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Feasibility Study on Thrust Produced by Stabilizing Fins in Waves

Jerzy Edward Matusiak
Marine Technology, Aalto University
Espoo, Finland

Patrik Pentti Rautaheimo
Elomatic Ltd.
Turku, Finland

ABSTRACT

The topic of the paper is to answer the question whether wave energy can be utilized to propel a ship. In particular, whether a smart control of stabilizing fins may, in some conditions, produce a thrust easing the action of the propulsion system without losing its stabilizing function.

KEY WORDS: Stabilizing fins; wave energy utilization; propulsion.

INTRODUCTION

The idea behind the described research comes from full-scale observations made on-board a large passenger vessel, where a bow-wise oriented force acting on a stabilizing fin was detected.

Stabilizing fins are commonly used, in particular in passenger ships, as a mean to dampen an unwanted roll motion. In still water or in head seas they are retracted in order not to produce additional resistance to the ship. Although the control logic of stabilizing fins is not clear to the authors, it seems that normally they are controlled to maximize damping roll moment without much concern for the resistance.

The idea of using oscillating fins to propel a ship, as an alternative to the traditional marine propeller, has been studied for over a century. This research stems from biomimetics, that is from the imitation of the models, systems, and elements of nature, which in this case is fish propulsion. A comprehensive review of this research is given by Politis & Politis (2014). From a hydrodynamic standpoint, the concept has potential for increasing the propulsive efficiency if adequate mechanisms are used (Martio and Caja, 2016).

The current idea, discussed in the following, is to transfer ship movement caused by the waves to the forward oriented force acting on the stabilizer fins and thus save energy. The origin of this idea is not new. Fixed, controlled and flapping fins attached to a ship hull were investigated by many researchers. A particularly valuable and fresh contribution, in the form of experimental evidence and a successful simulation model, is given by Bøckman (2016). Bøckman (2016) gives also a good review of the research related to this topic. Politis & Politis (2014) present an interesting active pitch control method to produce thrust of a wing propulsor under random heaving conditions.

In this paper we concentrate on application of stabilizing fins to generate additional thrust to a ship. In particular, we focus on the feasibility of using stabilizing fins in a number of realistic operational conditions, including oblique waves and large ship motions, that result in a thrust generated similarly as by oscillating foils in still water.

A 6 degrees-of-freedom ship dynamics model, called LaiDyn (Matusiak, 2013), is used as the platform for studying the possibility of generating thrust by proper control of stabilizing fins. A quasi-steady potential flow assumption is made when evaluating fin forces with the lifting line model. The kinematics of flow at the fins is governed by ship motion, wave action and fin angles. The viscous effects are taken into account in an approximate semi-empirical manner. An algorithm for fin angle control is derived yielding maximum thrust.

Simulations are conducted for a passenger vessel considering three different configurations of stabilizing fins in two sea states represented by irregular long-crested waves and three ship headings. Moreover, the case of no fins, fixed fins and fins controlled to produce the maximum thrust are considered.

CASE STUDY

The investigated case is a passenger vessel of the main dimensions presented in the table below.

Table 1. Main dimensions of the investigated vessel.

Length; L_{pp} [m]	260.5
Breadth; B [m]	32.2
Draft; T [m]	7.8
Block coefficient; C_b	0.65
Metacentric height; GM_0 [m]	2

Three different fin configurations were considered. These are presented in the Figure 1 below, where on top of the panel model of the ship hull the location of fins is sketched.

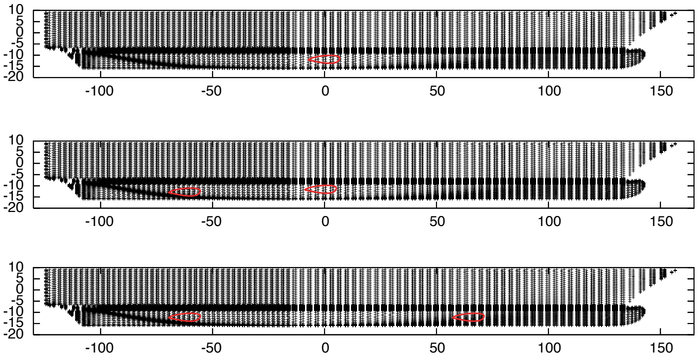

Figure 1 Three locations of fins considered in the study.

Each fin is of the same rectangular form with a span of 7.84 m, constant chord length 2.9 m and thickness 0.6 m.
Normally a pair of fins located at the mid-ship, as sketched at the top, is used. This is denoted as *fins_at_midship* in the following. The arrangement of two pairs of fins, similar to the one presented in the middle (denoted as *Voyager_fin*), was used, for instance, in the Voyager class passenger vessels. The arrangement at the bottom is taken into account to have the effect of pitch on the fin thrust seen. This one is denoted as *fin4ends*. Fins are horizontally oriented, that is they are parallel with the x-y plane of the body-fixed coordinate system.

The considered sea states, speeds and headings are summarized in the table below.

Table 2. The considered sea states, speeds and headings.

Frequency of occurrence [‰]	H_s [m]	T_1 [s]	Speed [kn]	Course [deg]
77	2.8	7.4	20.0	**45**, 135
23	3.5	8.2	20.0	**45**, 135, 180
9	4.5	8.9	21.0	**45**
2	4.5	10.5	21.0	**45**, 135, 180

The sea states are representative for the Atlantic Ocean East of the Caribbean islands. The considered conditions are realistic and relevant from the point of view of the expected gain in thrust (plain text) or causing ship roll resonance (bald text cases).

SIMULATION MODEL

The simulation model combines a coupled representation of a rigid ship motion in waves with the fins represented by the lifting line potential flow model.

Kinematics of a rigid ship

Ship motion in waves is evaluated with the aid of the *LaiDyn* method. The details of *LaiDyn* are presented in Matusiak (2013). *LaiDyn* combines maneuvering with time-domain seakeeping. The method incorporates sub-models for steering and propulsion devices. In this paper only the matters most relevant to the present study are discussed in detail. These are kinematics of the flow at the fins and the forces developed by the fins and their effect on propulsive power and ship motions. The lifting-line theory can be found in Katz & Plotkin (1991).

When considering kinematics of ship motion three coordinate systems are used. These are presented in the Figure 2 below.

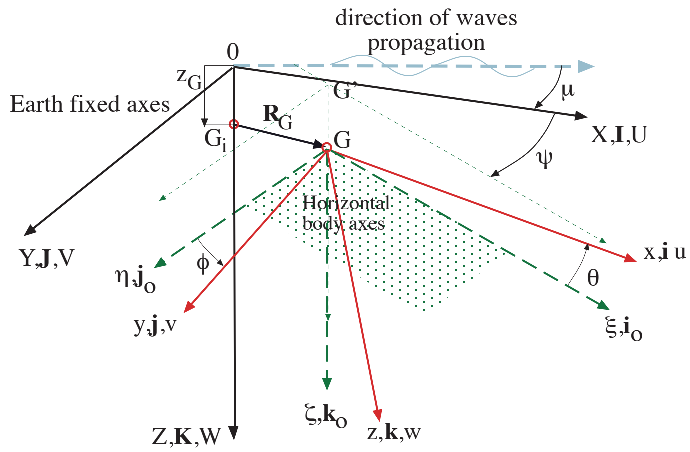

Figure 2 Coordinate systems used in ship dynamics.

An inertial Cartesian coordinate system fixed to Earth is denoted by XYZ. The X-Y plane coincides with the still water level. Surface waves are defined in this co-ordinate system. This co-ordinate system is used when giving the navigational position of a vessel by the vector $\mathbf{R}_G = X_G\mathbf{I} + Y_G\mathbf{J} + Z_G\mathbf{K}$. The angular position of a vessel is given by the so-called modified Euler angles (ψ, θ and ϕ). The vector

$$\dot{\mathbf{X}} = \begin{Bmatrix} \mathbf{U} \\ \dot{\gamma} \end{Bmatrix} = \left\{ \dot{X}_G, \dot{Y}_G, \dot{Z}_G, \dot{\phi}, \dot{\theta}, \dot{\psi} \right\}^T \tag{1}$$

comprises both the velocity components in the Earth-fixed co-ordinate system and the time derivatives of the Euler angles.

Another, the so-called body fixed coordinate system (x,y,z) is used to describe the ship geometry. Equations of ship dynamics are also expressed in this coordinate system with the aid of a state vector. The velocity components in this co-ordinate system are given by the state vector

$$\dot{\mathbf{x}} = \begin{Bmatrix} \mathbf{U} \\ \Omega \end{Bmatrix} = \left\{ u, v, w, p, q, r \right\}^T , \tag{2}$$

Where the angular velocity vector is $\Omega = p\mathbf{i} + q\mathbf{j} + r\mathbf{k}$.
The relation between the state vectors given in both frames can be expressed as

$$\dot{\mathbf{X}} = \begin{bmatrix} \mathbf{T}_1(\phi,\theta,\psi) & \mathbf{0}_{3\times3} \\ \mathbf{0}_{3\times3} & \mathbf{T}_2(\phi,\theta) \end{bmatrix} \dot{\mathbf{x}}\,, \tag{3}$$

where the matrices $\mathbf{0}_{3x3}$ are of a size three times three and they comprise zeros. The transformation matrices $\mathbf{T}_1$ and $\mathbf{T}_2$ are made-up by trigonemetric functions of the Euler angles as follows (Clayton & Bishop, 1982):

$$\mathbf{T}_1(\phi,\theta,\psi) = \begin{bmatrix} \cos\psi\cos\theta & \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi & \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi \\ \sin\psi\cos\theta & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi \\ -\sin\theta & +\cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix}$$

$$\mathbf{T}_2(\phi,\theta) = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix} \tag{4}$$

Mathematical model of fin flow

Assumptions

We make several assumptions when evaluating the flow over the fins. An inviscid flow model is used and the viscous effects are taken semi-empirically into account. In particular the viscous resistance of a fin is assumed to be independent from the angle of attack. Flow is regarded as quasi-steady. The argument is that there are no memory effects involved for a fin flow characterized by a very low Strouhal number. Stall is assumed to occur at angle of attack of 18 degrees. Fins do not contribute to wave-making. Hull radiation does not affect fin flow. Wave diffraction is disregarded as well. A simple control of fins is used such that angle of attack is instantly, without any delay, adjusted to the optimal value. There is not a significant gap between the fins and the hull. The effects of controlled fins on maneuvering is not considered.

Flow over a stabilizing fin

A fin is represented by the quasi-steady lifting line model of Prandtl, modified so that the inflow to the fin does not have to be span-wise uniform. The model makes it possible to deal with fins of different forms and load distribution. As there is no significant gap between the fin root and the hull the effective aspect ratio of the fin is twice the geometrical one. The lifting line model is represented by an equivalent symmetrical hydrofoil as shown in the Figure 3 below. The location of the hydrofoil in the ship hull is depicted by the position vector

$$\mathbf{r}_f = x_f\mathbf{i} + y_f\mathbf{j} + z_f\mathbf{k}\,.$$

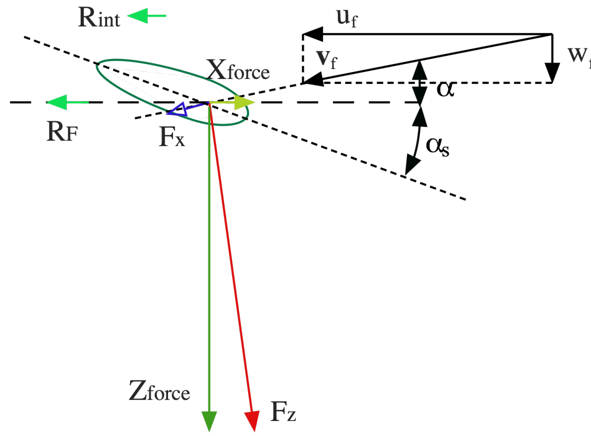

Figure 3 Flow components and forces acting on an equivalent foil.

The fin is set at the angle α_s with respect to the x-axis of the ship-fixed co-ordinate system. R_F is the viscous resistance of the hydrofoil evaluated using a semi-empirical expression given by Hoerner (1965)

$$R_F = 0.5\rho V_S^2 2SC_D\,, \tag{5}$$

where ρ is water density, V_s ship speed and S is projected plane area of the fin. Drag coefficient depends upon the Reynolds number Re and foil thickness to chord ratio t/c according to the formula

$$C_D = 0.03\,\mathrm{Re}^{-0.1428}\left[1 + 2\frac{t}{c} + 60\left(\frac{t}{c}\right)^4\right] \tag{6}$$

valid for Re>10^7.

The so-called interference drag R_{int} is added. This is estimated with the aid of the formula

$$R_{\text{int}} = 0.5\rho V_S^2 t^2 \left[0.75\frac{t}{c} - 0.0003/(t/c)^2\right]. \tag{7}$$

With the assumptions stated earlier, flow velocity components at the fin (u_f and w_f in Figure 3) are assumed to be a sum of the ship motion and the flow velocities in the undisturbed waves at the fin location. The contributions of ship motion can be evaluated as follows

$$\mathbf{v}'_f = u'_f\mathbf{i} + v'_f\mathbf{j} + w'_f\mathbf{k} = \mathbf{U} + \Omega \times \mathbf{r}_f\,.$$

In order to evaluate velocity components due to waves, the location of the fin in the global inertial co-ordinate system has to be determined first. This is done by a shift of origin by vector $\mathbf{X}_G$ and by the transformation of the fin position $\mathbf{r}_f$ as follows

$$\mathbf{R}_f = X_f\mathbf{I} + Y_f\mathbf{J} + Z_f\mathbf{K} = \mathbf{X}_G + \mathbf{T}_1(\phi,\theta,\psi)\bullet\mathbf{r}_f\,. \tag{9}$$

Wave elevation at the position of a fin can be evaluated using the expression

$$\xi(t) = \sum_{i=1}^{N} A_i\cos\left[\mathrm{k}_i\left(X_f\cos\mu - Y_f\sin\mu\right) - \omega_i t + \delta_i\right], \tag{10}$$

where irregular long-crested waves are represented by N cosines components, i depicts component number, A is wave amplitude, k wave number, μ wave propagation direction, ω wave angular frequency and δ random phase. Similarly, the velocity components due to wave motion at the position of the fin are given by the vector

$$\mathbf{v}_w = \begin{Bmatrix} u_w \\ v_w \\ w_w \end{Bmatrix} = \mathbf{T}_1^{-1}(\phi,\theta,\psi+\mu)\bullet$$

$$\begin{Bmatrix} \sum_{i=1}^{N} A_i\omega_i e^{-k_i(Z_f - Z_{COG}+T)} \cos\left[k_i\left(X_f\cos\mu - Y_f\sin\mu\right) - \omega_i t + \delta_i\right] \\ 0 \\ \sum_{i=1}^{N} A_i\omega_i e^{-k_i(Z_f - Z_{COG}+T)} \sin\left[k_i\left(X_f\cos\mu - Y_f\sin\mu\right) - \omega_i t + \delta_i\right] \end{Bmatrix}, \quad (11)$$

where matrix $\mathbf{T}^{-1}_1(\phi,\theta,\psi+\mu)$ transforms the fluid velocity due to waves with the x-directional component pointing in the direction of wave propagation to the ship-fixed co-ordinate system. Z_{COG} is the height of the ship's center of gravity from the ship's bottom. Finally, the flow velocity components at the fin are calculated summing up the body motion components with the contribution of waves as follows

$$u_f = u'_f - u_w$$
$$w_f = -w'_f - w_w . \quad (12)$$

With the inflow into the fin being known, the lift F_z and induced drag F_x are evaluated with the aid of the lifting line model. The projection of all the fin forces on the ship-fixed x-axis gives us

$$X_{force} = F_Z \sin\alpha - F_X \cos\alpha - R_F - R_{int} . \quad (13)$$

A positive value of X_{force} means the fin provides a positive thrust to the ship.

CONTROL OF THE FIN

We seek the control scheme of the fin angle α_s yielding maximum thrust X_{force}. For the sake of simplicity, we assume an elliptical lift distribution for which lift and induced drag coefficients are given by the simple formulae (Katz & Plotkin, 1991)

$$C_L = \frac{2\pi}{1+\frac{2}{\Lambda}}\left(\alpha+\alpha_s\right) \quad (14)$$

$$C_{Di} = \frac{C_L^2}{\pi\Lambda}, \quad (15)$$

where Λ is aspect ratio.

The lift and induced drag expressions

$$F_Z = 0.5\rho V^2 SC_L \text{ and } F_X = 0.5\rho V^2 SC_{Di} \quad (16)$$

are inserted into Equation 13 and differentiated with respect to α_s yielding the expression

$$\alpha_s = \frac{\Lambda+2}{4}\,\mathrm{tg}\,\alpha - \alpha \quad (17)$$

for the optimal fin angle. Introducing the gain factor, being the ratio of total inflow angle to the flow angle made-up by fin movement and wave action, the following expression is obtained

$$GAIN = 1 + \frac{\alpha_s}{\alpha} = \left(\Lambda+2\right)\frac{\mathrm{tg}\,\alpha}{4\alpha} . \quad (18)$$

It is clearly seen that the $GAIN$ is very weakly dependent on the angle of attack and can be assumed constant, especially for small angle values. For the considered fin case $GAIN \approx 1.9$.

RESULTS OF SIMULATIONS

In order to evaluate the potential gain of using stabilizing fins in different configurations we relate the thrust power of fins to the thrust power of propellers with the fins retracted. The considered sea states (see Table 2) are represented by irregular long-crested waves in the form of wave trains composed of 29 components with randomly distributed discrete frequencies and random phases (Matusiak, 2000). In order to have a fair comparison of different fin arrangements possible, the same wave train is used for different fin cases including both the optimally controlled and also the fixed fins. The duration of wave action and the simulated ship responses is 30 minutes. A simple proportional type controller of propeller shaft revolutions is used to sustain a prescribed ship speed. The results of simulations in terms of power gain are presented in Figures 4-6.

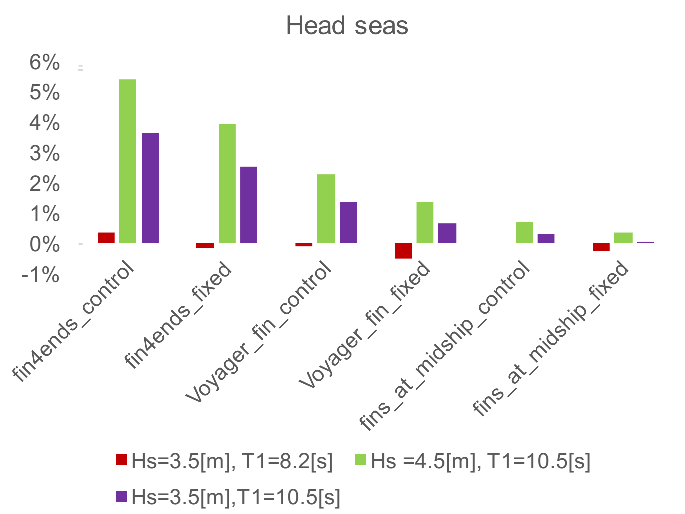

Figure 4 Fin power in relation to the thrust power of propellers. Head seas condition.

It is interesting to note that a significant gain in power can be expected in long head waves of significant height H_S=4.5 [m] with two pairs of fins located at bow and stern. With optimally controlled fins this gain is 5.5%. Even with the fixed fins the gain is as high as 4%. The waves' length (period) has a pronounced effect on the power gain.

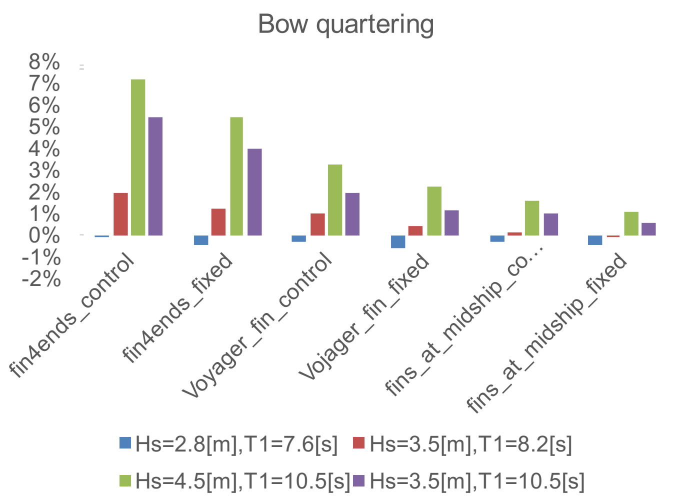

Figure 5 Fin power in relation to the thrust power of propellers. The condition of bow quartering seas.

Changing the course from head seas to bow quartering waves does not have much effect on the results. Moreover, observing the results for the average wave period T_1=10.5 [s] with two different wave heights indicates that the power gain is nearly linearly related to the wave height in case of two pairs of fins located apart (case *fin4ends*).

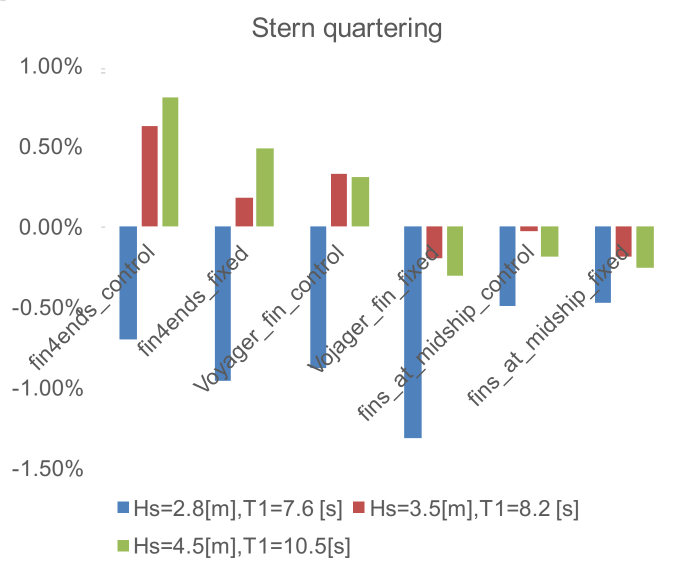

Figure 6 Fin power in relation to the thrust power of propellers. The condition of stern quartering seas.

In stern high quartering seas there is only a very limited power gain when using two pairs of fins located far away from each other. Otherwise, there is no power saving expected in the stern quartering condition.

The relation of thrust generated by stabilizing fins and ship motion is illustrated in Figure 7 as the time-histories of ship roll motion at resonance and thrust *Xfin* generated by two pairs of fins (case *fin4ends*).

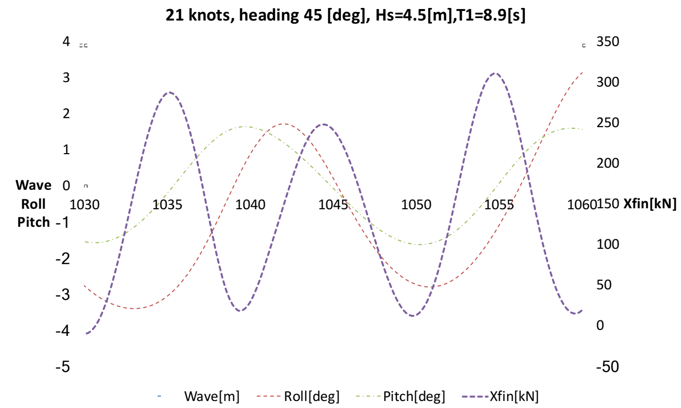

Figure 7 Thrust of four controlled fins in stern quartering seas.

Although the ship experiences roll resonance, the generation of fins' thrust is mainly associated with the pitch motion in terms of velocity. This explains the superior position of two pairs of fins located apart (case *fin4ends)* to generate thrust in head seas.

CONCLUSIONS

The study proves that using stabilizing fins in head and bow quartering long waves may produce extra thrust to the ship, which may be used to ease the main machinery effort. In particular two pairs of fins, located far apart, benefit from the pitch motion component of a ship and may produce a significant thrust.

Smart control of fins may be used to get the maximum benefit of ship motion energy transformation into propulsion energy. However, even with the fixed fins a positive effect of fins on ship propulsion in waves can be obtained.

An interesting topic of further development would be a control scheme for stabilizing fins which would at the same time maximize the roll damping and the thrust generated by the fins.

Just to bring this issue to economical content: If we have a ship with average propulsion power 20 MW, and sailing time 12 hours per day, 1% reduction of power need means about 1%x20 MW x 0,2 ton/MWh x 12 hours/day x 365 days/year x 600 $ / ton = 100 000 $ / years. With some additional optimization overall efficiency can be higher than 1% on average.

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