A NEW ENERGY SAVING TWIN RUDDER SYSTEM - GATE RUDDER

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ABSTRACT

Rudder and propeller of a ship share almost similar long service history. The rudder is usually placed behind the propeller to make use of the strong slipstream flow of the propeller. By changing the direction of the slipstream flow the rudder functions as a remarkably effective control surface to maneuver the ship. While this is the fact the rudder also has several disadvantages including: (a) increased ship resistance as an appendage to the hull; (b) modifications to the stern arrangement to accommodate the rudder that enforces restriction not only to the propeller aperture but also to the engine room arrangement; (c) a non-uniform flow imposed in the propeller plane that can easily increase the vibration and noise originated not only from the propeller but also from the combination of the propeller with the rudder; (d) cavitation erosion on the rudder which can be annoying for high speed vessels In order to eliminate the above disadvantages as well as saving further energy, a new concept of twin rudder system is invented one of the Authors and called *"Gate Rudder"* in which each of the asymmetric rudders is located aside the propeller to exploit the benefits of an accelerating duct device. The main objective of this paper is to give the background for the gate rudder development and present methodology for powering performance of a ship with the gate rudder using the Emerson Cavitation Tunnel facility. The analysis include model tests to measure the local forces on the stern part of a model hull and gate rudder system in the cavitation tunnel as well as the prediction of the gate rudder induced velocities using computational methods. The papers further presents a flow chart for the fine powering performance prediction technology and cost effectiveness analysis of vessels using the gate rudder system.

Key Words: Twin Rudder, Gate Rudder, Duct Effect, ESD, Maneuverability

1. INTRODUCTION

It is generally recognized that early ducted propellers, which were installed on large tankers or bulk carriers, suffered from severe cavitation erosion on the inner surface of their ducts even if the surface was protected by stainless steel. The energy saving by the ducted propeller was clear and many engineers tried to solve the above cavitation erosion problem. However, no credible research work has been noted until the invention of the Mitsui Duct which was introduced as a completely new idea in mid-80s (Narita et al. 1981). The inventor of the Mitsui Duct claimed that the duct performance would be improved if the duct was placed between the propeller of a ship and its stern. However the similar idea was already presented by van Lammeren (1949) who was to place a smaller duct in front of the propeller instead of a larger duct with similar diameter to the propeller's. The Lammeren duct was modified and much improved later on. These small ducts in front of the propeller seems most effective amongst other energy saving devices (ESD) which we are able to see so far.

Based on their hydrodynamic principles one may suggest to categorize the ESDs as in the following groups:

1) Post-swirl type

2) Pre-swirl type

3) Stern flow regulator type

4) Complex type

Figure 1 presents a summary of many different types of ESDs since 1980s to today. Around 1980, already two types of ESDs were invented in Japan. First one was the reaction fin of Mitsubishi Heavy Industries (Takekuma, et al. 1981) which belongs to group (1) while the second type was SAF (Sumitomo Arched Fin) of Sumitomo Heavy Industries (Sasaki and Nagamatsu1985) which belongs to group (2). The purpose of using reaction fin is to recover propeller rotational losses by pre-swirl fins in front of a propeller. In that the key issue is to design and place the fins so as not to generate the excess resistance or to generate the thrust. SAF (Sumitomo Arched Fin) was invented and installed on a large tanker in the beginning of 1980s to improve the flow field around the propeller and consequently to improve the propulsion factors without spoiling the ship resistance by the arched fin. In this concept the key issue is also to design the fin so as to generate thrust by accelerating the flow at the under part of the fin. The semi-circular fin can be regarded as part of a duct and based on the similar concept several ducts have been invented including Wake Equalizing Duct (WED), Super Stream Duct (SSD), Sumitomo Integrated Lammeren Duct (SLID), Mewis duct and Weather Adopted Duct (WAD) etc. The first complete small duct in front of a propeller was the WED (Schneekluth 1986) which was applied on many vessels because of its simplicity. The most sophisticated duct of this type is SSD (Kitazawa et al. 1982, Yamamori et al. 2001) which can minimize the resistance of the duct itself by using a wing shape ring (duct).

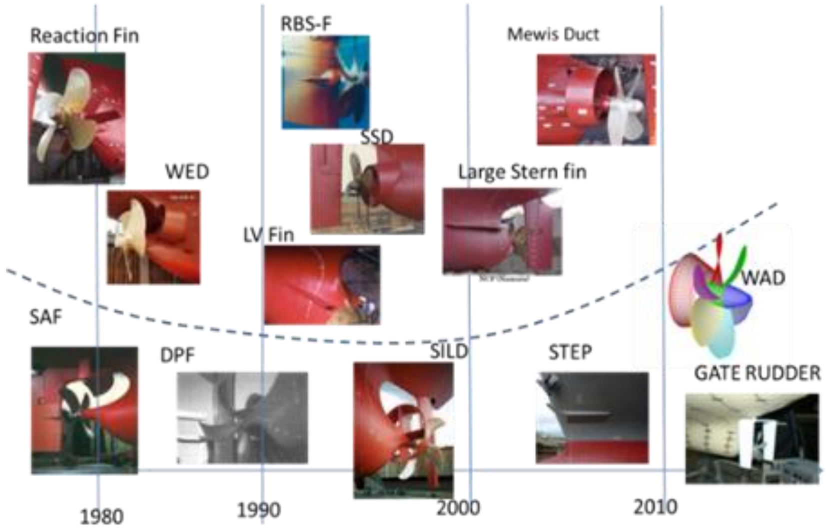


Figure 1. Typical ESDs from 1980-Today

Most ESDs can be included either in group (1) or group (2) or their combination (see in Figure 1). Furthermore there are three ESDs, which are also included in Figure 1, but considered to be saving energy based on different hydrodynamic principles. One of these three devices is STEP which was invented at NMRI to reduce the wave resistance due to severe weather conditions and is installed on the bow of a vessel (Kuroda et al. 2013). Therefore the energy saving with STEP can be observed only for the weather conditions higher than BF5 (wave height > 2m). The energy saving principle of the second device, which is called WAD, is also similar to STEP for which the focus is on the actual sea conditions instead of the calm sea condition such as during trials. The third device, which is named as WAD, is almost the half size of a conventional duct type, however it will increase the performance at actual sea conditions (Sasaki et al. 2013).

One should bear in mind that, depending on the location of an ESD before or after the propeller, the flow at the propeller plane can be affected adversely and consequently the propeller may have a risk of cavitation and noise problem. This risk will be increased if one prefers to obtain higher propulsive efficiency by enlarging the characteristic length or diameter of the ESD(s). Finally in Figure 1 the ESDs under the dotted line were invented by one of Authors of this paper, including the twin rudder system with asymmetric section (Gate Rudder) described in the next section.

The main objective of this paper is to introduce a new ESD system called "*Gate Rudder*" and present methodology for powering performance prediction of a ship with the gate rudder using the Emerson Cavitation Tunnel facility. The analysis include model tests to measure the local forces on the stern part of a model hull and gate rudder system in the cavitation tunnel as well as the prediction of the gate rudder induced velocities using computational methods. The paper further presents a flow chart for the fine powering performance prediction technology and cost effectiveness analysis of different size vessels using the gate rudder system.

2. NEW TWIN RUDDER CONCEPT – THE GATE RUDDER

As reviewed in Section 1, amongst many different types of ESDs in the market, the twin rudder system (Gate Rudder) is quite different with its asymmetric cross-section which works on a different principle than the existing types. The major advantage of the Gate Rudder system stems from the duct effect originated from the working propeller. By placing two asymmetric rudders at each side of a propeller, the rudders and the propeller are able to function like a ducted propeller. In addition to the increased propulsive efficiency due to the accelerated duct flow, the rotatable twin rudder system of the new ESD also provides improved maneuverability, and seakeeping ability. Although these advantages will be further elaborated in the paper the following list summarizes the advantages of the Gate Rudder in three categories, namely: economical; safety and habitability.

-Economical-

(1) higher propulsive efficiency owing to the duct effect

(2) avoiding a torque rich condition by slight change in rudder angles

(3) increase of cargo space by shifting the engine room further aft

(4) reduction of ship length, if necessary, by elimination of a conventional rudder

-Safety-

(5) remarkable stopping ability

(6) remarkable maneuverability utilizing rotatable twin rudders independently

(7) remarkable berthing performance (in crabbing mode)

(8) reduction of the rolling motion by controlling the rudder angles

-Habitability-

(10) reduction of propeller induced noise and vibration by improved stern flow (i.e. wake equalizing effect)

(11) increased cargo space by shifting the engine room afterward

(12) reduction of ship length, if necessary, by elimination of a conventional rudder

Figure 2 shows the typical conventional rudders for both a single rudder and twin rudders. As one can see, the rudder is positioned in the propeller slipstream for both cases while this not the case for the gate rudder, as the two smaller rudders are placed aside the propeller and, hence out of the propeller's slipstream.

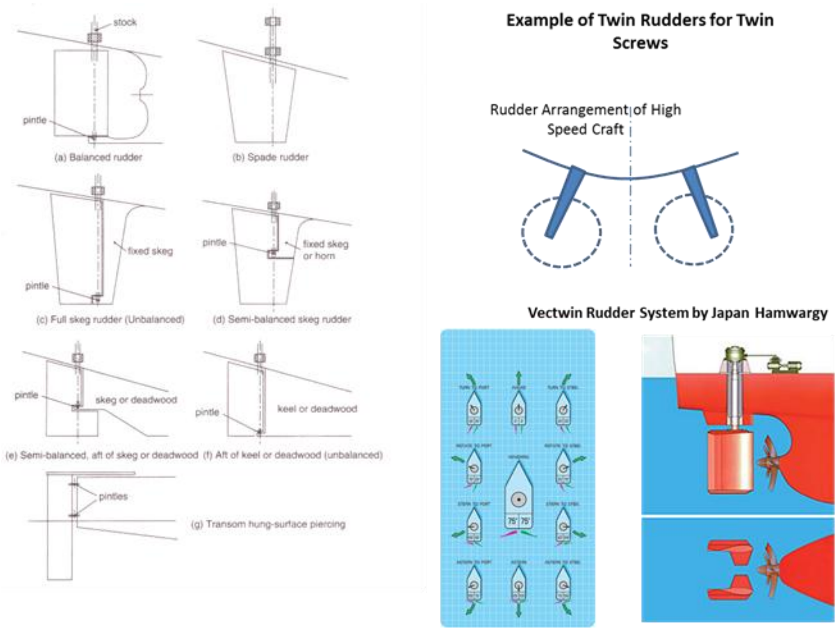


Figure 2. Typical conventional single rudders (Molland and Turnock 2007) and twin rudders

Figure 3 clearly shows the target position of the gate rudder compared to othr control devices in terms of its development strategy which aims to improve energy savings capability as well as maintaining safe maneuverability of a ship. Another words the gate rudder was proposed as a new ESD to combine a better propulsive performance with strong maneuverability at the same time.

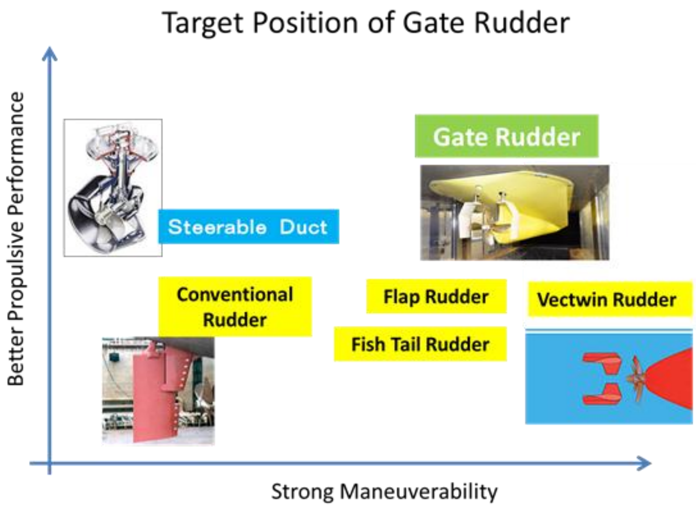


Figure 3. Target position of Gate Rudder in ESD development strategy

3. FINE POWERING PERFORMANCE PREDICTION TECHNOLOGY

The Emerson Cavitation Tunnel is one of the historical cavitation tunnels in the world as well as being only operational and modernised propeller cavitation tunnel in UK. The tunnel has been continuously upgraded since its establishment in 1950 and most recent upgrading has been in 2009 when the tunnel has been fitted with a modern and most accessible measuring section. This has provided the facility with a further enhanced testing capability to investigate the flow around complex shapes, including afterbody of ship models, using most sophisticated laser based optical devices (e.g. LDA/PDA, PIV). Figure 4 and

Figure 5 shows the sketch and current view of the Emerson Cavitation Tunnel while the further technical details of the tunnel can be found in Atlar (2011).

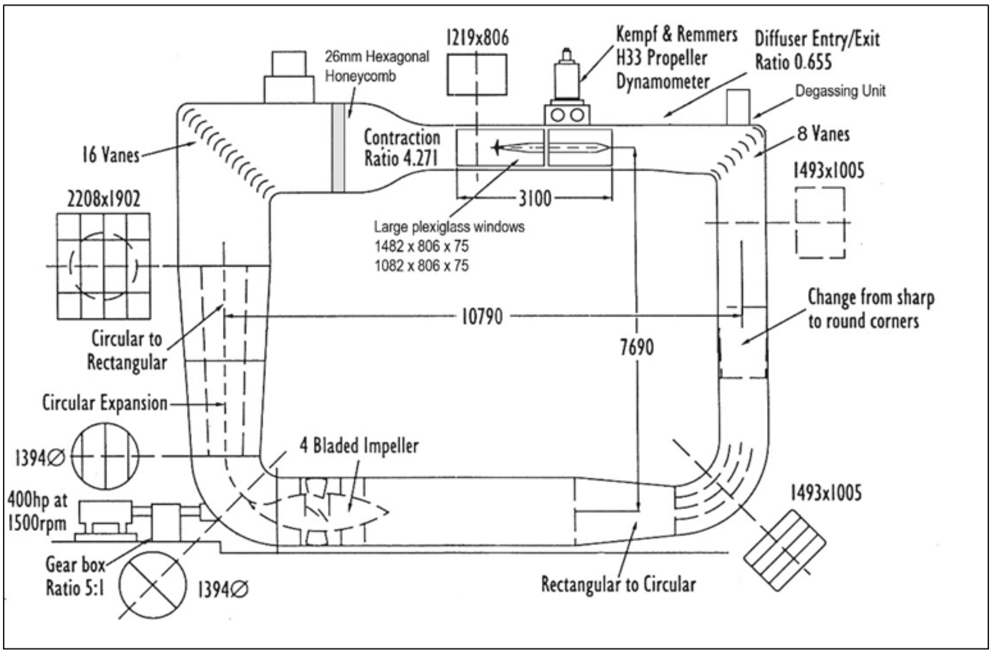


Figure 4. Sketch of present Emerson Cavitation Tunnel (Atlar, 2011)

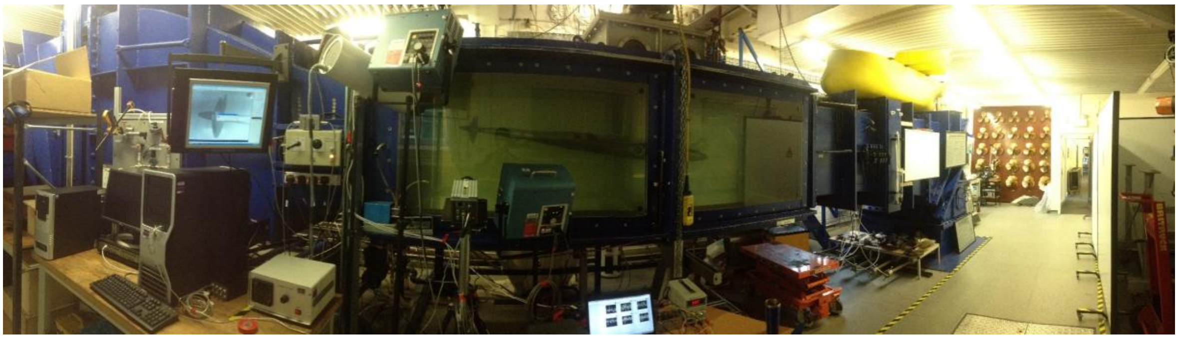


Figure 5. A panoramic view of Emerson Cavitation tunnel

Although large towing tanks in combination with large cavitation tunnels are ideal facilities to investigate and optimize current ESDs or to develop new ESDs, they are not necessarily the most practical, design oriented and cost economical facilities as being two separate and large facilities. However modern facilities, like the Emerson Cavitation Tunnel, with the state-of-the-art equipment and support of CFD can provide an effective environment to study the ESDs which requires detailed investigation on the complex stern flow in the presence of the propeller's action. Within this framework the recent R&D activities in the ECT have focused on the development of a new powering performance prediction technology, especially for ship hulls with the ESDs, like the Gate Rudder and this is called "Fine powering performance prediction technology" as shown in Figure 6 in a schematic manner.

The main advantages of the Fine Powering Performance Prediction Technology can be summarized as follows:

1. More insight into the understanding of the complex propeller/rudder/hull interaction
2. Direct information on the causes of energy losses and proper direction for improvement
3. Combined information on the force and flow acting on the stern, propulsor and rudder as well as other appendages which provide the full picture for understanding some important phenomena that may affect the stern arrangement

4. Further understanding on the above will facilitate the development of new technologies including ESDs

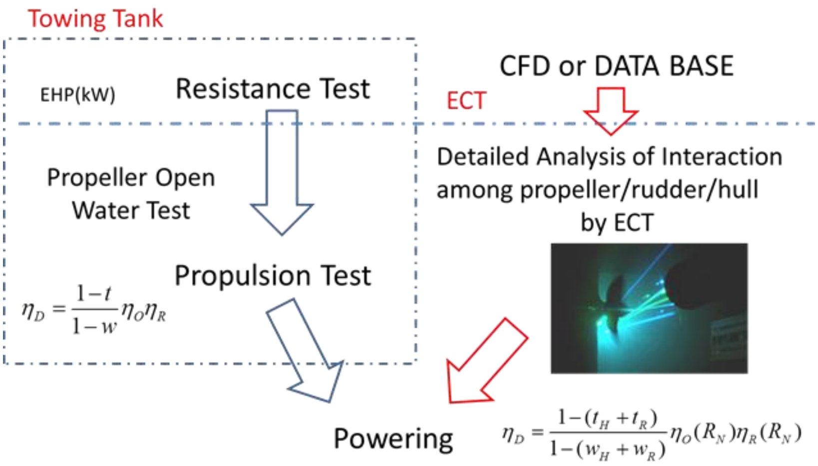


Figure 6. Fine powering performance prediction technology

The prediction of a power saving by a new ESD is the most difficult task for the ship designer because the conventional powering methods such as those recommended by ITTC were not developed for this purpose requiring further efforts and time. The uncertainty in the power prediction of a ship with a new ESD strongly depends on the potential scale effects to be caused by the low Reynolds number due the small ESD size. By using a reasonably large size model at relatively high Reynolds number in a medium size cavitation tunnel more insight on the complex interaction amongst the hull model, propeller and a rudder can be obtained closer to the full-scale than to be obtained from a self-propulsion test in a towing tank.

Based on the above rationale "The fine powering performance prediction technology" has been applied in the ECT to study the various details of the Gate Rudder and its further development. In order to apply this prediction technology a specially designed dummy hull have been fitted with an initially proposed gate rudder system by using the K&R H-33 propeller dynamometer of the ECT. In order to measure the local forces on the gate rudder as well as on the aft part of the segmented dummy hull various load cells are also combined as shown in Figure 7. The segmentation of the aft end and representative drag force and rudder thrust measured on these element are also shown in Figure 8.

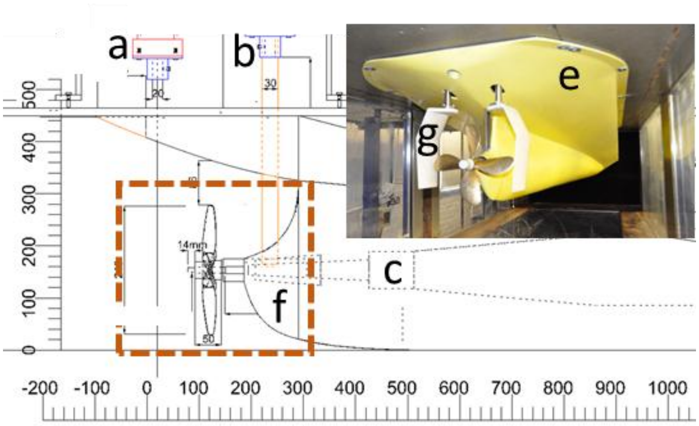


Figure 7. Measurement System of Emerson Cavitation Tunnel

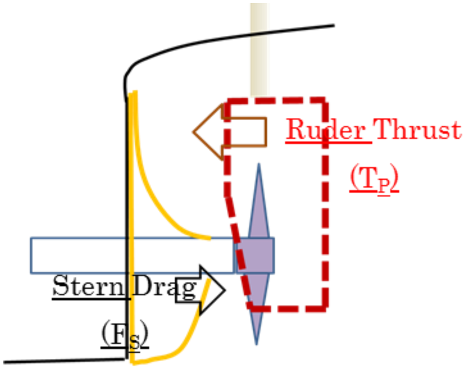


Figure 8. Representative interaction among stern, propeller and gate rudder

4. PREDICTION OF GATE RUDDER FORCES

The main advantage of the gate rudder is due to the additional thrust developed by this device instead of generating pure resistance which is the case for the conventional rudder. Therefore it will be very important to investigate the forces acting on the gate rudder and especially the rudder thrust during propulsion.

The formulation of a gate rudder's thrust (T_{GR}) can be given by Equation 1 based on the simple wing element theory

$$T_{GR} = \int_{btm}^{top} L(z)\cos\psi(z) - D(z)\sin\psi(z)dz - R_{SFT} \tag{1}$$

$$L(z) = \frac{1}{2}\rho V^{*2} * C_L(z) * c(z) \tag{2}$$

$$D(z) = \frac{1}{2}\rho V^{*2} * C_D(z) * c(z) \tag{3}$$

$$V^* = \sqrt{V_X^{\ 2} + V_Y^{\ 2}} \tag{4}$$

$$\psi = \tan^{-1}(\frac{V_Y}{V_X}) \tag{5}$$

where, R_{SFT} indicates the resistance of the rudder stocks which are exposed to the flow and this resistance component is relatively large compared with the resistance of the conventional rudder stock because the flow velocity at the gate rudder is almost equal to the ship speed.

L and D represents the lift and drag while C_L and C_D are the lift and drag coefficients given in Equation (6) and (7), respectively

$$C_L(z) = 2\pi\sin(\psi - \alpha_0)\frac{\lambda}{2.2 + \lambda} \tag{6}$$

$$C_D(z) = 2 * C_F * (1 + \frac{t(z)}{c(z)})) + (\frac{t(z)}{C(z)})^2 + C_{D_i} \tag{7}$$

$$C_{D_i} = \kappa \frac{{C_L}^2}{\pi\lambda} \tag{8}$$

Having formulated the gate rudder thrust, the lateral components (X & Y) of the forces acting on the gate rudder can be presented by Equation (9) and (10), respectively

$$F_{RX}(z) = L(z)\cos\psi(z) - D(z)\sin\psi(z) \tag{9}$$

$$F_{RY}(z) = L(z)\sin\psi(z) + D(z)\cos\psi(z) \tag{10}$$

Table 1 presents the principal dimensions of a representative bulk carrier for gate rudder application. Having designed a suitable gate rudder system and using the above derived equations the effect of the designed gate rudder in terms of the normalized velocity, horizontal flow angles and rudder thrust are calculated and shown in Figure 9. This was followed by the design of each section in line with the optimum attack angle for specific horizontal position.

Table 1: Principal dimensions of bulk carrier

	Conventional	Gate Rudder
Lpp	225	
B	48.8	
d	13.5	
CB	0.8	
M/E O/P	12,000kW * 125PM	
Prop. Dia.	6.4m	
Rudder	Conventional	Gate Rudder

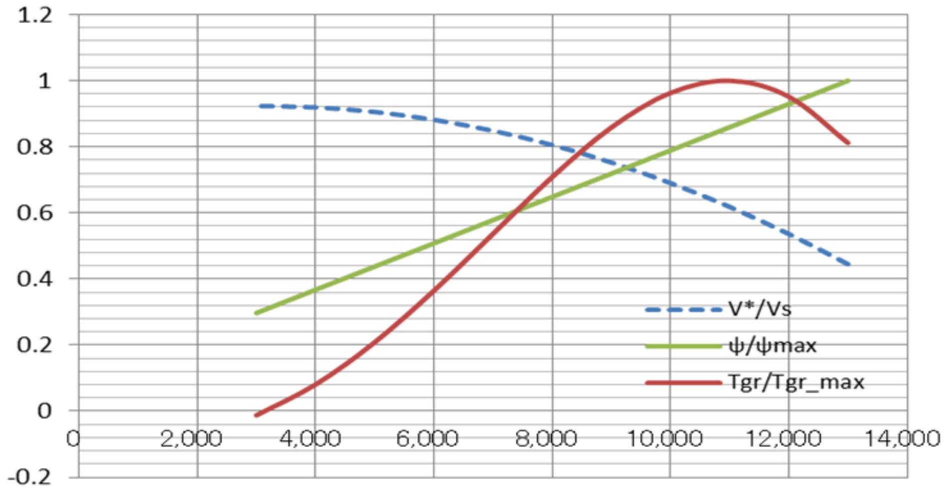


Figure 9. Span-wise distribution of the normalized velocity, flow angle and rudder thrust

Equation 11 through 15 present further insight into the Gate rudder forces and moments with respect to its port and starboard rudder component.

$$F_{RX}(cal) = \int_{bottom}^{top} F_{RX}(z)^{port} dz + \int_{bottom}^{top} F_{RX}(z)^{starbord} dz - R_{SFT} \quad (11)$$

$$F_{RY}(cal) = \int_{bottom}^{top} F_{RY}(z)^{port} dz - \int_{bottom}^{top} F_{RY}(z)^{starbord} dz \quad (12)$$

$$N^{port}(cal) = \int_{bottom}^{top} F_{RY}(z)^{port} \cdot l^{port} dz \quad (13)$$

$$N^{pstarbord}(cal) = \int_{bottom}^{top} F_{RY}(z)^{pstarbord} \cdot l^{starbord} dz \quad (14)$$

Where, l is a center of effort at each rudder section and given by equation 15.

$$l = (X_{RP} / Cm(z) - 0.35) \cdot Cm(z) \quad (15)$$

X_{RP} is the distance of rudder post from the leading edge of each section.

Figure 10 shows the ratio of the gate rudder thrust to ship hull resistance over different ship speeds. As one can see from this figure the rudder thrust amounts to 6% of the hull resistance and this may suggest that the entire power saving of the gate rudder is coming from the rudder thrust and we know that the conventional rudder does not generate thrust but creates resistance.

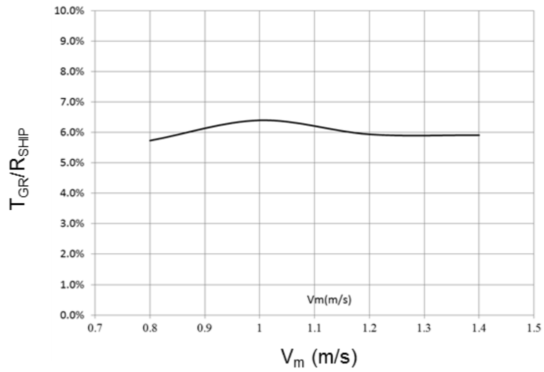


Figure 10. Ratio of gate rudder thrust to ship hull

It was also found that the directions of F_{RY} of both starboard and portside rudder component are towards to ship centerline and opposite. Therefore the total side force (F_{RY}) is very small as the individual rudder forces balance each other out.

5. GATE RUDDER INDUCED VELOCITIES IN PROPELLER PLANE

The two side rudders of a gate rudder system act in the similar manner to the duct of a ducted propulsor. The induced velocity created by the gate rudder in the propeller plane can be estimated by Equation 16 based on the Biot-Savart law as follows.

$$vi(0, y_0, z_0) = \int_{z_B}^{z_T} \frac{\Gamma(z)}{2\pi r} dz \quad (16)$$

where $\Gamma(z)$ is the circulation around the gate rudder which can be related to lift force *L(z)* generated on the gate rudder according to the Kutta-Joukovski law by Equation 17 as follows

$L(z) = \rho V^*(z)\Gamma(z)$ (17)

If $C_L(z)$ is the non-dimensional coefficient associated by *L(z),* induced velocity $v_i(0, y_0, z_0)$ can be represented using Equation (17) and (18) as follows.

$$v_i(0, y_0, z_0) = \int_{Z_B}^{Z_T} \kappa \frac{V^*(z) \cdot \psi(z) \cdot C_L}{r_i} \quad (18)$$

where, the definitions for *V** and *ψ* are the same as defined in section 4.

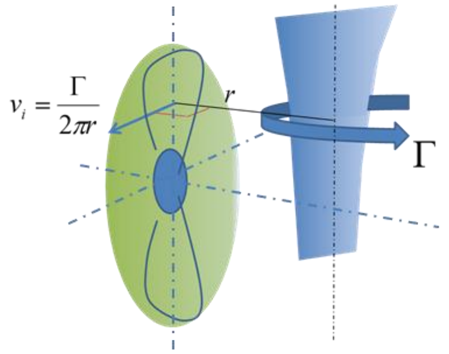


Figure 11. Induced velocity in a propeller plane originated from gate rudder

By using Equation (18) the gate rudder induced velocities were predicted and compared with the difference of two effective wakes obtained from with and without gate rudder using the same procedure as self-propulsion tests. Because the difference of effective wakes between with and without gate rudder is originated from the induced velocity of gate rudder, we can the same magnitude in these two wakes. From Figure 12, we can conclude that the flow acceleration in the propeller plane can be explained by the induced velocity of gate rudder same as the relation between a propeller and duct of a ducted propeller.

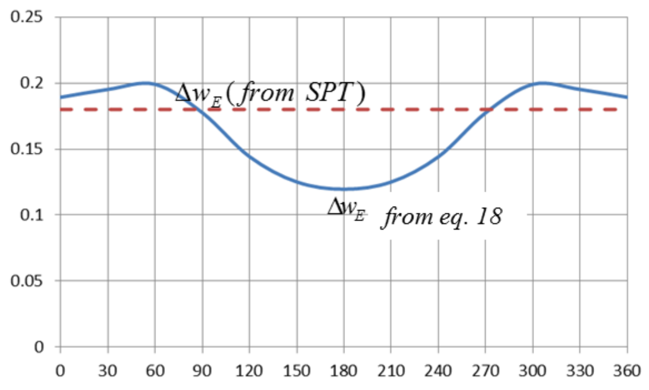


Figure 12 Effective wake change obtained from experiment (SPT) and calculation

6. NUMERICAL STUDY OF THE GATE RUDDER SYSTEM

In the following the flow field around the gate rudder was investigated at full scale by using commercial CFD package Starccm+ finite volume stress solver for the bulk carrier whose principal dimensions are given in Table 1. κ-Ω turbulence model is chosen for the effect of turbulence on the fluid. The number of the phases were chosen as multiphase flow (water and air) and actuator disc was used to represent propeller behind the hull as shown in Figure 13. Trimmer mesh, prismatic boundary layers are created for two regions. Symmetry boundary condition also applied to reduce the computation time. The ship speed was 13knot and corresponding propeller speed was 7rps. From the CFD calculation it is expected to see that how the gate rudders affect the flow field by changing the velocity pattern at the stern region.

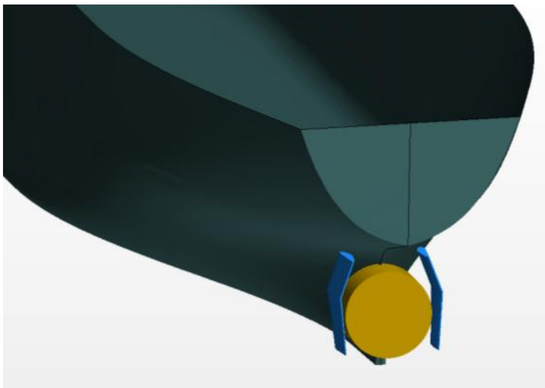


Figure 13. CFD arrangement of gate rudders with actuator disc as a representative propeller

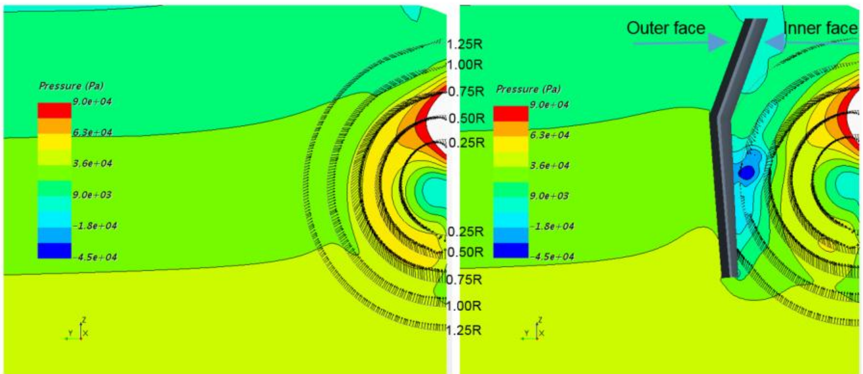


Figure 14 shows the simulation of the pressure field and the velocity vectors at the actuator disc area. The gate rudder generates lower pressure on the inner face flow with the contribution of the rotational flow of the propeller and the hull wake.

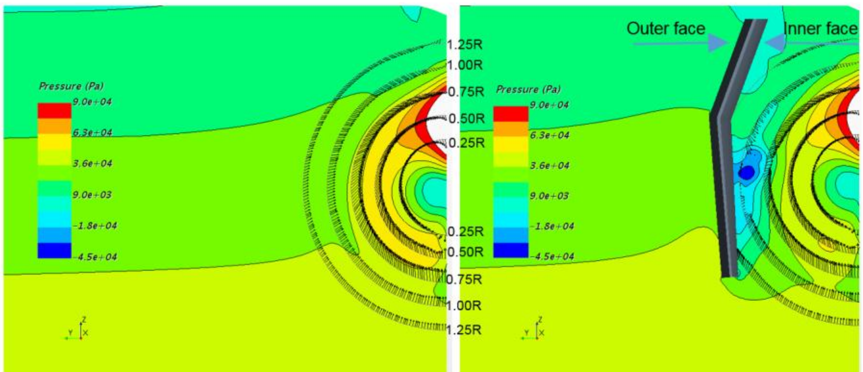


Figure 14. CFD computation of the flow field at actuator disc area with and without gate rudder (view from aft to fore and “R” is the propeller radius).

CFD study also showed that the propeller has the biggest contribution to induced velocity by the gate rudder. Figure 15 present two different locations of the gate rudder and pressure field and velocity vector differences. The left picture in Figure 15 shows that the gate rudder's initial location at around 1.5R from the propeller rotation center. No significant effect of the gate rudder was observed at 1.5R in terms of gaining extra thrust or changing the flow field in the after body region of the hull. The right picture shows the gate rudder was located closer to the propeller plane (around 1.25R). At the second location the gate rudder generates lower pressure than the initial location due to high velocity field generated by the propeller and %10 extra thrust was generated.

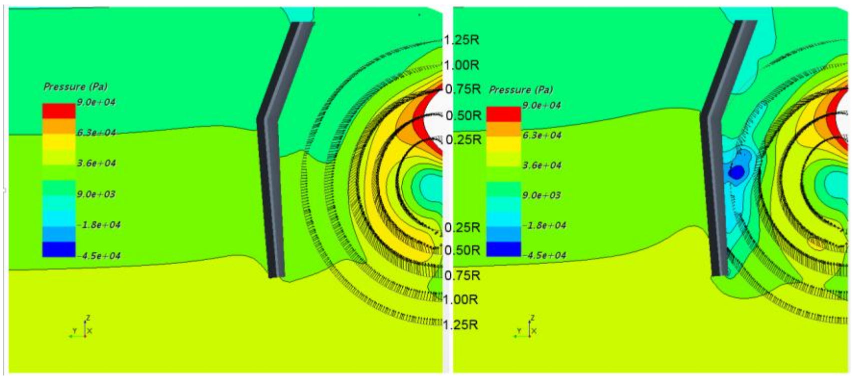
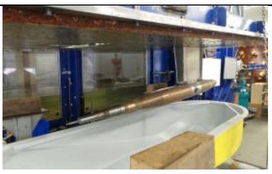


Figure 15. The gate rudder location vs. pressure contours in the propeller plane area

7. MEASUREMENTS OF GATE RUDDER FORCES

For this study a dummy hull and the Emerson Cavitation tunnel lid were modified to install the loadcells and pass the struts of the rudders and stern as also shown in Figure 7. Table 2**Error! Reference source not found.** presents further details of the model and its fitting arrangement in the tunnel during the tunnel tests. The measurement system consists of two 6- component load cells to measure the forces (thrust) on the gate rudders in the longitudinal axis (x), transverse axis (y) and moment about horizontal axis (z). A single component load cell was used to measure the force (drag) on the segmented stern section in the longitudinal axis. The same load cell can be also used to measure side forces on the stern by rotating it 90 degree about the z axis. This way gives opportunity to investigate the rudders performance in terms of maneuverability.

Table 2: Specification of the ECT measurement system and equipment.

a. Load on the rudders (Fx, Fy, Mz)	DHI 6-Component Force Transducer	
b. Load on the stern (Fx)	Novatech single component F320-Z 200N	
c. RPM, thrust and torque	H33 dynamometer	
d. DAQ	Multichannel receiver, amplifier, notebook	
e. Dummy hull	Length 2500mm, fiberglass (E-glass)	
f. Stern bulb	Length 105mm , fiberglass (E-glass) with brass, carbon fiber strut,	
g. Gate rudders	DuraFoam PA, C3 finish	
h. Conventional rudder	Fiberglass (E-glass) with brass strut	

By using the experimental set-up in the ECT the forces acting on the each component of the gate rudder were measured and compared with the forces action on a conventional rudder. There are ways to set operation speed of the tunnel flow velocity and the propeller rotational speed which are the representative of full scale operation condition (ITTC 2002, ITTC 2011, Johannsen 1992). In this experiment, the thrust coefficient and advance speed of the propeller were chosen as a similarity parameter for the operation condition in the behind condition. The definition of the thrust coefficient K_T and advance ratio (or coefficient) J is given in the following

$$K_T = \frac{T}{\rho n^2 D^4} \qquad (19)$$

$$J = \frac{V_A}{nD} \tag{20}$$

where T is the thrust, ρ is the tunnel water density, n is the revolution speed per second (rps), D the propeller diameter and V_A is the advance speed that is velocity of the water behind the hull. During the test tunnel current velocity was kept constant and rps were adjusted for the advance ratio that corresponding to thrust coefficient.

The results of the measurements with both configurations (i.e. conventional rudder and gate rudder) are shown in Figure 16 in comparison. As one can see while the gate rudder produces additional thrust with increasing flow velocity by the propeller the conventional rudder presents additional drag.

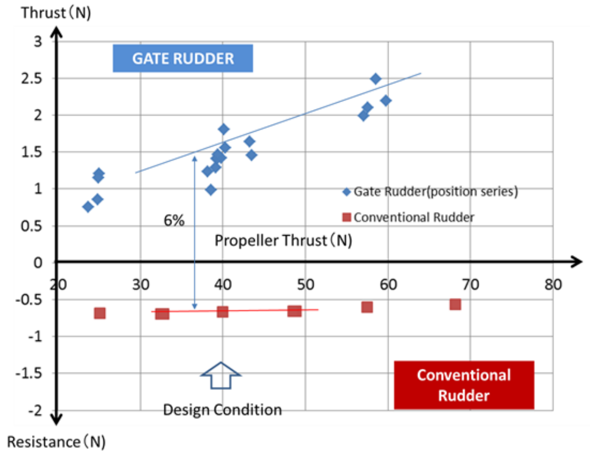


Figure 16 Measured force (in axial direction) on of a Gate Rudder and conventional rudder

The thrust of the gate rudder is proportional to the thrust of the propeller. The presented result is for one rudder of the gate rudder system. The result may be multiplied two as the gate rudder system has two rudders.

8. POWER PERFORMANCE PREDICTION METHOD

The powering procedure can be the most difficult task in evaluating an ESD device and one needs to consider different methods and evaluate the differences amongst them. If these differences are negligibly small, the procedure may be considered reliable otherwise the methods should be further scrutinized step by step.

Based on the model tests conducted with and without a conventional rudder and a gate rudder, our experiences can be summarized as follows:

(1) Resistance test without a conventional rudder presents 1-3% reduction in the hull resistance due to the absence of the rudder. Whereas resistance test with the gate rudder indicates 1-3 % reduction in the hull resistance due to the favorable thrust of the gate rudder.
(2) Self-propulsion tests with the gate rudder present 4-8% higher (1-t) value compared to the tests with the conventional rudder.
(3) The comparative analysis of the open water data for a propeller with a gate rudder and with a conventional rudder present 15-25% higher (1-w) values with the gate rudder.

Figure 17 shows the reflections of the above experiences on the EHP predictions while Table 3 shows the details at 15.0 knot service speed for the vessel given in Table 1.

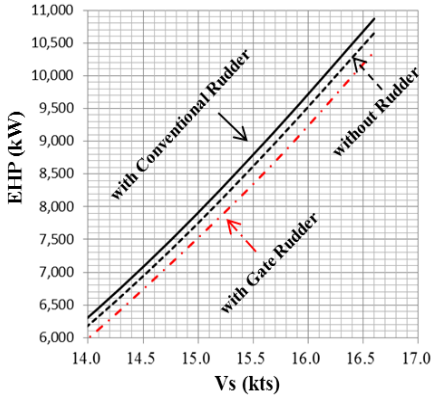


Figure 17. Comparative power data

Table 3: Summary of powering data for service speed

	Conventional Rudder		Gate Rudder	
Ship Speed (kN)	15.0			
rudder	without	with	without	with
EHP(kW)	7770	7930	7770	7520
1-t		0.836	(0.836)	0.880
1-wm		0.600	(0.600)	0.738
1-ws		0.691	(0.691)	0.792*
η_R		0.990	(0.976)	0.976
η_0		0.550	(0.598)	0.613
η		0.659	(0.706)	0.672
DHP(kW)		12033	(11004)	11190*
		100	91.5	93.0

Assuming the interaction between the hull and propeller with a gate rudder is similar to that of the interaction with a conventional rudder, increment of (1-t) and (1-w) can be represented by the change in the efficiency of the propeller system which is assumed to be consisted of the propeller and gate rudder. Because the propeller system efficiency will be higher than the efficiency of the propeller with conventional rudder due to the thrust contributions of the gate rudder, the efficiency gain of the gate rudder can be represented by the following simple formulae.

$$\frac{\eta_{GR}}{\eta_{CR}} = \left(\frac{T_P + T_{GR}}{T_P}\right) \tag{21}$$

However one may have a question on the above made assumption of the similar interaction for the gate rudder and conventional rudder systems. It is generally recognized that the propeller with a conventional rudder and ducted propeller system presents the similar self-propulsion factors if we analyze their self-propulsion test data with the system open water characteristics. The gate rudder can regarded as a system similar to the ducted propeller system or a propeller with a larger diameter keeping the constant thrust.

Figure 18 shows the comparison of the measured resistance on the floating (segmented) part of the stern with the gate rudder and conventional rudder. As one can see in this figure the similar resistance data measured with both rudder configurations supports the earlier made assumption that the Interaction force between the hull and gate rudder system is similar to the conventional rudder system. This means that we can use the same (1-t) values as the conventional vessels for the gate rudder configurations if we apply the proposed method.

Regarding the effective wake, we already show that the difference of velocity vector and the pressure contour in a propeller plane can be explained by an induced velocity due to the gate rudder. This fact also can be explained by RANS code as shown in Figure 14.

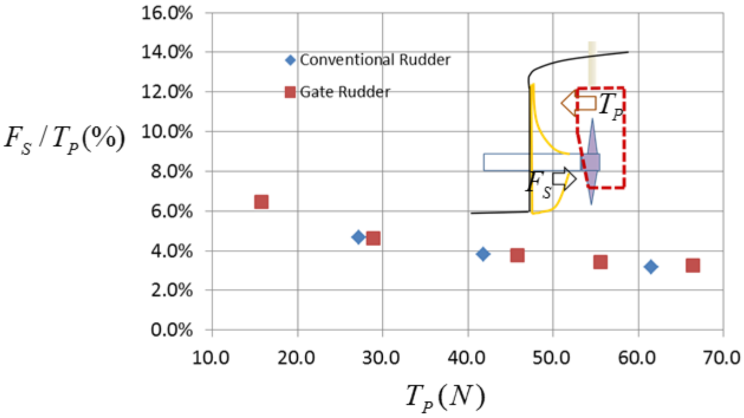


Figure 18 Comparison of aft end resistance with gate rudder and conventional rudder

As a conclusion, both powering predictions given in Table 3, which include the data with/without the gate rudder and with/without the conventional rudder are very close and the consideration of the propeller and gate rudder as a single propulsion system will be more reasonable.

Based on the above justification one may suggest a practical power prediction method for a ship with the gate rudder as in the chart given in Figure 19. According to the proposed method the powering prediction should start with the hull resistance data without the gate rudder either from model tests or other sources. Next is the accurate estimation of the hull-gate rudder-propeller interaction coefficients (ie self-propulsion factors). This would require self-propulsion tests with the gate rudder. Alternatively one can conduct open water tests with the gate rudder (i.e. gate rudder system open water tests) together with the measurements of the rudder thrust from which the gate rudder induced velocities can be estimated. Based on the induced velocities, hull wake and propeller data the effective wake and other self-propulsion factors can be derived which will enable to make the final delivered power estimation.

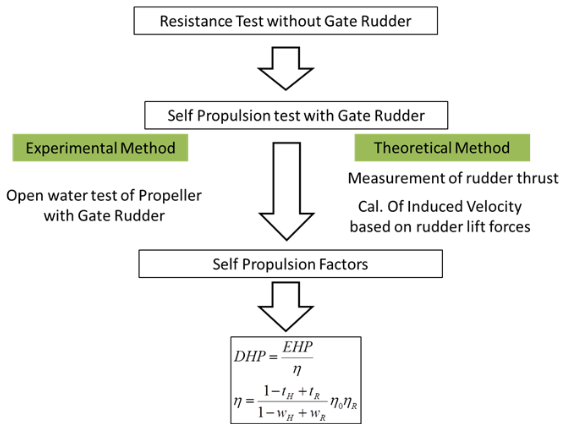


Figure 19 Flow chart for details of fine powering performance prediction method

Within the above framework the earlier mentioned “fine power performance prediction technology” based on the Emerson Cavitation Tunnel (ECT) facility is an attractive procedure. This is because the open water data of the gate rudder system can be easily obtained using the ECT dynamometer system. Furthermore, the measurement of the gate rudder lift as well as the resistance on the stern part of the hull (if necessary) can be readily measured using the suitable load cell components and dummy hull of the facility. Moreover the ECT is equipped with the sophisticated LDA/PIV system to measure the detailed flow around the gate rudder, propeller and hull aft end including detail wake flow to support the estimation of the propulsion factors. Finally the depressurizing facility of the tunnel will allow to analyse the cavitation characteristics and propeller excited hull vibration of the gate rudder system as well as the underwater radiate noise using the noise data collection system of the tunnel.

10. COST EFFECTIVENESS

Cost effectiveness is very important for any new ESD. In the following the cost estimation is given for fitting the gate rudder on different size of vessels based on a previous study. Following assumptions were made for the estimations;

1. The vessel will be built as a new ship
2. Energy saving by the gate rudder will be between 3%-8% depending on ship fullness
3. Bunker oil price is assumed as 0.220k$/ton reflecting the recent low oil price
4. Two small rudders will be installed replacing a large conventional rudder
5. One additional rudder is considered for cost wise
6. The cost of rudder is estimated based on 3.75k$/ton
7. The cost of steering gear is estimated based on 0.67k$/ton-m
8. The cost of upgrading of the software for the new system was estimated as 25% of hardware

Table 4: Return of investment (ROI) for Gate Rudder applications

	Lpp	B	d	CB/(L/B)	M/E Output	70%	SFO	ton/day	days	ton/year
CAPE	300	50	18.3	0.145	18000	12600	180	54	300	16,330
COAL	223	50	13.45	0.173	11760	8232	180	36	300	10,669
PANAMAX	225	32.2	14	0.125	11000	7700	180	33	280	9,314
HANDY	180	30	12.2	0.133	8000	5600	180	24	280	6,774
VLCC	320	60	20.8	0.156	28000	19600	180	85	300	25,402
AFRA	230	42	14	0.150	12000	8400	180	36	300	10,886

Additional Contruction

	Rudder Area	Rudder Weight	Cost of Rudder	St. Gear Capa	Cost of St. G
	m**2	ton	k$	ton-m	k$
CAPE	46	35	130	75	50
COAL	25	16	58	30	20
PANAMAX	26	17	62	32	22
HANDY	18	11	40	19	13
VLCC	55	46	171	102	68
AFRA	27	17	64	33	22
			3.75 /ton		0.67 /ton-m

				COST UP					
	Power Save	FO save	**FO Save**	Rudder	ST. GEAR	System	DOCK	**Total Cost Up**	**ROI(year)**
	%	ton/year	**K$/year**	k$	k$	k$	k$	k$	
CAPE	5.3	868	**191**	130	50	45	0	**225**	**1.18**
COAL	7.4	793	**174**	58	20	20	0	**98**	**0.56**
PANAMAX	3.7	349	**77**	62	22	21	0	**104**	**1.36**
HANDY BC	4.4	300	**66**	40	13	13	0	**66**	**1.00**
VLCC OIL	6.1	1,557	**342**	171	68	60	0	**299**	**0.87**
AFRA OIL	5.7	618	**136**	64	22	21	0	**107**	**0.79**

As shown in Table 4, the Return of investment (ROI) is 0.56- 1.18 which indicates a period of return, less than a year for almost of the vessels. These figures may vary depending on oil price, shipyards standard. However the range of the fluctuations will be around 10 % and the ROI of the gate rudder will be still attractive.

11. CONCLUSIONS

A new energy saving device called "gate rudder" is introduced and its energy saving principles and other advantages are presented.

The gate rudder system can generate thrust on its twin rudders that can be as high-as 6-8% of the hull resistance and this results in similar amount of power saving compared to the same hull with a conventional rudder.

The recent experimental investigations in the Emerson Cavitation Tunnel confirm the above as well as providing further opportunity to study the complex interaction amongst the hull-propeller and gate rudder components.

A medium size cavitation tunnel, like the Emerson Cavitation tunnel, may offer to make fine power predictions of ships fitted with a gate rudder or similar energy saving device as proposed in this paper.

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