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A new logic for controllable pitch propeller management

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ABSTRACT: In this study we want to propose an active logic that, continuously, optimizes the configuration of the propeller and motor speed taking into account changes in resistance and wake.

The working principle of the control system is based on the measurement of the torque absorbed by the propeller and the engine speed, to obtain the actual thrust and advance speed coefficients.

Based on these data, the controller identifies the configuration of the propeller for the best performance of the entire propulsion chain, from engine to propeller. Moreover, in addition to torque and speed limits of the engine, the control system chooses pitch angle taking into consideration the propeller's cavitation.

1 INTRODUCTION

1.1 *The informing principle*

Controllable pitch propellers allow a greater flexibility in propulsion; at a given operating point the required thrust can be obtained with different pairs of propeller pitch and speed values. The same ship motion can be achieved with several pairs of speed and pitch but with different efficiencies.

This paper presents an active logic that, continuously getting measurements of propeller shaft torque, estimates the optimum CPP pitch and rotational speed to minimize fuel consumption.

The knowledge of propeller torque allows to identify the actual hydrodynamic working point, from open water characteristics of propeller, according to a procedure that is quite similar to a towing tank self propulsion test.

The optimization is based not only looking at the best propeller efficiency (η_0) but at engine efficiency (η_m) also, evaluating the combined efficiency ($\eta_0 \cdot \eta_m$).

1.2 *Services and working point suitable for the control system proposed*

For the estimation of high propulsive efficiency, the knowledge of the actual hydrodynamic working point of the propeller is more useful more are the diversified services and the sailing conditions of the ship.

The application of this control is quite effective because of unpredictable sailing point: as a case in point, when high thrust and low advance speed of the propeller is high over an extended period of time.

In these conditions the crossing velocity of the water through the propeller disk is strongly dependent on the suction of the propeller and on small variations of ship's speed. In other words, small variations of the working point causes significant variations of the propeller diagram, taking in to account the engine behaviour.

Sharing the above-mentioned considerations, is well-founded to suppose that same types of ship (Trawlers and Tugs but also Patrol ships and Cutters) are particularly suitable to resort to the logic here exposed.

Finally, the use of propeller as gauge to measure the V_A entails three further advantages:

- the evaluation of wake variations in time due to the increase of momentum given to the viscous field (typically for growth of fouling),
- the overcoming of the scale effects and inaccuracies due to the limitations of experimental and numerical methodologies and
- the online evaluation of η_0 (and its partial derivative) allows the system to consider values near the envelope of maximum efficiency. That values are avoided because of they are close to a zone that involves the greatest gradient of η_0.

2 PROPELLER AND ENGINE CHARACTERISTICS FORMULATION

2.1 *Controllable pitch propeller open water characteristic*

To achieve our purpose we need a flexible tool to describe the propeller; an unusual way to represent the characteristics of controllable pitch propellers is proposed.

The propeller open water characteristic is given by the following parameters:

Advance Coefficient:	J	$= V_A / (n\,D)$
Trust Coefficient:	K_T	$= T / (\rho\, n^2 D^4)$
Torque Coefficient:	K_Q	$= Q / (\rho\, n^2 D^5)$
Prop. efficiency:	η	$= V_A T / 2\pi\, n\, Q$
		$= J/2\pi\, (K_T / K_Q)$

where:

- D = propeller diameter (m)
- ρ = water density (kg/m^3)
- n = rotational speed of propeller (s^{-1})
- T = thrust (N)
- Q = torque (N m)
- V_A = speed of advance (m/s)

For a fixed blades propeller the adimensional coefficients K_T and K_Q are functions of the advance coefficient J only. For a CPP these coefficients are also functions of the blade orientation, so they are expressed as follow:

$K_Q = K_Q(J;\, p)$
$K_T = K_T(J;\, p)$

where p is the blade orientation angle starting from a reference pitch P_0.

The orientation angle p has the same role of the *Pitch/Diameter Ratio* of a classical propeller systematic series.

The characteristics of fixed blade propellers are usually described with a polynomial form of J. Typically a polynomial of degree four is enough to describe a single quadrant propeller characteristic; a more complex form is necessary to describe a four quadrant characteristic.

Regarding the single quadrant the characteristics are expressed as shown:

$K_T(J) = A_4 J^4 + A_3 J^3 + A_2 J^2 + A_1 J + A_0$
$K_Q(J) = B_4 J^4 + B_3 J^3 + B_2 J^2 + B_1 J + B_0$

where A_i and B_i are constants.

To describe a CPP, coefficient A_i and B_i must be functions of blade orientation:

$$K_T(J;\, p) = A_m(p)J^m + \ldots + A_4(p)J^4 + A_3(p)J^3 + A_2(p)J^2 + A_1(p)J + A_0(p)$$
$$K_Q(J;\, p) = B_m(p)J^m + \ldots + B_4(p)J^4 + B_3(p)J^3 + B_2(p)J^2 + B_1(p)J + B_0(p)$$

It is possible to describe A_i and B_i as a polynomial form of blade angle

$A_i(p) = a_{in}p^n + a_{in-1}p^{n-1} + \ldots + a_{i2}p^2 + a_{i1}p + a_{i0}$
$B_i(p) = b_{in}p^n + b_{in-1}p^{n-1} + \ldots + b_{i2}p^2 + b_{i1}p + b_{i0}$

In this way the open water CPP characteristics are completely described by $2 \times n \times m$ constants.

To simplify the discussion we will use the following vector notation:

$\mathbf{p}^{\mathbf{T}} = \{1, p, p^2, \ldots, p^n\}$
$\mathbf{p_P}^{\mathbf{T}} = \{0, 1, 2p, 3p^2, \ldots, np^{n-1}\}$
$\mathbf{J}^{\mathbf{T}} = \{1, J, J^2, \ldots, J^m\}$
$\mathbf{J_J}^{\mathbf{T}} = \{0, 1, 2J, 3J^2, \ldots, mJ^{m-1}\}$

The coefficients are organized in the following matrices:

$$\mathbf{A} = \begin{pmatrix} a_{00} & \ldots & a_{0n} \\ \ldots & \ldots & \ldots \\ a_{m0} & \ldots & a_{mn} \end{pmatrix} \qquad \mathbf{B} = \begin{pmatrix} b_{00} & \ldots & b_{0n} \\ \ldots & \ldots & \ldots \\ b_{m0} & \ldots & b_{mn} \end{pmatrix}$$

We could describe K_Q, K_T and η_0 functions in a more simple way:

$K_T(J;p) = (\mathbf{J^T A p})$ $K_Q(J;p) = (\mathbf{J^T B p})$
$\eta_0(J;p) = J/2\pi\, (\mathbf{J^T A p})\, (\mathbf{J^T B p})^{-1}$

Also for the partial derivative:

$$\frac{\partial \eta_0}{\partial J} = 1/2\pi(\mathbf{J^T BP})^{-2}\{[(\mathbf{J^T Ap}) + \mathbf{J}(\mathbf{J_J}^{\mathbf{T}}\mathbf{Ap})] (\mathbf{J^T Bp}) - [\mathbf{J}(\mathbf{J^T Ap})(\mathbf{J_J}^{\mathbf{T}}\mathbf{Bp})]\}$$

$$\frac{\partial \eta_0}{\partial p} = J/2\pi(\mathbf{J^T BP})^{-2}\left[(\mathbf{J^T Ap_p})(\mathbf{J^T Bp})] - (\mathbf{J^T Bp_p})(\mathbf{J^T Ap})\right]$$

$$\frac{\partial K_T}{\partial J} = (\mathbf{J_J}^{\mathbf{T}}\mathbf{Ap}); \quad \frac{\partial K_T}{\partial p} = (\mathbf{J^T Ap}_{\mathrm{p}})$$

$$\frac{\partial K_Q}{\partial J} = (\mathbf{J_J}^{\mathbf{T}}\mathbf{Bp}); \quad \frac{\partial K_Q}{\partial p} = (\mathbf{J^T Bp}_{\mathrm{p}})$$

Given propeller diameter, advance speed and trust, to find the propeller operating point, the adimensional coefficient K_T/J^2 is used. This coefficient does not depend on rotational speed of propeller:

$K_T/J^2 = T / (\rho D^2 Va^2) = J^{-2}\, (\mathbf{J^T Ap})$

Whose partial derivatives are:

$$\frac{\partial \dfrac{K_T}{J^2}}{\partial p} = J^{-2}\{J^{-2}(\mathbf{J_J}^{\mathbf{T}}\mathbf{Ap}) - 2J(\mathbf{J^T Ap})\}$$

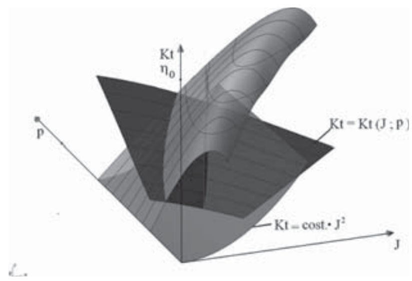

Figure 1. Shapes of open water characteristic of controllable pitch propeller.

$$\frac{\partial \frac{K_T}{J^2}}{\partial J} = J^{-2}\{J^2(\mathbf{J}^T\mathbf{B}\mathbf{p}_p) - (\mathbf{J}^T\mathbf{A}\mathbf{p}_p)\}$$

To set the coefficients of the matrices **A** and **B** the two unconstrained optimization problems

$\min_{\mathbf{A}} \|\mathbf{y} - \hat{\mathbf{y}}\|^2$
$\min_{\mathbf{B}} \|\mathbf{w} - \hat{\mathbf{w}}\|^2$

have to be solved.

In the above formulas **w** and **y** are the sets of experimental K_Q and K_T values while $\hat{\mathbf{w}}$ and $\hat{\mathbf{y}}$ are the corresponding sets plotted by the proposed formula.

Applying this procedure on many CPP open water experimental data, the order of magnitude of $\|\mathbf{y} - \hat{\mathbf{y}}\|^2$ and $\|\mathbf{w} - \hat{\mathbf{w}}\|^2$ are 10^{-4} and 10^{-5} respectively; moreover no value of $|y_i - \hat{y}_i|$ and $|w_i - \hat{w}_i|$ are greater than 0.4%.

The high effectiveness of the solution used to find matrices **A** and **B** is determined by the smoothness of the functions that describe the phenomenon.

2.2 *Engine characteristic*

To work simultaneously on engine and propeller effectiveness is necessary to obtain an agile formulation of engine fuel consumption. These data are usually expressed in engine maps, as shown in Figure 2.

With this purpose we follow the same steps of paragraph 2.1, finding the polynomial formulation of fuel consumption in terms of power and rotational speed

$\mathbf{N}^T = \{1; N; N^2\}$; $\mathbf{n}^T = \{1; n_m; n_m^2; n_m^3; n_m^4; n_m^5\}$
$C_s = \mathbf{N}^T\, \mathbf{C}\, \mathbf{n} \in [n_{min}; n_{max}] \times [N_{min}; N_{max}]$

Where:

- **C** = coefficients matrix
- n_m = rotational speed of engine (s^{-1})
- H_i = Net heating value (MJ/kg)
- Cs = specific fuel consumption (g/kWh)
- N = engine power (kW)

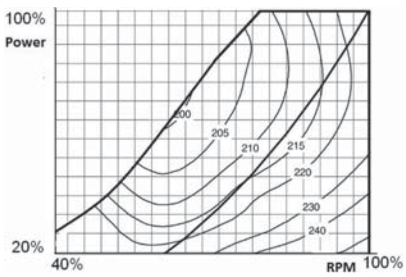

Figure 2. Typical engine performance diagram.

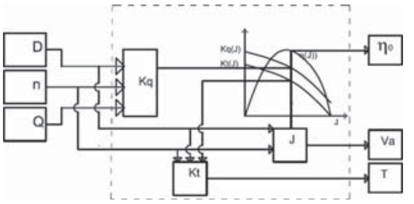

Figure 3. Thrust and advance velocity estimation, at a given pitch.

Finally the engine efficiency is given by:
$\eta_m = 3600/H_i\, C_s$

2.3 *Estimation of self propulsion coefficients*

To obtain a continuous estimation of the operating point, torque and rotational speed have to be measured on the shaft line. In this way it is possible to have an indirect estimation of wake using the propeller as a measurement instrument: basically like a self-propulsion towing tank test.

Compared to towing tank procedure, here the thrust will be indirectly estimated by the propeller characteristic and not measured.

Obviously in this way it is not possible to evaluate the wake distribution on disk propeller; usually this effect is taken into account by introducing the relative rotative efficiency η_R, that can be estimated through a direct thrust measurement. Thrust measurements are commonly done in towing tank tests but are not effective onboard.

3 OPTIMIZATION PROBLEM

3.1 *Objective function*

To minimize fuel consumption the only conscious manageable losses, varying the pitch, are those related to the engine performances and to isolated propeller efficiency. Therefore the objective function to be maximized is $\eta_0 \times \eta_m$.

3.2 *Equality constrain*

To operate an optimization without varying the operating point of the ship it is necessary to introduce an equality constrain that does not depend on propeller rotational speed, represented by the K_T^*/J^2 term, that represents the thrust coefficient required, function of trust, diameter and advance velocity.

$K_T^*/J^2 = T / (\rho D^2 Va^2)$

The equality constrain could be written in this form:

$$\frac{Kt(p;J)}{J^2} - \frac{Kt^*}{J^2} = 0$$

The first term is the thrust coefficient obtainable by propeller at different pitch and advance coefficient.

In an explicit form:

$J^{-2}\,(\mathbf{J^T A p}) - T / (\rho D^2 Va^2) = 0$

3.3 *Inequality constrains and parameters bounds*

The inequality constrains presented are substantially:

- the operational limit of the propeller and the engine;
- great variation of propeller efficiency;
- cavitation.

The propeller limits represent the boundary of experimental data expressed by:

$$\begin{cases} J - J_{\min} \geq 0 \\ J_{\max} - J \geq 0 \\ p - p_{\min} \geq 0 \\ p_{\max} - p \geq 0 \end{cases}$$

The engine limits, that are presented in paragraph 2.2, are:

$$\begin{cases} n - n_{\min} \geq 0 \\ n_{\max} - n \geq 0 \\ N_{\max}(n) - N \geq 0 \end{cases}$$

where $N_{max}(n)$ is a function that describes the upper power limit varying the rotational propeller speed.

In order to avoid working points subjected to great efficiency variations a gradient constrain on propeller efficiency can be introduced.

$$\frac{\partial \eta_0}{\partial J} \geq 0$$

This means that the zone with negative derivative, that involves the greatest variation, is neglected in whole pitch angle range. In Figure 4 is shown the cross out zone for a fixed pitch position.

The constrain could be written in the following explicit form:

$1/2\pi\,(\mathbf{J^T B p})^{-2}\,\{[(\mathbf{J^T A p}) + J(\mathbf{J_J{}^T A p})] \geq 0$

To implement a cavitation limit, if there are no experimental or numerical data for the considered propeller, an equivalent Burril cavitation curves can be considered:

$$\tau - \tau_{cr}(\sigma) \geq 0$$

3.4 *Constrained optimization*

The whole problem could be expressed in the following form

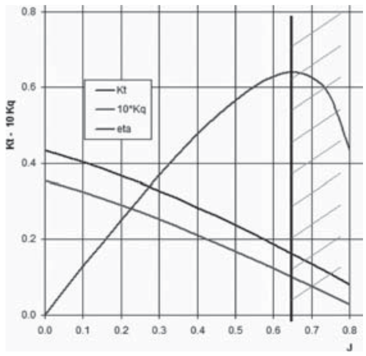

Figure 4. Cross out zone for a fixed pitch position.

Figure 5. optimal control block (identification logic).

$$\begin{cases} \max_p \eta_0(p;J)\cdot\eta_m(N(p,J);n(p,J)) \\ \begin{cases} J - J\min \geq 0 \\ J\max - J \geq 0 \\ p - p\min \geq 0 \\ p\max - p \geq 0 \end{cases} \\ \begin{cases} n - n\min \geq 0 \\ n\max - n \geq 0 \\ N - N\min \geq 0 \\ N\max(n) - N \geq 0 \end{cases} \\ \eta_{0J}(p;J) \geq 0 \\ \dfrac{Kt(p;J)}{J^2} - \dfrac{Kt^*}{J^2} = 0 \\ \tau - \tau_{cr}(\sigma) \geq 0 \end{cases}$$

Solving this problem is possible to obtain optimal surfaces that return the optimal propeller pitch and speed as functions of trust and advance speed. In Figure 5 the scheme of the optimal control system is shown.

4 CONTROL STRATEGIES

Onboard ships fitted with CP propeller the thrust is normally achieved by setting propeller pitch and speed according to a curve called propeller combinator curve.

This curve, for each command lever position assigns univocally a pairs of values for speed and pitch, controlling in this way the set point of main engine governor and of propeller pitch actuator, generally hydraulic.

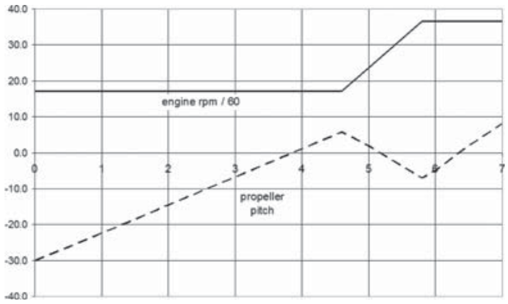

Figure 6. Classical combinator curve.

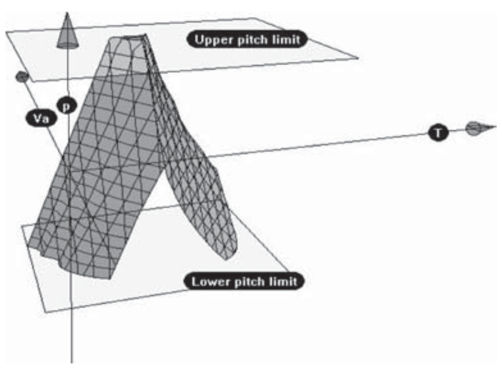

Figure 7. Combinator surface (Optimal pitch surface).

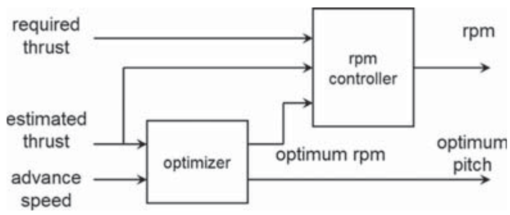

Figure 8. Control logic.

The combinator curve is determined at a design stage or at propulsion system commissioning stage.

Some times one or more combinator curve can be provided, but the master has to switch manually from one curve to another. In any case, according to ship operating conditions and to master sensitivity, the propeller runs closer or not to its optimum.

If getting the best propulsion system performances at any operating condition is desired, a propeller combinator surface must be considered instead.

An optimal CPP control system chooses the working condition not only on the basis of command lever settings but of ship running condition also. The command lever does not determine univocally the values of propeller pitch and speed, due to the degree of freedom that the system allows.

From the optimization procedure the optimal values of propeller speed and pitch are expressed as function of thrust coefficient and speed of advance, but none of these two parameters is suitable to be used directly as a command input.

To determine the ship running condition it seems reasonable to consider the thrust in a dimensional form.

The command lever acts by setting a desired value of thrust, so that the ship will reach a speed depending on loading and environmental condition; it is concern of ship master to select a proper thrust value. In this way the effectiveness of propulsion chain doesn't affect the ship speed.

To get the required thrust a controller is needed; it takes into account the actual thrust estimate and sets the propeller rotational speed, n. If the estimated thrust is different from the required one, the controller varies engine rpm setting in order to cancel any difference.

The corresponding pitch value is determined by the optimizer as function of actual thrust and advance speed estimate. The optimizer gives also the optimal propeller speed n*; the thrust controller must achieve the required thrust by minimizing the difference n*-n.

In this way, during the transient time the pairs of speed and pitch can be considered laying close to a Pareto frontier.

After transient time, the propulsion system will find a steady state working condition with an optimal pair of pitch and rotational speed.

Because the optimizer consider also a cavitation limit (in the sense that a limited amount of cavitation could be tolerated, i.e., 5%), the system will preserve the optimal working point by excessive cavitation.

The Figures 9a and 9b show the schemes of the whole control system.

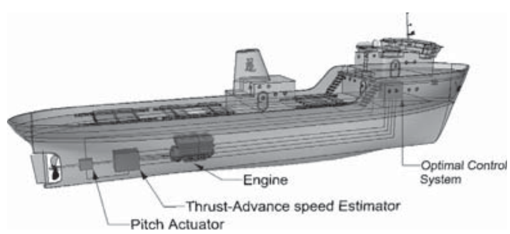

Figure 9a. Control system.

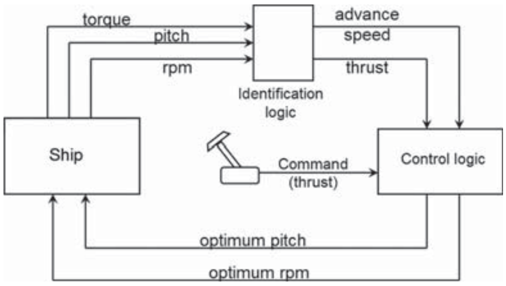

Figure 9b. Control system: working diagram.

5 TEST CASE

As a starting step to assess the feasibility of the proposed optimal control system a series of test on a simulation model has been conducted.

The ship modeled is a 24 meter long passenger ferry, having a maximum speed of 13 kn, powered by a 100 kW@2200 rpm diesel engine, subjected to payload variations (about 40% of displacement) and to wave resistance variations induced by sailing in shallow water (up to 15%). The propeller considered is the propeller E.028 tested in Towing Tank of *Dipartimento di Ingegneria Navale* of Naples.

The model allows to evaluate difference in terms of specific fuel consumption between the ship propelled with a typical combinator CPP curve and the control system proposed.

The simulations start from design conditions so that the output of optimal control system matches the combinatory output. After a certain time a resistance variation occurs and, unlike the classical combinator control, the optimal control system searches new values of pitch and speed, as shown in the following diagram.

Table 1 shows the results of simulation carried out with a traditional combinatory curve control. Starting from an initial sailing condition, because of an increasing in resistance imposed, the ship find a new steady condition, obviously a lesser speed occurs.

Table 2 shows the same conditions but with the optimal control working. The comparison shows, in that particular case, a improvement of efficiency with respect to the case of traditional control.

Because the optimal control maintains the thrust to a required value, when an increase of hull resistance occurs the ship will experience a speed reduction greater than in the case of a traditional control. To compare date at same speed an increasing of required thrust is considered when the resistance rises, so to obtain the same ship speed as in traditional command; the results are shown in Table 3, confirming that the system improves any case the whole system efficiency as the reduction of specific fuel consumption shows.

As the specific fuel consumption values shows, the initial operating condition for the ship tested are not the best, but this is the case where this approach has sense.

It has also to be pointed out that the simulation model is based on hull resistance, propeller

Table 1. Results of simulation with traditional combinator curve control.

	Engine Speed [rpm]	Pitch [deg]	Speed [m/s]	SFOC [g/kWh]
Initial condition 1	1398	–3.3	5.57	294.1
with disturbance	1398	–3.3	5.38	304.2
Variation			**–0.19**	**10.1**
Initial condition 2	1545	–4.9	5.78	299.1
with disturbance	1545	–4.9	5.58	311.5
Variation			**–0.20**	**12.4**
Initial condition 3	1704	–6.4	5.98	306.4
with disturbance	1704	–6.4	5.78	321.3
Variation			**–0.20**	**15.0**
Initial condition 4	1875	–7.9	6.19	315.6
with disturbance	1875	–7.9	5.98	333.2
Variation			**–0.21**	**17.6**
Initial condition 5	2060	–9.3	6.40	323.9
with disturbance	2060	–9.3	6.19	343.5
Variation			**–0.21**	**19.6**

Table 2. Results of optimal control without thrust correction.

	Engine Speed [rpm]	Pitch [deg]	Speed [m/s]	SFOC [g/kWh]
Initial condition 1	1398	–3.3	5.57	294.1
with disturbance	1379	–3.4	5.31	291.2
Variation			**–0.26**	**–2.9**
Initial condition 2	1545	–4.9	5.78	299.2
with disturbance	1519	–4.9	5.49	297.0
Variation			**–0.28**	**–2.2**
Initial condition 3	1704	–6.4	5.98	306.6
with disturbance	1664	–6.3	5.68	305.3
Variation			**–0.31**	**–1.3**
Initial condition 4	1875	–7.9	6.19	315.8
with disturbance	1817	–7.6	5.86	315.5
Variation			**–0.33**	**–0.3**
Initial condition 5	2060	–9.2	6.40	324.3
with disturbance	1980	–8.9	6.04	325.1
Variation			**–0.35**	**0.9**

Table 3. Results of optimal control with thrust correction.

	Engine Speed [rpm]	Pitch [deg]	Speed [m/s]	SFOC [g/kWh]
Initial condition 1	1398	–3.3	5.57	294.1
with disturbance	1433	–4.0	5.38	293.2
Variation			**–0.19**	**–0.9**
Initial condition 2	1545	–4.9	5.78	299.2
with disturbance	1589	–5.6	5.58	300.5
Variation			**–0.19**	**1.3**
Initial condition 3	1704	–6.4	5.98	306.6
with disturbance	1752	–7.1	5.78	311.1
Variation			**–0.20**	**4.5**
Initial condition 4	1875	–7.9	6.19	315.8
with disturbance	1927	–8.5	5.98	322.3
Variation			**–0.20**	**6.5**
Initial condition 5	2060	–9.2	6.40	324.3
with disturbance	2117	–9.9	6.19	330.4
Variation			**–0.21**	**6.2**

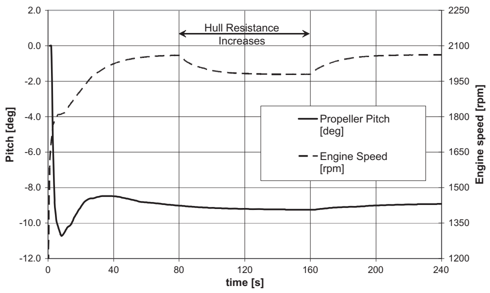

Figure 10. Test case simulation results.

and engine data curves that are not affected by scale effects.

In a real case there will be more uncertainties than in a simulation model: it is to be noted that the η_R coefficient, that represents in a certain manner an uncertainty coefficient of the propeller open water curves, has been considered in the model of ship but obviously the optimization routine doesn't consider it. This aspect leads to an error in the estimate of the effective propeller thrust.

Nevertheless the system finds a working condition that allows the best efficiency.

6 FURTHER COMMENTS ON CONTROL

More considerations must be done in order to improve the comprehension of the control system and to make it appropriate for a practical application onboard.

First of all, the control system proposed estimates propeller advance speed and thrust by torque measurement; the quality of acquired data is a fundamental aspect of the matter. The measured torque data can be affected by disturbances due to sensor noise and to environmental noise.

Many authors have dealt with this topic in depth, mainly in works concerning dynamic positioning plants.

Moreover another important aspect is the quality of ship, engine and propeller data used to carry out the optimization procedure.

In particular, the error propagation of thrust estimate must be considered.

To assesses the effectiveness of this proposed control its sensitivity to measurements errors, model uncertainty and external disturbance must be evaluated.

The controller used in the simulation has a simple PID structure and gives good results in a simplified model; more advanced controller may improve performance and stability robustness also considering more realistic disturbances and uncertainties.

7 OPTIMIZZATION TECNIQUES

Optimization techniques are used to find a set of design parameters, $\mathbf{x} = \{x_1, x_1, ..., x_n\}$, that can in some way be defined as optimal. In a simple case this might be the minimization or maximization of some system characteristic that is dependent on x. In a more advanced formulation the objective function, $f(x)$, to be minimized or maximized, might be subject to constraints in the form of equality constraints, $g_i(\boldsymbol{x}) = 0$ (i = 1, ..., n); inequality constraints, $h_i(x) = 0$ (i = 1, ..., m); and/or parameter bounds, x_l, x_u.

General Problem description is stated as

$$\begin{cases} \min_x f(x) \\ h_i(x) = 0 \\ g_i(x) \le 0 \end{cases}$$

methods could be focused on the solution of the Karush-Kuhn-Tucker (KKT) equations:

$$\nabla f(x_0) + \sum_{i=1}^{m} \mu_i \nabla g_i(x_0) + \sum_{i=1}^{l} \nu_i \nabla g_i(x_0) = 0$$
$$\mu_i g_i(x_0) = 0, \mu_i \ge 0, i = 1, ..., m$$

The KKT equations are necessary conditions for optimality of a constrained optimization problem. If the problem is a so-called convex programming problem, that is, $f(x)$ and $g_i(x)$, i = 1, ..., m and $h_i(x)$, i = 1, ..., n are convex functions, then the

KKT equations are both necessary and sufficient for a global solution point.

First a sequential quadratic programming is solved to obtain modification of **d**, where **d** is the descent direction and $\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)}\ \alpha\mathbf{d}$ is the line search.

The SQP (sequential quadratic programming) is presented as follow:

$$P(d) = F(x^{(k)}) + \nabla F^T\left[x^{(k)}\right]\cdot d + \frac{1}{2}d^T \cdot H^{(k)} \cdot d$$
$$h_i\left[x^{(k)}\right] + \nabla h_i^T\left[x^{(k)}\right]\cdot d = 0 \qquad i = 1, N$$
$$g_i\left[x^{(k)}\right] + \nabla g_i^T\left[x^{(k)}\right]\cdot d \le 0 \qquad i = 1, M$$

That represent a quadratic form of the objective function and a linearization of constrains.

Where **H** is the Hessian matrix of KKT equation:

$$H = \nabla^2 F + \sum_{i=1}^{M} \mu_i \nabla^2 g_i\left(x_0\right) + \sum_{i=1}^{N} \nu_i \nabla^2 g_i\left(x_0\right)$$

To find the solution the Quasi Newton method. Descent direction is defined as follow:

$\mathbf{d} = -\mathbf{Q}\nabla\mathrm{F}$

were Q is an approximation of the Hessian matrix. To find Q, BFGS (Broyden-Fletcher-Goldfarb,-Shanno) method was used.

8 CONCLUSIONS

Direct measurements of thrust and torque gives a knowledge of propeller hydrodynamic parameters, so that, in the case of CP propeller, the best pair of revolution speed and pitch values can be set. Torque measurements are quite easier and more practicable, than thrust.

Thrust estimation based on torque measures are used for positioning system control fitted with fixed pitch propellers (L. Pivano et al., 2009).

On the other hand, optimization of CPP has already been considered by other authors (R.A. Morvillo 1996), based only on an advance speed estimate, statistically or experimentally (in model scale) predetermined and referring to a limited number of propeller working points.

In the present work a procedure based on thrust estimate has been proposed, with aim to choose objectively the optimum propeller speed and pitch.

The problem has been dealt by creating a combinator surface that take into account the combined efficiency $\eta_0 \times \eta_m$, where optimum propeller pitch and rotational speed are expressed in terms of thrust and advance speed.

The procedure has been tested on a quite simple model making use of an unsophisticated controller.

On the test model the results shows that in the case the sailing condition varies, the optimum controller achieves better efficiencies than a traditional combinatory curve control, maintaining a stable behavior.

In many types of vessels that solution could be particularly suitable to offer large reduction of consumption because of unpredictable sailing condition.

Finally it is possible to synthesize that the procedure showed:

1. has highlighted the reliability of the informing principle;
2. has confirmed the validity of the interpolation technique and of the characteristic surfaces-computation procedures;
3. has demonstrated that a quite simple and unsophisticated controller is able to reach the appointed objective.

In the same time, herein it has been highlighted some critical point that should bee studied in depth. In particular the research will be developed towards three directions:

1. the individuation of ship types and services suited to take advantage of the potential of the logic presented;
2. the realization of robust procedures of measurement, signal treatment and computation of hydrodynamic coordinates indispensable to identify the working point of the propeller;
3. the implementation of new control logics directed towards different objective functions, for example the realization of the maximum trust.

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