{21} \cdot J^2 \cdot p \end{aligned}$$

For fixed pitch propellers all coefficients related to the pitch p are zero here.

Because the flow behind the ship is not homogeneous, a correction has to be made to find the torque of the propeller behind the ship Q_S.

Increased roughness of the propeller blade surface due to fouling will also increase the torque:

$$Q_S = \frac{\left(K_Q + \Delta K_Q\right) \cdot r \cdot D^5 \cdot n^2}{h_r}$$

in which h_r is the relative rotative efficiency and ΔK_Q is the fouling coefficient of propeller.

The relative rotative efficiency can be found from model experiments or information given in the literature. The ship’s speed has a little effect on this efficiency and the effect of draft can - in general - be neglected:

$$h_r = e_0 + e_1 \cdot V$$

The determination of the fouling coefficient of the propeller will be explained in appendix III and is assumed to be zero here for this “new” condition of the ship.

The power required by the propeller behind the ship to maintain the speed V at a given pitch and rpm is:

$$P_S = 2p \cdot Q_S \cdot n$$

When the mechanical efficiency of the shaft bearing h_m is estimated the power at the propeller-shaft P_{SH} is known:

$$P_{SH} = \frac{P_S}{h_m}$$

Diesel-Electric Power

The foregoing is in general valid, the following is valid for a diesel-electric power plant as given in Figure 1.

The relation between the electric power output bound for propulsion and the mechanical power at the PS and SB propeller shaft is approximated by a linear relation:

$$P_{MGS} = 2 \cdot \left(p_1 + p_2 \cdot P_{SH}\right)$$

The coefficients follow from information of the manufacturer or full-scale

measurements as will be explained in appendix II.
The electrical power output of a main generator is:

$$P_{MG} = \frac{P_{MGS} + P_{EL}}{n_{me}}$$

in which P_{EL} is electric power delivered to the electric system of the ship and n_{me} is number of main engines in use.
For P_{EL} the following relation is used:

if $P_{MG} < P_1 + P_2 / n_{me}$ then

$$P_{EL} = n_{me} \cdot P_3$$

else

$$P_{EL} = 0$$

The values of P_1, P_2 and P_3 depend on the system used and the experience with it. The relation between the electric power output of the main generator of the main engine has to be delivered by the manufacturer.
Normally, a linear relation can be used:

$$P_{ME} = p_3 + p_4 \cdot P_{MG}$$

Fuel Consumption
The manufacturer of the propulsion plant delivers information on fuel consumption characteristics. The fuel consumption of the main engine, which has a constant rpm, is here approximated by:

$$F = f_1 + f_2 \cdot P_{ME}$$

F is the fuel consumption in cubic meter per hour.

The fuel consumption is depending on the quality of the fuel. On-board measured fuel data during the trials are used to determine the coefficients, see Appendix II. The coefficients can be adjusted when the quality of the fuel changes during service, see Appendix III.

APPENDIX II: Use of Full Scale Measurements

Provided that reliable and calibrated measuring instruments have been used, measured data can be used to determine some of the coefficients mentioned in Appendix I. Other coefficients follow from models, theories, etc.

Effective Wake Fraction
The effective wake fraction can be derived from full-scale measurements by a "torque-indentity" method:

Calculated Torque = Measured Torque

If power and rpm have been measured this condition leads to an equivalent torque coefficient.
If the mechanical power and the rpm of the propeller shaft have been measured the equivalent torque coefficient will. be:

$$K_Q{}^* = \frac{h_r \cdot h_m}{2p \cdot r \cdot D^5 \cdot n^2} \cdot \frac{P_{SH}}{n^3}$$

If this mechanical power is not measured, the electric power output for propulsion of the main generators and the nominal rpm of the propeller can be used:

$$K_Q{}^* = \frac{h_r \cdot h_m}{2p \cdot r \cdot D^5 \cdot n^2} \cdot \frac{P_{MGS} - 2p_1}{n^3 \cdot 2p_2}$$

This equivalent value should be equal to a third degree function of the speed ratio J, derived from the torque characteristics and the measured pitch:

$$K_Q{}^* = cq_0 + cq_1 \cdot J + cq_2 \cdot J^2 + cq_3 \cdot J^3$$

This equation delivers in the normal working area of the propeller just one solution: the equivalent speed ratio J^*.
This results into an equivalent effective wake fraction:

$$w^* = 1 - \frac{J^* \cdot n \cdot D}{V}$$

If this fraction will be determined at a range of amidships drafts, trim values and speeds, it appears that the speed effect is neglectable. With a least squares method the coefficients of $w^*(T_m, tr)$ can be determined, see example in Figure 12.

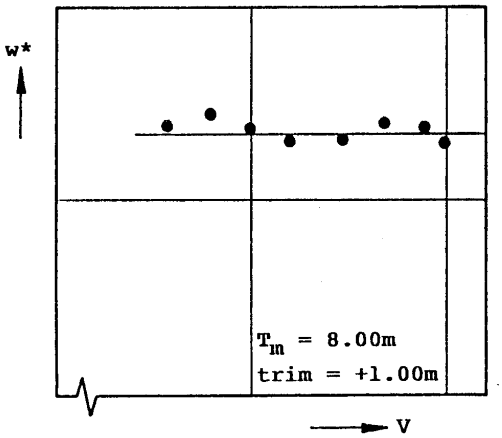

Figure 12 Equivalent Wake

Residuary Resistance Coefficient

After the determination of the equivalent effective wake fraction an equivalent residuary resistance coefficient can be determined at each trial from the following condition:

Calculated Speed = Measured Speed

at a setting of pitch and rpm.

To avoid inaccuracies caused by estimations and calculations of wind and waves, the trials to estimate the C_r^* coefficient should be carried out in calm water or moderate beam to following wind and waves. A separate computer program has been made to calculate C_r^* in such a way that this condition is fulfilled. A least squares method delivers the coefficients of $C_r^*(T_m, tr, V)$. An example is given in Figure 13.

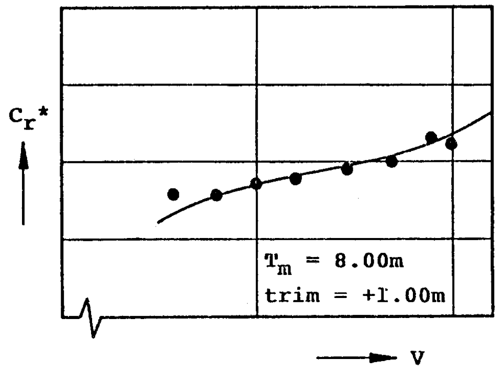

Figure 13 Equivalent Residuary Resistance

Electrical and Mechanical Losses

If both, the mechanical power at the propeller shaft P_{SH} and the electric power output for propulsion of the main generators, have been measured a least squares gives delivers the coefficients:

$$P_{MGS} = 2 \cdot (p_1 + p_2 \cdot P_{SH})$$

Care should be taken that pitch and rpm of both propellers are equal, to justify the use of the factor 2.

Fuel Consumption

The fuel consumption per hour will be derived from the mechanical power output of the main engine by:

$$F = f_1 + f_2 \cdot P_{ME}$$

This power can be derived from the measured mechanical power at the propeller shaft P_{SH} or the measured electric power output for propulsion of the main generators P_{MGS}. A least squares method delivers the coefficients.

APPENDIX III: Adjustable Coefficients

Just after determining the coefficients according to Appendix II the calculations are very accurate, at least in calm weather conditions.
However, some phenomena can change during the lifetime of the ship:

- the increased roughness of the ships hull due to fouling or damage, expressed in the fouling coefficient ΔC_f,
- the increased roughness of the propeller blades due to fouling, expressed in the fouling coefficient ΔK_Q,
- the quality of the fuel, better or worse than during the trials, mentioned in Appendix II and
- the effect of variable deck load on the wind resistance.

Fouling of the Ship's Hull
When the ship's captain notices in calm weather conditions too high calculated speeds this is most probably caused by fouling of the ship's hull. A fouling coefficient ΔC_f, which was originally set to zero, can be adjusted by a "trial and error" method in such a way that the calculated and measured speed agree again.

Fouling of the Propeller Blades
When the ship's captain notices in calm weather conditions too high calculated power values and the calculated speed is correct, this is most probably caused by fouling of he propeller blades. A fouling coefficient ΔK_Q, which was originally set to zero, can be adjusted by a "trial and error" method in such a way that the calculated and measured power agree again.

Fuel Consumption
When the ship's captain notices that the calculated and measured specific fuel consumption (ltr/kWh) does not agree, the coefficient f_2 can be changed by input of a power value with a specific fuel consumption to match. Calculated and measured fuel consumption will agree again.

Variable Deck Load
Wind coefficients for deck load can be adjusted by the ship's captain, based on information from the owner's organisation.