Continuous Optimization of Controllable Pitch Propellers for Fast Ferries

F. Balsamo  
Università degli Studi di Napoli "Federico II", Naples Italy

F. De Luca  
Università degli Studi di Napoli "Federico II", Naples Italy

C. Pensa  
Università degli Studi di Napoli “Federico II”, Naples, Italy

ABSTRACT: Nowadays Controllable Pitch Propellers (CPP) are employed on several ships whose speed is an important item of the desiderata. Significant examples are the large Ro-Pax, 27 ÷ 31 kn fast, connecting harbours at distance of 200 ÷ 700 nautical miles, or smaller fast ferries for inshore route sailing at the same speed range. It is well-known that CPP are employed because they are very suitable for harbour manoeuvring but induce a remarkable propulsive efficiency reduction at cruising speed. Moreover, many times, the fast ferries operating on inshore route sail at low speed or in shallow water conditions where thrust loading and speed of advance are different from the same quantity induced by the standard conditions. In this study we want to propose an active logic that, continuously, optimizes the configuration of the propeller according to the actual conditions of the ship. In particular, the logic and the control system, have the purpose to select the best pitch angle taking in account changes in resistance and wake. The working principle of the logic is based on the engine speed and the measure of the torque absorbed by the propeller, to obtain the actual self-propulsion coefficients. Based on these data, the controller identifies the pitch angle for the best performance of the propeller.

1 INTRODUCTION

At the DIN a logic control of CPP, designed to maximize efficiency or thrust, identifying the optimum pitch is, at the present, object of study in depth. The obvious fields of interest for these technologies are ships with propellers working with various thrust and hydrodynamic characteristic hardly predictable (Tugs, Trawler, etc.). Nevertheless, studying deeply the logic it has been noticed that the effectiveness of the principle informing the control, could be significant also for high speed vehicles whose services imply great variations of displacement or speed (e.g. patrol boats, SaR or ferry operating both in restricted and open waters or on winter-commercial and summer-tourist services).

1.1 Informing principle

The active logic shown in this work estimates continuously the optimum pitch for a CPP to minimize fuel consumption. The informing principle of the work is based on two actions:

• the individuation of the actual hydrodynamic working point of the propeller and
• the attainment of highest value of the product ($\eta_0 \times \eta_m$).

The evaluation of the working point of the propeller, is based on the computation of the Speed of Advance $V_A$ and the thrust $T$. $V_A$ and the rotational speed of propeller set univocally the actual blade velocity diagram at a given pitch. From a certain point of view this procedure is quite similar to self propulsion towing tank tests, in the sense that the propeller is considered a measure instrument. In particular, it is meant to measure, continuously on the sailing ship, the propeller torque and the rotational speed to calculate, known the diameter, Torque Coefficient $K_Q$. With this coefficient and the propeller open water characteristic is possible to pick out the Advance Coefficient $J$ and, consequently, $V_A$ and $T$. 

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Regarding the second point, it is important to observe that $\eta_0$ and $\eta_{in}$ usually reach the highest values at different rotational speeds. So, it is necessary to consider the values of the product in the actual point matching propeller and engine characteristics. Moreover to be acquainted with the hydrodynamic working point of the propeller, enables to have further advantages. In particular:

- the inaccuracy due to scale effects, peculiar of model-ship correlations of self-propulsion tests, are drastically reduced;
- the system allows to reduce considerably the risk of cavitation and
- to consider values very close to the maximum values of efficiency (values usually avoided because these zones are too close to the strongly decreasing branches of the $\eta_0$ curves).

1.2 HSC application

To exploit the feasibility of the proposed procedure for HSC vessels a preliminary steady state analysis is performed on a typical fast ferry arranged with CP propellers and operating in the bay of Naples. The aim is to evaluate the effectiveness in fuel consumption reduction, already verified for other particular ship types.

2 PROPELLER AND ENGINE
CHARACTERISTIC FORMULATION

2.1 Controllable Pitch Propeller open water characteristic

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: $\eta_0 = V_A \, T / 2 \, \pi \, n \, Q = J / 2 \, \pi \, (K_T / K_Q)$

Where:

- $D =$ propeller diameter (m)
- $\rho =$ water density (kg/m$^3$)
- $N =$ rotational speed of propeller (s$^{-1}$)
- $T =$ trust (N)
- $Q =$ torque (N m)
- $V_A =$ speed of advance (m/s)

For a CPP the adimensional coefficients $K_T$ and $K_Q$ are functions of advance coefficient $J$ and blade orientation, so they are expressed as follow:

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

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

The characteristics of fixed blade propellers are usually described with a polynomial form of $J$ and $p$:

$$K_T(J; p) = A_0 + A_1 \, p + ... + A_i \, p^i + ... + A_n \, p^n$$

$$K_Q(J; p) = B_0 + B_1 \, p + ... + B_i \, p^i + ... + B_n \, p^n$$

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

$$A_i (p) = a_{i0} + a_{i1} \, p + ... + a_{in} \, p^n$$

$$B_i (p) = b_{i0} + b_{i1} \, p + ... + b_{in} \, p^n$$

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:

- $P_T = \{1, p, p^2, ..., p^n\}$
- $P_P = \{0, 1, 2p, 3p^2, ..., np^{n-1}\}$
- $J_T = \{1, J, J^2, ..., J^n\}$
- $J_J = \{0, 1, 2J, 3J^2, ..., m^{m-1}\}$

The coefficients are organized in the following matrices:

$$A = \begin{pmatrix}
    a_{00} & ... & a_{0n} \\
    ... & ... & ... \\
    a_{m0} & ... & a_{mn}
\end{pmatrix}$$

$$B = \begin{pmatrix}
    b_{00} & ... & b_{0n} \\
    ... & ... & ... \\
    b_{m0} & ... & b_{mn}
\end{pmatrix}$$

We could describe $K_Q$, $K_T$ and $\eta_0$ functions in a more simple way:

$$K_T(J; p) = (J^T A_p) \, K_Q(J; p) = (J^T B_p)$$

$$\eta_0(J; p) = J / 2 \, \pi \, (J^T A_p) \, (J^T B_p)^{-1}$$

Also for the partial derivative:

$$\frac{\partial \eta_0}{\partial J} = 1 / 2 \, \pi \, (J^T B_p)^{-2} \, [(J^T A_p) + (J J^T A_p)]$$

$$\frac{\partial K_T}{\partial J} = (J J^T A_p); \quad \frac{\partial K_T}{\partial p} = (J^T A_p)$$

$$\frac{\partial K_Q}{\partial J} = (J J^T B_p); \quad \frac{\partial K_Q}{\partial p} = (J^T B_p)$$

To evaluate the operating point of the ship it is necessary to use a coefficient that does not depend
on propeller rotational speed, represented by the $K_T/J^2$ term, that correspond to a thrust coefficient, given by thrust, diameter and advance velocity.

$$K_T/J^2 = T / (\rho D^2 V a^2) = J^2 (J^T A p)$$

Whose partial derivatives are:

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

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

By the solution of the two unconstrained problem the matrices $A$ and $B$ were found:

$$\begin{aligned}
\min_A \| y - \hat{y} \|^2 \\
\min_B \| w - \hat{w} \|^2
\end{aligned}$$

where $w$ and $y$ are vectors of experimental $K_Q$ and $K_T$ and $\hat{w}$ and $\hat{y}$ are the corresponding sets plotted by the proposed formula.

### 2.2 $E\ 028$ propeller

This paragraph shows the solution of the two unconstrained problem, proposed in the previous section, applied to the CPP E028 (tested in Towing Tank of Dipartimento di Ingegneria Navale of Naples). Data obtained are than compared with experimental data. Applying this procedure on open water experimental data, the order of magnitude of $\| y - \hat{y} \|^2$ and $\| w - \hat{w} \|^2$ are $10^{-3}$ and $10^{-5}$ respectively; moreover no value of $|\hat{y}_i - \hat{y}_i|$ and $|\hat{w}_i - \hat{w}_i|$ is 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

$$A = \begin{pmatrix}
4.90E-01 & 1.94E-02 & -3.19E-04 & -1.65E-05 \\
-5.44E-02 & 1.50E-02 & 1.53E-03 & 1.88E-05 \\
-8.64E-01 & -2.36E-05 & 1.74E-03 & 1.19E-04 \\
-1.20E-01 & -3.89E-02 & -5.26E-03 & 2.24E-06 \\
1.89E-00 & -1.44E-02 & -6.85E-03 & -5.56E-04 \\
-2.44E-01 & 4.12E-02 & 6.53E-03 & 5.05E-05 \\
-1.65E+00 & 3.27E-02 & 9.25E-03 & 7.62E-04 \\
1.38E-01 & -1.29E-02 & -2.67E-03 & -4.95E-05 \\
5.10E-01 & -1.54E-02 & -3.81E-03 & -3.11E-04 \\
\end{pmatrix}$$

$$B = \begin{pmatrix}
7.48E-02 & 6.46E-03 & 1.54E-04 & -1.49E-06 \\
-2.16E-02 & -6.32E-04 & 3.90E-04 & 2.73E-05 \\
-1.10E-01 & -7.31E-03 & 1.23E-04 & 2.48E-05 \\
4.76E-02 & 2.19E-03 & -1.38E-03 & -9.02E-05 \\
2.22E-01 & 1.18E-02 & -1.32E-03 & -1.24E-04 \\
-9.94E-02 & -3.77E-03 & 1.63E-03 & 1.05E-04 \\
-1.93E-01 & -6.49E-03 & 2.12E-03 & 1.70E-04 \\
4.07E-02 & 1.45E-03 & -6.08E-04 & -3.94E-05 \\
6.05E-02 & 1.18E-03 & -9.24E-04 & -7.00E-05 \\
\end{pmatrix}$$

The surface representing efficiency $\eta_0$ as function of Pitch and Advance Speed has been plotted in order to easily compare the solution with experimental data. The Figure 1 shows data for $J > 0$.

![Figure 1. Data comparison in terms of efficiency.](image1)

After that, diagrams of efficiency and Advance coefficient vs $K_T/J^2$ and $p$ (a sort of BP diagram) was plotted by the use of the proposed formulation.

![Figure 2. E.028 BP diagram](image2)
2.3 Engine characteristic

The performances of engines are commonly represented in engine maps. To optimize simultaneously engine and propeller performances, they have to be comparable, therefore a polynomial formulation in terms of power and rotational speed has been worked out.

\[
N^T = \{1; N; N^2\}; \quad n^T = \{1; n_m; n_m^2; n_m^3; n_m^4; n_m^5\}
\]

\[
C_s = N^T C n \in [n_{\text{min}}; n_{\text{max}}] \times [N_{\text{min}}; N_{\text{max}}]
\]

Where:

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

Finally the engine efficiency is given by:

\[
\eta_m = \frac{3600}{H_i} C_s
\]

3 ESTIMATION OF SELF PROPULSION COEFFICIENTS.

3.1 Main principles

To estimate the operating point the propeller is used as a measure instrument: by measuring pitch, torque and rotational speed it is possible to estimate thrust and advance speed through propeller characteristic.

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 \(\eta_R\), that can be estimated through a direct thrust measurement, that is commonly done in towing tank tests but is not effective onboard.

\[
\eta_m = \frac{3600}{H_i} C_s
\]

Figure 3. Scheme of thrust and advance velocity estimation, at a given pitch.

3.2 Estimation problems

The control logic is based on the estimate of hydrodynamic propeller state by measuring torque as accurately as the current technology allows.

In order to evaluate the effects of torque, pitch and shaft speed measurement errors on the whole procedure, that means how small variations affect thrust estimation, an accurate error propagation analysis has to be considered.

The most critical measure regards the torque, so that the term \(\frac{\delta K_T}{\delta K_Q}\) can give an idea of the error behaviour in thrust estimation.

Considering the formulas given in 2.1 the partial derivative \(\frac{\delta K_T}{\delta K_Q}\) has been calculated for the propeller E028 in whole pitch and advance range (see Figure 4). The diagram shows that error in estimation strongly depends on pitch and could be critical, particularly at lower pitch and advance.

4 OPTIMIZATION PROBLEM

4.1 Objective function

The only conscious manageable efficiency to minimize fuel consumption, varying the pitch, are \(\eta_0\) and \(\eta_m\). Therefore the objective function to be maximized is \(\eta_0 \times \eta_m\).

4.2 Equality constrain

To preserve ship speed during the optimization, the thrust must be maintained constant; so an equality constrain has been introduced where the thrust is presented in an non dimensional form through \(K_T/J^2\) term, that represents the thrust...
coefficient required, function of trust, diameter and advance velocity.

\[ K_T^*/J^2 = T / (\rho D^2 V_a^2) \]

The equality constrain could be written in this form:

\[ \frac{K_t(p; J)}{J^2} - \frac{K_t^*}{J^2} = 0 \]

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

In an explicit form:

\[ J^2 (J^T A_p) - T / (\rho D^2 V_a^2) = 0 \]

4.3 Inequality constrains and parameters bounds

The inequality constrains presented are substantially:

- the operational limit of the propeller and the engine;
- propeller working point where great variation of its efficiency is expected;
- cavitation.

The propeller limits, boundary of experimental data:

\[
\begin{align*}
J - J_{\min} & \geq 0 \\
J_{\max} - J & \geq 0 \\
p - p_{\min} & \geq 0 \\
p_{\max} - p & \geq 0
\end{align*}
\]

The engine limits :

\[
\begin{align*}
n - n_{\min} & \geq 0 \\
n_{\max} - n & \geq 0 \\
N_{\max}(n) - N & \geq 0
\end{align*}
\]

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

To avoid working points subjected to great efficiency variations a constrain on partial derivative 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 5 is shown the cross out zone for a fixed pitch position.

4.4 Constrained optimization

The whole problem could be expressed in the following form

\[
\begin{align*}
\max_{p, \eta_0} (p; J) \cdot \eta_m(N(p, J); n(p, J)) \\
J - J_{\min} & \geq 0 \\
J_{\max} - J & \geq 0 \\
p - p_{\min} & \geq 0 \\
p_{\max} - p & \geq 0 \\
n - n_{\min} & \geq 0 \\
n_{\max} - n & \geq 0 \\
N - N_{\min} & \geq 0 \\
N_{\max}(n) - N & \geq 0 \\
\eta_{ij}(p; J) & \geq 0 \\
\frac{K_t(p; J)}{J^2} - \frac{K_t^*}{J^2} & = 0 \\
\tau - \tau_{cr}(\sigma) & \geq 0
\end{align*}
\]

The solution of the problem returns the optimal pitch, then the optimal propeller speed, as function of thrust and advance speed as shown in the scheme below.
5 TEST CASE: STEADY STATE ANALYSIS

5.1 The ship

To evaluate the effectiveness of this kind of solution on HSC a typical design of a small fast ferry, operating in the bay of Naples has been worked out.

The main characteristics are reported:

- Lenght over all = 45.0 m
- Max Beam = 8.1m
- Design speed = 25 kn
- N° of passengers = 395
- Light Displacement = 230 t
- Medium Displ. = 250 t
- Heavy Displ. = 270 t

A 3D view of general arrangements is shown in Figure 6:

\[ R_T = v_s^T R_d \]
\[ \eta_R = v_s^T H_d \]
\[ (1-t) = v_s^T T_d \]
\[ (1-w) = v_s^T W_d \]

where:

\[ v_s^T = \{1, V_s, V_s^2, \ldots, V_s^n\} \]
\[ d^T = \{1, \Delta, \Delta^2, \ldots, \Delta^n\} \]

5.2 Data comparison

At first a combinator curve has been calculated, taking into account the engine map and the hull behaviour at medium displacement:

Many points at different RPM have been considered choosing the power related to the lower consumption. Then the best propeller pitch has been calculated for each rotational speed.

The consumption has been estimated for each displacement in whole speed range taking into account the combinator curve showed in Figure 9. For the same conditions the solution of the problem proposed in paragraph 4.4 has been found. Results and comparison are showed in terms of consumption.
It is important to focalize the attention on the consumption in Figure 11: though the combinator curve is worked out at this displacement, the optimization logic allows a lower fuel consumption; This result underline that the best solution is not always on the best engine performances but a lower engine efficiencies sometimes allows a better propeller efficiency, so big to maximize the objective function proposed in 4.1.

Diagrams are shown in Figures 11 ÷ 15

The differences in fuel consumption that has been found at high values of speed are due to the greater resistance variation with displacement.
6 CONCLUSIONS

Despite the optimization of propulsion parameters is expected to give the most interesting results for ship subjected to great variation of working conditions, the preliminary steady state calculations presented in the paper demonstrate that favourable results are possible also for fast passenger ferries.

In this case the more relevant irregularity source is the number of boarded passengers, that varies the ship displacement. However, a fast ship is affected by other factors that determine variations of ship working point, like wind, shallow water and hull fouling.

The improvement in fuel consumption depends on the characteristics of engine and propeller and ship.

The steady state analysis allows to understand the effectiveness of the system and justify a deeper analysis. The case study considered has shown that displacement variation for a fast ship propelled by CPP justifies the adoption of this kind of control, at least after a preliminary evaluation.

In the paper other aspects have been considered, as the sensitivity of estimated values on the measurement errors.

To apply onboard such an optimal propulsion system, a reliable control strategy has to be developed. The control has to determine at the same time two parameters, propeller speed and pitch, so that some difficulties may arise.

As an example, let us consider the ship working at an operational point that is not optimal; when the optimizer determines a new set of propeller speed and pitch, the path followed by control system to get the desired working condition assumes a great importance. There will be a transient during which the sets of speed and pitch stated by the optimizer could became unstable. Moreover, unlike the combinatory control, in this case there would not be a direct correspondence between the master command lever and the output of the controller. As a possible solution, there could be a double control level; the first one maintain the thrust (estimated) to the value desired by the helmsman, the other performs the optimization task.

7 REFERENCES


