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A new method for a preliminary definition of a high–performance rudder for tuna purse seiners

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ABSTRACT

The aim of this paper is to provide a simple method for the definition of a rudder for tuna purse seiners. The model achieved by the application of this method ensures the manoeuvrability of initial turning, course keeping and yaw checking. For this, the results obtained by other authors, through rudder tests and manoeuvrability tests of fishing vessels have been integrated with the recommendations of the International Normative. Finally, in the paper the method is applied to the case of a tuna vessel, providing a rudder model which could be optimised with CFD (Computer Fluid Dynamics) in further tests. The method proposed can be applied to other vessels whose main dimensions are met.

Key words: rudder optimisation; vessel manoeuvrability; tuna vessel design

INTRODUCTION

Limited manoeuvrability is one of the most significant weak points in the operation of the fishing vessels when compared to other vessels. This is mainly due to the activity of fishing, which means shipping with nets. This characteristic not only leads to inefficient operation and therefore to high fuel consumption, but also to a higher risk of accidents.

Above all, these threats stand out in the case of tuna purse seiners because of their particular manoeuvrability needs throughout their entire voyage; during navigation (the rapid pursuit of fish shoals), during manoeuvres (the releasing of nets at high speed) and whilst tacking (the stability of the vessel during collection of catch).

In order to minimise these weak areas, the current construction tendency in these types of vessel is based on wider dimensions, optimised hydrodynamic behaviour, usage of controllable propellers and high–performance rudders. The objective of these improvements is to reduce running costs and to increase safety during operation.

The main purpose of this paper is to contribute to the definition of high–performance rudders for tuna fishing vessels. For that, a simple definition method will be shown of an optimised rudder model for this type of boat, which serves as a starter point for further trials with CFDs.

The method not only takes into account the manoeuvrability recommendations provided by the International Rules (IMO, SOLAS, and DNV), but also the results achieved in previous experimental manoeuvrability test studies with fishing vessels and rudders.

As a result of the application of this method, the first step obtains the minimum forces necessary of the rudder to meet certain existing manoeuvrability requirements. Then, the data from previous studies will be taken into account in order to relate these forces with the rudder geometric characteristics and its relative position in the vessel.

The rudder model obtained ensures meeting certain manoeuvrability demands and the Classification Societies' (CS) requirements. However, other requirements are not ensured by the model, for this reason some requirements must be checked through testing with CFDs.

This paper shows the base application method for a tuna fishing vessel, thus obtaining the definition of a rudder model.

The method presented can easily be repeated to define rudders for tuna fishing vessels, guaranteeing their compliance to certain operational characteristics.

METHODS

The manoeuvrability requirements considered have been determined by SOLAS Part C [7], IMO MSC/Circ.1053 and MSC.137 (76) [5, 6] and the Regulations of the Classification Society Det Norske Veritas [4] (Part 3, Chapter 3, Section 2). In addition to the previous compulsory regulations and recommendations, the results achieved during manoeuvrability tests in fishing vessels carried out in the "El Pardo" model basin [2, 3] have been considered, together with the conclusions extracted from other rudder tests [8, 9].

As a consequence of the integrated recommendations provided by these sources, a series of useful expressions will be obtained. These expressions will allow the definition of the rudder geometry, and its relative position in the vessel ensures the realization of certain manoeuvrability requirements such as:

Turning ability. It is a critical issue for tuna purse seiners due to their operational activity. Adhering to the Gertler acceptability criteria, the following expression can be used [2]:

$$D < (-5C_b + 7.2) \cdot L_{pp} \quad (1)$$

The turning circle diameter value can be calculated through the expression [3]:

$$\frac{D}{L_{pp}} = \frac{0.048L_{pp}}{sen(2\alpha)B} \cdot \frac{\frac{1}{{C_b}^2}\left(1 + \frac{25(T_{pp} - T_{pr})}{L_{pp}}\right)}{\left(\frac{dF_n}{d\alpha}\right) L_{pp}} MV^2 \quad (2)$$

The initial capacity for manoeuvrability is regulated by the IMO [7]. In accordance with this, the advance (A_v) must not exceed 4.5 times the length of the vessel, and the tactical diameter (D_t) must be less than 5 times the turning circle length.

Therefore, as a result of model trials and sea testing, the following expression is found:

$$D_t = 1.65D\ C_b + 0.08 \quad (3)$$

After analysis of turn manoeuvre tests with models [2] for boats with block coefficients of less than 0.6 (which is the case of tuna fishing vessels), the following relations can be concluded:

$$D_t = D_v + 0.55D \quad (4)$$

$$D_v = 0.5A_v \quad (5)$$

This way one can define the advance as a function of the turning diameter (D). Taking into consideration the limitations of the D/Lpp ratio and the advance value limit in relation to vessel length, the maximum value turning circle diameter value can now be expressed, as well as the normal minimum force per angle unit.

Course keeping. This can be defined as the ability to maintain a selected straight line course. By varying the rudder degree angle (spiral test) the progression can be observed in relation to the changes. It is desirable that the evolution is stable, positive and that hysteresis does not occur. The degree of leeway for this quality can be determined via the evaluation of the hysteresis loop width (a).

$$a = 18.12 - \frac{46.43}{T'} \quad (6)$$

Where:

$$T' = f\left(\frac{1}{\frac{C_{ft}}{\alpha}}\right) \quad (7)$$

and:

$$\frac{C_{ft}}{\alpha} = \frac{\frac{F_t}{\alpha}}{\frac{1}{2}\rho \cdot A_r \cdot V_r^2} \quad (8)$$

In order to minimise this value it is necessary to maximise (Ft/α).

The yaw checking ability. This ability is verified by the zigzag manoeuvre test, in which moderate changes of course within time and space are measured. The initial zigzag manoeuvre can be evaluated by measuring the number P of Norrbin, which defines the angle of course turned per unit of rudder angle used, once a determined length is navigated [3]:

$$P = K'(1 - T' + T'e^{-1/T'}) > 0.275 \quad (9)$$

The number P is also accepted by IMO [6] to evaluate the initial progression capacity for manoeuvrability.

Through the Nomoto equation, the following expression is obtained [3]:

$$\frac{K'}{T'} = 0.325 \cdot \frac{F_t}{\alpha} \cdot \frac{L_{pp}}{MV^2} \cdot \frac{1}{K_i^2 + K_j^2} \quad (10)$$

This defines the minimum value for the lift force on the rudder by angle unit (Ft/α)

In order to ensure these forces per angle unit of the operation of the rudder (see Fig. 1) it is necessary to relate the said forces to design parameters that are controllable: the relative position of the rudder in the vessel, and the dimensional geometric characteristics of the rudder.

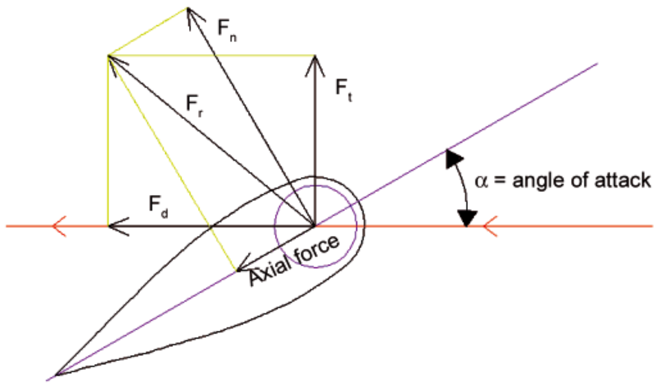

Fig. 1. *Notation of forces on the rudder*

Rudder behaviour is determined to a great extent by the conditions in which it operates, and these are defined greatly by the relative position of the rudder in the vessel, the propeller and the hull [2, 9, 11].

The principle objectives aimed for in the definition of a high performance rudder are the following: the increase of lift force and the decrease of drag force. This resistance is greatly conditioned by the boundary layer of water which is created around the rudder surface. If there is turbulent water flow (high Re), the profile velocity increases and the pressure falls (Bernoulli), which is clearly unfavourable as the drag force increases and lift force decreases.

$$Re = c.Vr/\nu \quad (11)$$

Another motive for avoiding turbulent water flow is the appearance of cavitation. This phenomenon is determined by the profile pressures of the rudder. Profile pressure varies with the rudder section, and in addition to this cavitation can be found in the propeller wake caused by water accelerating from the root to the extremes of the blades. For this we encounter the lowest flow pressures at the extremes of the propeller, and therefore the highest risk of cavitation. Sections of the rudder that coincide with the extremes of the propeller will be critical from the point of view of cavitation.

The influence of rudder angles in cavitation is noticeable, with the risk of cavitation increasing the greater the rudder angle. Rudder angles have an important bearing on tuna purse seiners and the risk of cavitation should be avoided.

$$\sigma \leq -C_p \quad (12)$$

$$\sigma = \frac{P_{at} + \rho \cdot g \cdot hg - P_v}{0.5\rho V_r^2} = \frac{P_0 - P_v}{0.5\rho V_r^2} \quad (13)$$

$$C_p = \frac{P_l - P_0}{(0.5\rho V_r^2)} \quad (14)$$

The relation between pressure and lift coefficients can be expressed in the function of distance ($\hat{\gamma}$) from the origin to the profile surface by:

$$C_{cf} = -\hat{y} \int \left(\frac{C_p}{c}\right) dl \quad (15)$$

Furthermore, the effect of the propeller on rudder behaviour is significant. The propeller creates axial thrust to the water, so the effect is that the water arriving at the rudder has higher velocity. Using Bernoulli and the Gutsche correction, we arrive at the following expression [9]:

$$V_r = V(1 - 0.8C_b + 0.26) \cdot \left(1 + 0.5 + \frac{0.5}{1 + \frac{0.15}{\frac{X}{d}}} \left(\left(1 + 8 \cdot \frac{K_t}{\pi J^2}\right)^{0.5} - 1\right)\right) \quad (16)$$

$$J = \frac{V(1 - 0.8Cb + 0.26)}{N\, d} \quad (17)$$

In order to try to minimise the effects of turbulent flows, it is necessary to achieve a low V_r value. For this a low x/d is recommendable, taking into account the minimum values given by CS which must be fulfilled to avoid problems of vibration.

Tuna vessels however achieve high J values (0.35 to 0.94). For these ranges of J, experimental rudder tests [8, 9] have demonstrated that the value of C_{ft}/α versus the relation X/d increases proportionally (C_{fd}/α decreasing) to X/d = 0.4 (for low values of J the trend is reversed).

Considering tuna vessel characteristics (Table 1), and the previous points, the initial value selected is X/d = 0.22, which complies with the minimum requirements of CS, and would avoid reaching high Re without the penalising lift force.

The flow straightening effect also has to be taken into account [10], influenced greatly by the stern of the vessel, which causes a reduction in water flow speed when reaching the propeller (see Fig. 2). The usual consequence of the straightening effect is to increase the rudder attack angle (α_e). Its effect can be measured by using the flow straightening factor (γ), which relates the ship drift angle, β_R, with the flow attack angle to the ship axis for zero lift (α_0).

$$\gamma = \alpha_0 / \beta_R \quad (18)$$

$$\alpha_e = \alpha - \gamma . \beta_R \quad (19)$$

As can be seen, the value of (γ) should be as small as possible to widen α_e.

The γ values obtained during trials, carried out with rudders that protrude vertically [10] in the superior extreme of the propeller diameter, have been high. This leads to the election of the Z/d value that indicates the relative position between the rudder and propeller. According to the trial results, it would be advisable to place the rudder so that it does not protrude beyond the highest blade tip of the propeller (Z/d > 1) to obtain a low flow straightening factor. However, it is recommended that the ratio Z/d < 1 is used in order to guarantee the coverage of the rudder span. As a consequence to the previous points, the ratio Z/d = 1 can also be recommended when considering bending movements and rudder blade height. Finally, the ratio Y/d = 0 obtained from rudder tests [10] has achieved the highest values of C_{ft}/α, and the minimum values for α_0, and therefore also the minimum values of γ.

In order to determine value limits for forces on the rudder, it will be necessary to act on its geometry and to understand the consequences of this. For this, a real tuna purse seiner will be used an example (Table 1).

Tab. 1. *Characteristics of the tuna purse seiner "Draco" (Source: Infomarine, May 2006)*

L (m)	95.70
L_{pp} (m)	82.70
B (m)	15.20
T (m)	6.70
M (Tn)	4 642
V (m/s)	9
C_b	0.54
X_b (m)	–2.55
Main engine Power	6000 kW (750 rpm)
Propeller	Controllable 152 rpm (4 blades)
Propeller Diameter (m)	4.3

The taper ratio (TR) is the relation between the lower and higher chords. If the value of this coefficient increases, both the lift force and the separation angle of water flow also rise.

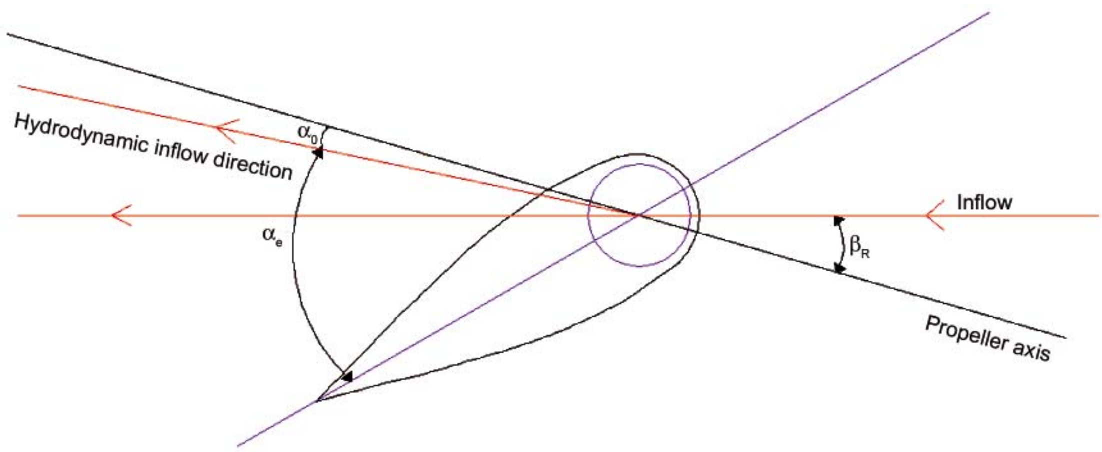

Fig. 2. *Angles of the flow straightening effect*

This also leads to an increase in the bending moment, and the majority of the rudder is adversely affected by the propeller wake. Due to these reasons the ratio TR = 1 has been taken for the calculations.

Another characteristic to be defined is the leading edges of the rudder. a square leading edge shape has been used for high rudder angles, necessary for the operation of tuna vessels; the drag force is less than for rudders with rounded edges.

Finally, a rudder with a flap has been selected due to the quick turning speed and rapid evolution, which makes it ideal for the high manoeuvrability needed by tuna purse seiners. Furthermore, the rudder is going to support minimum vertical forces and bending moments.

Calculation of the minimum normal force per rudder angle unit

This force is calculated bearing in mind the turning circle abilities applicable to the acceptability criteria of Gertler, Eq. (1), to the vessel base (Table 1).

$$D/L < -5C_b + 7.2 = 4.5 \text{ m}$$

Therefore, D_{max} = 372.15 m is obtained. With this value, for a turn angle of 35° (0.61 rad), Eq. (2) must be applied. For this, using the vessel base, a minimum normal force value is obtained of:

$$dF_n/d\alpha = 1545.31 \text{ kN/rad}$$

Alternatively, to verify this maximum diameter obtained complies with the IMO requirements regarding turning ability:

$$A_v < 4.5L = 372.15 \text{ m}$$

Now considering expressions (3) – (5) and substituting the values, the result is:

$$D_{max} = 372.15 < 601.76 \text{ m}$$

Therefore, for the minimum value of F_n/α would lead to the turning ability requirements of the IMO being met.

To calculate the minimum lift per angle unit for the correct operation of the vessel, firstly the number P through Eqs. (9) and (10) is analysed. Nevertheless, in order to find the minimum value of lift force by turn angle, it is necessary to define the relations between K' & T' with F_t/α. To obtain these relations, expressions (16) and (17) are integrated into the following formulae:

$$T' = \frac{K_i^2 + K_j^2}{0.27 + 0.258(F+0.38)^{0.39} - 0.5 + \frac{X_b}{L_{pp}}} \cdot \frac{1}{G+1} \quad (20)$$

$$G = 0.0193\,\frac{L_{pp}}{B}\,\frac{1}{C_b^2}\left(1 + \frac{25(T_{pp}+T_{pr})}{L_{pp}}\right) \quad (21)$$

$$F = \frac{\frac{F_t}{\alpha}}{\frac{1}{2}\cdot\rho\cdot V_r^2} \cdot \frac{(1.26 - 0.8C_b)^2}{T} \cdot \left(\frac{1}{B}\right)\left(\frac{1}{C_b{}^2}\right)\left(1 + \frac{25(T_{pp} - T_{pr})}{L_{pp}}\right) \quad (22)$$

The previous expressions have been empirically obtained from reference [3].

Considering also the values of the vessel base (Table 1) the relations are finally obtained:

$$T' = \frac{0.065}{0.258\left(7.19\cdot 10^{-6}\frac{F_t}{\alpha} + 0.38\right)^{0.39} - 0.26} \quad (23)$$

$$K' = 3.788\cdot 10^{-7} \cdot \frac{\frac{F_t}{\alpha}}{0.258\left(7.19\cdot 10^{-6}\frac{F_t}{\alpha} + 0.38\right)^{0.39} - 0.22} \quad (24)$$

The P number can be expressed as a function of F_t/α. In order to evaluate the lower limit of this value, the functions which make up expression (9) will be analysed:

$$P = (1 - T' + T'e^{-1/T})K' = f_1 \cdot f_2 > 0.275$$

Where:

$$f_1 = 1 - T' + T'e^{-1/T} \quad (25)$$

and:

$$f_2 = K' \quad (26)$$

Function f_1 (Fig. 3) is not continuous on T' = 0 and its limits tend infinitely towards 0 and 1.

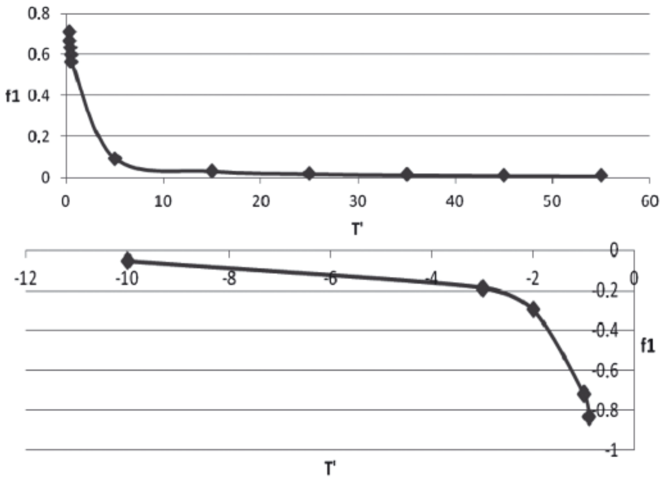

Fig. 3. Tendency of function f_1 of the number P of Norrbin against T'

If function f_2 (Fig. 4) is analysed, which depends on F_t/α, it can be seen that a discontinuity in f_2 = K' = 0 also exists. The maximum of function f_2 is obtained by F_t/α = 441 kN/rad.

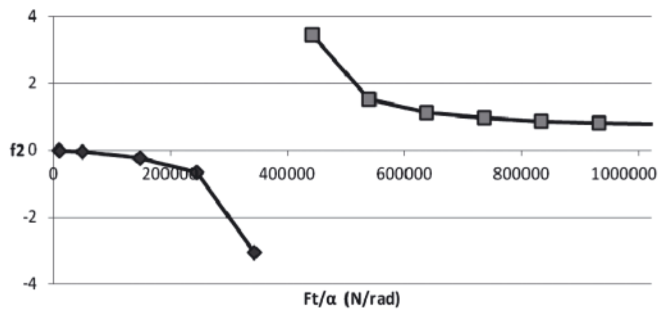

Fig. 4. Tendency of function f_2 of the number P of Norrbin as a function of F_t/α

This value of F_t/α signifies that T' < 0 and, therefore f_1 takes negative values. To ensure T' > 0 it will be necessary to use F_t/α > 838.3 kN/rad, even though this value does not comply with the requisite given in Eq. (9). For this it is necessary to use expression F_t/α > 2009 kN/rad (Fig. 5), which will correspond to the minimum lift force required per unit angle.

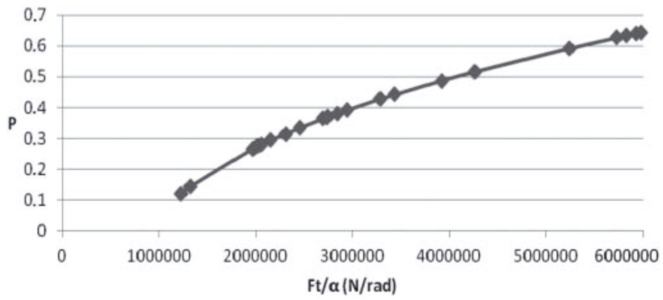

Fig. 5. Tendency of number P of Norrbin against Ft/α (N/rad)

Although the increase in the F_t/α value is favourable for complying with expression (9), this increase penalizes the ability to keep course (6). In addition, these high values of F_t/α implicate an enlargement of the servomotor and rudder.

The leeway for the course keeping ability is measured by the width of the hysteresis loop, which only has meaning for positive values. Despite the fact that expression (6) is zero for T' = 2.56 (Fig. 4), for this value expression (9) (P = 0.128, f_1 = 0.174 y f_2 = 0.737) is not carried out.

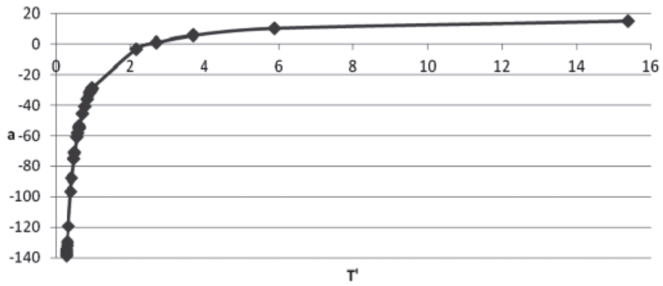

Fig. 6. Width tendency of the hysteresis loop against T'

Following the previous results, the minimum lift force per angle turn was assumed by:

$$(F_t/\alpha)_{min} = 2744 \text{ kN/rad}$$

This allows the value to comply with expression (9) without excessive risk to the course keeping ability (6).

Calculation of main characteristics

The fundamental geometric characteristics that identify a rudder are: span (h) defined in the normal flow direction, chord (c) which is the measurement of the rudder blade, thickness (t), perpendicular to the longitudinal axis of the vessel (see Fig. 7). Other parameters are: the profile type (t/c), area of the rudder (A_r), defined as the product span by the chord:

$$A_r = h.c \tag{27}$$

and the aspect ratio (λ), which is the relation between the rudder span and the average chord measurement (elongation):

$$\lambda = h/c \tag{28}$$

Firstly, in order to select the rudder characteristics it is necessary to take into account the following points:

- The stern post characteristics (for a relation ratio Z/d ≈ 1) limit the span of the rudder (h) to 6 m.
- In accordance with CS, the minimum area of the rudder blade [5] is limited to A_r = 8.26 m^2 for the vessel base according to:

$$A_r = \frac{TL_{pp}}{100}\left(1 + 50C_b^2\left(\frac{B}{L_{pp}}\right)^2\right) \tag{29}$$

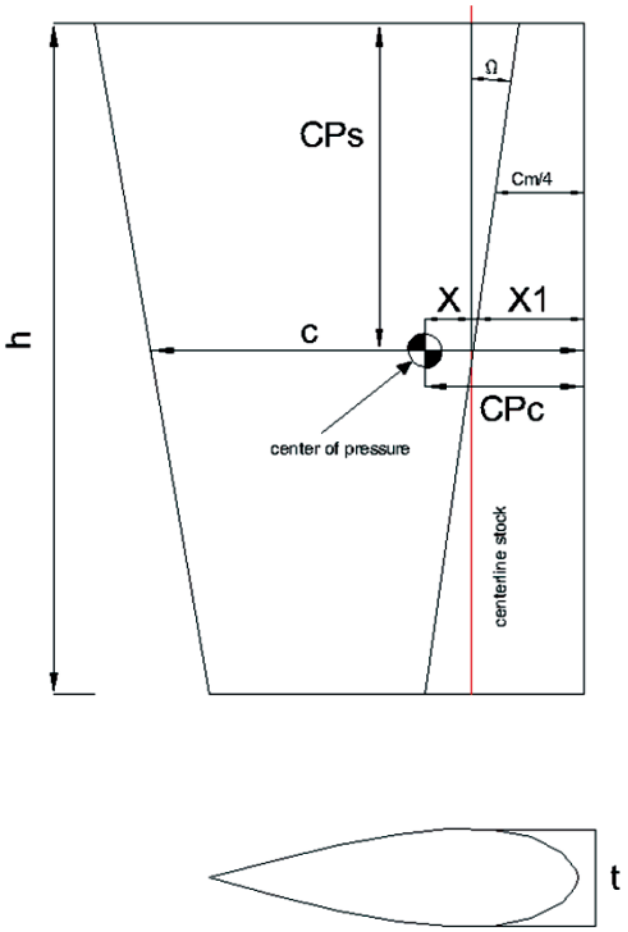

Fig. 7. Notation of the main parameters in the rudder

- It is recommended that the elongation ratio (λ) is as high as possible because of the increase in the lift force. However, on the other hand, for flap rudders the chord must be wider. Due to the restriction of the space on tuna vessels, the possible maximum span is 6 m.
- Observing the flow speed on the rudder and the possible chords (16), the Re values are expected to be high. Therefore, as the lift coefficient increases (C_{ft}) the drag decreases (C_d), and the separation angle (α_s) and cavitation risk also increase (see Table 2).
- Finally, note that for equal values of Re, the drag force coefficient (C_{fd}) increases when the t/c ratio also rises [11].

$$C_{fd}/_{\alpha} = \frac{F_d/_{\alpha}}{\frac{1}{2}\rho \cdot A_r \cdot V_r^2} \tag{30}$$

Table 2 shows different calculated possibilities of rudders for different Re values (and therefore chords), analysing their respective stall angles. These have been calculated through expressions (17), (27) and (28) integrated into [3]:

$$\alpha_s(\text{degrees}) = 7.11\left(1 + 7\cdot\frac{t}{c}\right)\left(1 + \frac{1.25}{\lambda}\right)\cdot \left(1 + 0.048\left(\ln\left(1 + \frac{8K_t}{\pi J^2}\right)\right)^{0.5}\right)\cdot\frac{h}{d} \tag{31}$$

The previous expression has been obtained from model tests and verified with real fishing vessels up to 6 m of rudder span. In addition to this, for the t/c calculation expressions (8) and (16) have been integrated together with the minimum lift force value obtained in [3]:

$$\frac{C_{ft}}{\alpha} = \frac{\frac{F_t}{\alpha}}{\frac{1}{2} A_r V_r^2} = \frac{2\pi\lambda}{\lambda + 2.55}\left(1 - 0.35\frac{t}{c}\right)\cdot$$
$$\cdot\left(1 + K_t \frac{\frac{8}{(\pi J^2) d}}{h}\right)\left(\frac{C_b + 0.3}{1 + 1.214\left(1 - e^{-0.3\left(\frac{K_t}{J^2}\right)}\right)}\right) \tag{32}$$

Finally, the expression used is:

$$\frac{t}{c} = \frac{1}{0.35}\left(1 - 12.41\frac{\lambda + 2.55}{h(h + 4.52)}\right) \tag{33}$$

Tab. 2. *Rudder geometric characteristics for different Re values with their respective stall angles*

Re	C (m)	λ	H (m)	t/c	A_r (m²)	α_s (rad)
3 10⁷	3	1.85	5.55	0.07	16.65	0.39
		1.90	5.70	0.15	17.10	0.56
		1.95	5.85	0.23	17.55	0.72
		2.00	**6.00**	**0.30**	**18.00**	**0.88**
2.9 10⁷	2.9	1.90	5.51	0.00	15.98	0.22
		1.95	5.66	0.08	16.40	0.27
		2.00	5.80	0.16	16.82	0.43
		2.05	5.95	0.24	17.24	0.58
		2.10	6.09	0.31	17.66	0.73
2.8 10⁷	2.8	2.00	5.60	0.01	15.68	0.28
		2.05	5.74	0.09	16.07	0.43
		2.10	5.88	0.16	16.46	0.58
		2.15	6.02	0.23	16.86	0.72

Table 2 shows the valid solutions achieved which meet the maximum span rudder allowed (6 m) with relation t/c remaining positive. The chosen option is that highlighted in Tab. 2. This option is the most interesting for a flap rudder as it has the wider chord (c), a not very high t/c profile relation and the highest stall angle (critical for tuna vessels). This option also complies with the minimum rudder area demanded by CS.

Stall angle correction

The stall angles, indicated previously, have been calculated using empirical expressions obtained in successive tests on tuna vessels of fixed rudders blades with taper ratios different to one. Therefore, one must consider the effect of the rudder with a taper ratio value equal to one in the stall angle calculation. For this, the following expressions (suitable for rudders with a squared blade tip) have been used [9], where the angles shown are expressed in degrees:

$$C_{ft} = \left(1.95\frac{\pi}{57.3\left(1 + \frac{3}{\lambda}\right)}\right)\alpha + \frac{C_{dc}}{\lambda}\left(\frac{\alpha}{57.3}\right)^2 \tag{34}$$

$$Cdc = 0.1 + 1.6.\ TR \tag{35}$$

It will be assumed that in the most unfavourable condition ($\alpha = \alpha_s$), the value of (F_t/α) will be the minimum obtained in section 2.1. Substituting this value in expression (8) C_{ft}/α is obtained. With this initially assumed value of TR = 1 plus the C_{ft}/α value now acquired, we see that the separating angle is 52.24° or 0.91 rad (a difference of 3.4% with respect to the value calculated through expression (31)).

Being prudent, the most unfavourable separating angle regarding the vessel axis is taken (0.88 rad), therefore it is necessary to adjust expression (35):

$$C_{dc} = 0.1 + 1.62\ TR \tag{36}$$

Because of this, we arrive at a new more conservative expression that defines the law for lift force per unit of flap rudder angle (34), which will be evaluated later.

$$C_{ft}/\alpha = 0.04 + 2.61 \cdot 10^{-4} \cdot \alpha \tag{37}$$

Calculation of the rudder forces and profile type

In this section, the forces per angle turn of the rudder will be evaluated to determine whether the minimum force demanded is achieved (section 2.1). For this, force coefficients will be analysed, of which the normal force is:

$$C_{fn}/\alpha = \frac{\frac{F_n}{\alpha}}{0.5 \cdot \rho \cdot V_r^2 \cdot A_r} \tag{38}$$

Taking into account the value of $(F_t/\alpha)_{min}$ calculated in section 2.1, with α as 0.61 rad (35°) in equation (38) $(C_{fn}/\alpha)_{min}$ can be obtained.

On the other hand, in fishing vessels the transverse components and normal force on the rudder can be connected in the following form [3].

$$F_n = F_t/C \tag{39}$$

Where C is a constant determined empirically, and is defined as:

$$C = 1 - 0.00286\alpha \tag{40}$$

By substituting these two expressions in equation (38), and bearing in mind (37), a new equation is defined, as a function only of turning angle α:

$$\frac{C_{fn}}{\alpha} = \frac{\frac{C_{ft}}{\alpha}}{C} = \frac{0.04 + 2.61 \cdot 10^{-4} \cdot \alpha}{1 - 0.00286\alpha} \tag{41}$$

In this expression, we have already remembered the selected rudder (with flap and taper ratio equal to 1), because expression (37) is used, and it was modified for this particular case.

Although it would be convenient to evaluate expression (37) by comparing it with another expression of lift force coefficient for rudders with flaps [9]:

$$C_y = 2.262\alpha + 0.9453\beta - 0.9329\alpha^2 + \\ - 0.6039\beta^2 + 0.4736\alpha\beta \tag{42}$$

Where β is the angle that forms the flap with the rudder axis. Setting a relation between α and β that, α/β = 1 [4], for 35ş one determines that C_y is 1.91 and C_{ft} is 1.95. That is to say, they achieve similar values; therefore expression (37) can be given as valid.

So for 35° $(F_n/\alpha)_{min}$ = 1545.31 kN/rad (see section 2.1) according to equation (38).

$(C_{fn}/\alpha)_{min} = 0.0306$

And, alternatively, with respect to equation (41) for 35ş:

$C_{fn}/\alpha = 0.054 > (C_{fn}/\alpha)_{min} = 0.0306$

Like this, the manoeuvrability requirements are met, in accordance with the normal forces and that of lift required.

To test the rudder evolution at different angles (Fig. 8) expressions (8), (30) and (41) are used. The resistance coefficients for drag and the resulting force can be calculated by:

$$C_{fn} = C_{ft} \cdot \cos\alpha + C_{fd} \cdot \sin\alpha \quad (43)$$

$$\frac{C_{fr}}{\alpha} = \left(\left(\frac{C_{ft}}{\alpha}\right)^2 + \left(\frac{C_{fd}}{\alpha}\right)^2\right)^{0.5} \quad (44)$$

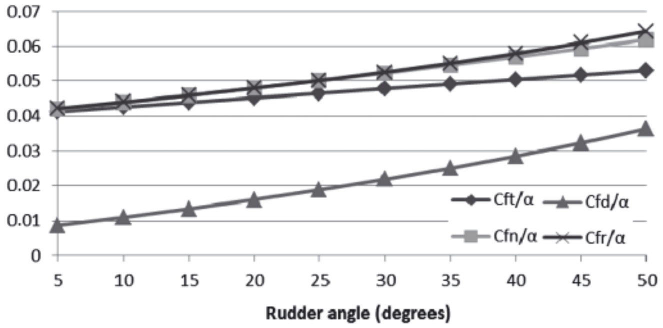

Fig. 8. Evolution of dimensionless force coefficients on the rudder for different angles

One can see in Fig. 9 that, for whatever the angle of rudder turn, it complies with P > 0.275.

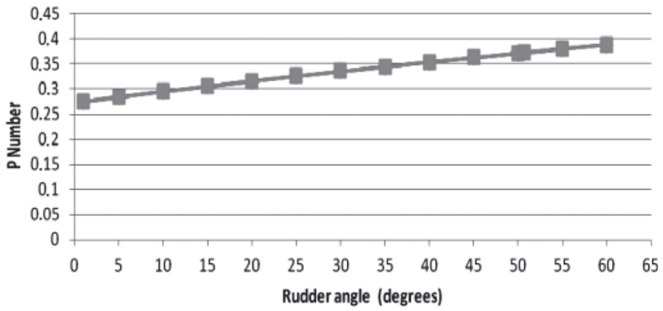

Fig. 9. Number P of Norrbin for different angles

The main characteristic that defines the type of profile is the relation t/c (33), as it will affect the minimum resistance and the stall angle. The profile characteristics are those which have greatest influence on cavitation.

For the study of the flap rudder, a symmetrical NACA 0030 profile was used (Table 2). In this profile we shall examine whether cavitation exists in each section, for each angle of action according to expressions (12) and (13).

Firstly, the pressure coefficient (C_P) has been obtained from expression (15), taking into account the profile surface perimeter (I), where pressure is expressed as:

$$1 = \int \left(1 + y'(x)^2\right)^{0.5} dx \quad (45)$$

At the same time, the profile thickness referred to as axis "y" is a function of the position (x) considered on the chord (c). Consequently, for the NACA 0030 profile [1], y (x) is a percentage of c:

$$y(x) = \pm \frac{tmax}{0.20} \cdot$$

$$\cdot \begin{pmatrix} 0.26690x^{0.5} - 0.12600x + \\ -0.35160x^2 + 0.28430x^3 - 0.10150x^4 \end{pmatrix} \quad (46)$$

The chord point considered for this study is the pressure centre for each angle of attack of the rudder. The evolution of C_P with angle of turn is shown in Fig. 10.

The cavitation coefficient (σ) was calculated for different angles of attack of the rudder (α), and from different sections of the rudder (Table 3). The calculation of P_0 in each one of them (defined by their hg values) has been found by considering the draft (T) and the project trim for the vessel base (see table 1).

Tab. 3. Cavitation number for different transversal sections of the rudder

	Sections	hg (m)	P_0 (Pa)	σ
1	The nearest to the heel pintle	6.36	165161	3.17
2	Coincident with the lowest propeller tip	5.99	161535	3.09
3	Coincident with the propeller axis	3.84	139938	2.67
4	Coincident with the top propeller tip	1.69	118341	2.25
5	The nearest to the rudder root	0.66	107904	2.05

For every section considered and the range of rudder angles analysed, the risk of excessive cavitation is not noticeable (Fig. 10), therefore it seems correct to assume the initially selected NACA0030 profile.

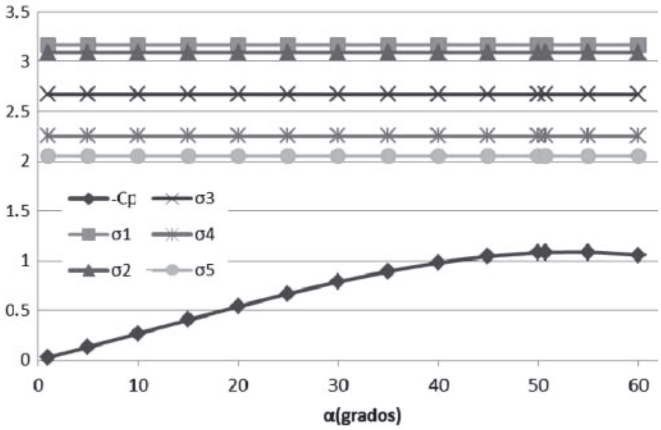

Fig. 10. Pressure coefficient and cavitation numbers by section for different angles

Selection of rudder balancing

The compensation (X_1) is the relation between the blade surface to the bow axis for turning, and the total surface area. This parameter has a fundamental importance for reducing torque moments and therefore on the stock diameter. Its principal limitation is that the centre of pressure, considering that this moves with the angles of turn, always remains at the stern.

The evolution of the transverse pressure centre position (CP_c), measured as a percentage of the chord from the bow (see Fig. 7), for distinct attack angles has been calculated with expressions (36) and (41) together with [9]:

$$CP_c = \left(0.25 - \frac{\frac{C_{mc}}{4}}{C_{fn}}\right) \quad (47)$$

$$\frac{\frac{C_{mc}}{4}}{\alpha} = 0.25+ \quad (48)$$

$$-\left(\left(0.5 - \frac{1.11((\lambda^2+4)^{0.5})+2}{4(\lambda+2)}\right) \cdot 1.95 \frac{\pi}{57.3\left(1+\frac{3}{\lambda}\right)}\right) +$$

$$-0.5 \cdot \frac{C_{dc}}{\lambda} \cdot \frac{\alpha}{57.3^2}$$

Substituting the values for the base vessel (Table 1) the following expression is reached (with α in degrees):

$$CP_c = 0.25 - \frac{3 \cdot 10^{-3} - 1.49 \cdot 10^{-4}\alpha}{\frac{0.04 + 2.61 \cdot 10^{-4}\alpha}{1 - 0.00286\alpha}} \quad (49)$$

In addition, the values achieved for TR = 1 (see section 2) should be displaced by 1% to the stern [9] (Fig. 8). The longitudinal centre of pressure is expressed as:

$$CP_s = \left(\frac{0.85}{(5+\lambda)^{0.25}} TR^{0.11}\right) \quad (50)$$

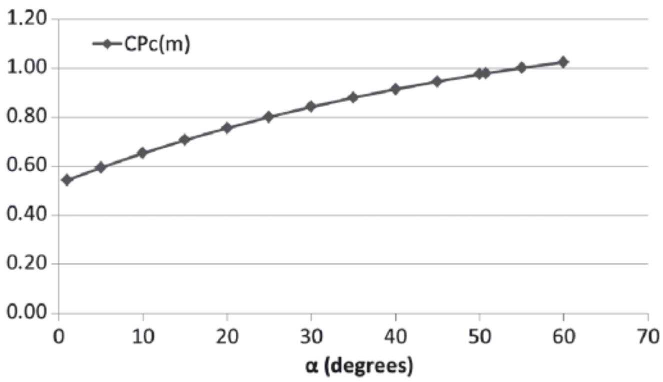

Fig. 11. Distance from the transverse pressure centre with the rudder angles

Figure 11 shows that for angles close to zero, the distance from the transverse pressure centre (CP_c) is 0.54 m. Therefore, X_1 = 0.54 m will be used as this guarantees positive torque moments. The compensation factor for the value of X_1 is 18%, and the reduction of torque respective to a compensation of 0% is shown in Fig. 12.

The torque moment supported by the rudder at 35° (the bending moment) exceeds the minimum values demanded by DNV [4] for balanced rudders, as well as the recommendations on maximum compensable area (23%) and the maximum compensable chord (35%).

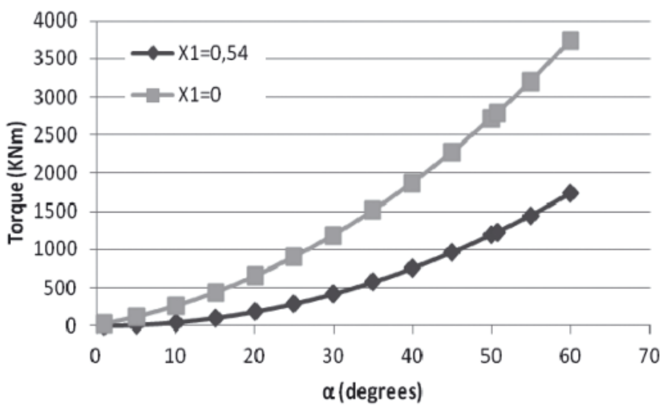

Fig. 12. Torque moments for zero compensation and of 18% (X_1 = 0.54) for different rudder angles

Calculation of the stock diameter

For this calculation the following equation will be used [4]:

$$d_m = 42\left(1 + \frac{4}{3} \cdot \left(\frac{M_f}{M_t}\right)^2\right)^{\frac{1}{6}} \cdot \left(\frac{M_t}{F1}\right)^{\frac{1}{3}} \text{ (mm)} \quad (51)$$

This expression requires that the torque moments (M_t) are calculated along with the bending moments (M_f), for a rudder angle of 35%. For these calculations expressions (50), (47), (38) and (44) are used.

$$M_t = F_n\big((CP_c \cdot c) - X_1\big) \quad (52)$$

$$M_f = F_r(CP_c/7) \quad (53)$$

Finally, the diameter obtained d = 334.46 mm meets to the CS requirements [4].

Selection of rudder flap

From the trials taken on symmetric profiles NACA for the rudders, with a ratio aspect, λ = 2, and Re = $0.125 \cdot 10^6$ [9], it could be concluded that the lift forces were almost double for rudders with a flap ratio of 0.25, and a relation of flap angle/rudder angle = 2.

A fundamental parameter, that affects the effectiveness of a rudder flap, is the compensation factor. In section 2.5, a compensation of 18% was defined, and for this, according to experimental results mentioned, the greatest relation C_{ft}/C_{fd} is given for the relation flap chord/total chord = 0.4. It is this value that is taken in order to proceed with the calculations.

RESULTS

As a consequence of the steps indicated in the previous sections, an optimised rudder model, which is actively supported and adapted to the vessel base, has been obtained. This model has a NACA 0030 profile, a flap chord of 40% and squared edges. The rudder characteristics are summarised in Table 4 and its relative position is shown in Fig. 13.

Tab. 4. Operating and geometric characteristics of the rudder

c (m)	λ	h(m)	t/c	x1	TR	Ω	Re
3	2	6	0.3	18%	1	0	$3 \cdot 10^7$

The rudder defined has been designed to comply with the forces per angle unit and moments, which allow the certain existing operational requirements of the regulations to be achieved, as well as those recommended by the experimental test results obtained (section 2).

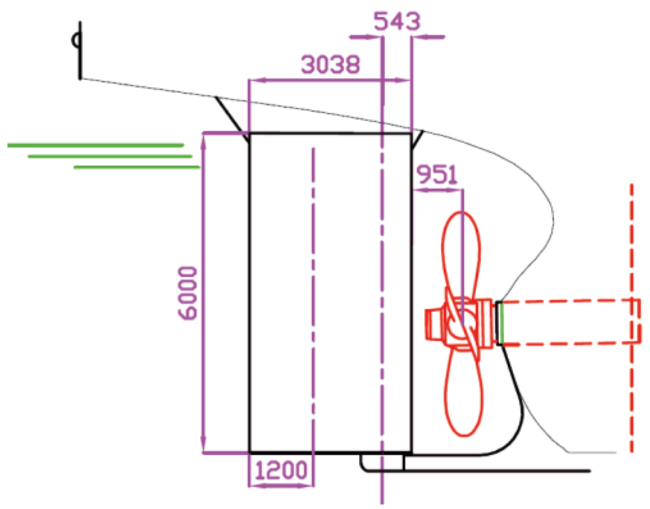

Fig. 13. Dimensions and relative position of the rudder for tuna purse seiners (mm)

However, other demands are not guaranteed, such as the SOLAS Chapter II–1, Rule 29 extreme, or the aptitude in order to correct the yaw in respect to OMI Circular MSC.1053. For that it will be necessary to model the rudder defined here in a hydrodynamic design tool, which allows the model used to be optimised with evolutionary algorithms.

DISCUSSION

- This paper has introduced a method of definition for the principal characteristics of a high–performance rudder and its relative position in the boat, in order to optimise the manoeuvrability of the fishing vessel.
- The method is initiated with the definition of the minimum normal, and lift forces per rudder unit angle, which must be exerted on the rudder to assure the "turning ability", `course keeping´ and "yaw checking". Integrating the results obtained from trials with fishing vessels and rudders have defined expressions that relate the rudder geometry and its relative position in relation to the propeller and said forces.
- Finally, the method is applied to a representative vessel with high manoeuvrability demands: a tuna purse seiner. The results obtained allow not only knowing all the parameters that define the rudder, but also its behaviour in various sections and for different angles. Also, the rudder has been checked for compliance to the Classification Societies' requirements.
- Even though the rudder defined assures certain manoeuvrability conditions in the vessel, other regulative demands must be checked. For that, the model obtained and its respective evolution can be anticipated by the application of evolutionary algorithms which will be tested with CFDs.
- The results acquired for the base vessel show a remarkably high Re value reached at service speed. This, together with the need for manoeuvrability at large rudder angles, leads to a high risk of reaching early separating angles. For this, it is proposed that subsequent simulations of the behaviour of these models consider the `flow straightening´ effect, and that of cavitation along the profile surface where the laws of pressure show lower values than at all other respective points.

NOMENCLATURE

a – hysteresis loop width (m)
A_r – rudder area (m^2)
A_v – advance (m). The distance travelled by the centre of the vessel in the direction of the original course from the initiation of the turning manoeuvring until that the course has been modified by 90ş
B – breadth (m)
c – average rudder chord (m)
C – empirical coefficient which relates transversal and normal rudder force components
Cb – block coefficient
Cdc – transversal advance resistance coefficient
C_{fd} – dimensionless rudder drag force coefficient
C_{fn} – dimensionless rudder normal force coefficient
C_{fr} – dimensionless resultant force coefficient
C_{ft} – dimensionless lift force coefficient
C_p – dimensionless pressure coefficient
CP_s – vertical distance to pressure centre (m)
CP_c – transversal distance to pressure centre (m)
$C_{mc}/4$ – torque coefficient on the first quarter of the chord
C_y – lift coefficient for flap rudders
d – propeller diameter (m)
d_m – stock diameter (mm)
D – turning circle diameter (m)
D_t – tactical diameter (m)
D_v – course deviation (m)
F_n – normal force to the axial plane of the rudder (N)
F_t – lift force perpendicular to the inflow direction on the rudder (N)
F_r – resulting force (N)
F1 – material factor (see DNV rules, Pt.3 Ch.3, Sec.2)
g – gravity (9.8 m/s^2)
h – rudder span (m)
hg – distance to the rudder section considered from the floating line (m)
J – propeller advance ratio.
K', T' – coefficients of hydrodynamic absorption
K_i – transversal radius of inertia of the mass of the vessel (in fishing vessels 0.24–0.26)
K_j – inertial radius for the dragged water of the vessel (0.2 for the base vessel [3])
K_t – propeller thrust coefficient (0.18 for the base vessel with 0.55 of blade area ratio and P/D = 1).
l – length of the profile surface where the lift is acting (m)
L – total length of the vessel (m)
L_{pp} – length between perpendiculars (m)
M – displacement of the vessel (T)
M_t – torque moment (Nm)
M_f – root bending moment (Nm)
N – propeller rate of revolutions (rps)
P – Norrbin P number
P_0 – free flow pressure (Pa)
P_{at} – atmospheric pressure (Pa). Pat = 101325 Pa.
P_l – local pressure on the sections (Pa)
P_v – local vapour pressure (Pa). P_v = 1706 Pa for an average temperature of the sea 15şC
Re – Reynolds Number
t – rudder section thickness (m)
T – average design draft (m)
T_{pp} – aft draft related to the design draft (m)
T_{pr} – fore draft related to the design draft (m)
TR – taper ratio
V – service speed of the vessel (m/s)
V_r – inflow speed on the rudder (m/s)
X – separation between the fore edge of the rudder and the propeller plane (m)
X_1 – rudder compensation (%)
x – point on the chord profile
X_b – longitudinal distance from the midship of the vessel to the centre of buoyancy (m)
Y – distance from the propeller axis to the longitudinal axis of the rudder (m)
y(x) – profile thickness law relative to the chord
Z – distance from the top tip of the propeller blade to the lower tip of the rudder blade (m).

α – angle of attack (rad except where another unit is mentioned)
α_0 – angle between the axis vessel and the hydrodynamic inflow direction on the rudder for lift zero (rad except where another unit is mentioned)
α_e – effective rudder angle (rad except where another unit is mentioned)
α_s – stall angle with respect to the vessel axis
γ – flow straightening factor
ρ – sea water density 1.025×10^{3} (Kg/m^3)
ν – kinematic viscosity of water (10^6 m^2/s for an average temperature of the sea of 20şC and normal atmospheric conditions)
β – rudder turning angle. The angle that forms the flap with the rudder axis.
β_R – drift angle
λ – aspect ratio
σ – cavitation number

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