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Comparative study of Maneuvering performance of Conventional and Fishtail rudder of a Ship

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***Abstract*— Modelling of rudder plays an important role while designing a ship as the rudder is mainly responsible for the manoeuvring performance of a ship. In this paper an innovative rudder design inspired from the body of fish has been developed to attain the higher lift coefficients and improve the manoeuvring performance of ship. The hydrodynamic forces on the rudder is calculated using numerical approach of Computational Fluid Dynamic (CFD) study using ANSYS Fluent 14.0 a non-commercial software. The results were compared with other conventional rudder which has same area as that of fishtail rudder. NACA 0018 is used as the section for conventional rudder. The Numerical simulations were run on rudder at various angles of attack such as 0°, 10°, 20°, 30°, 35°. Mathematical model of ship manoeuvring was developed with intent to evaluate the manoeuvring performance of ship in a seaway based on International Maritime Organization (IMO) standards on turning test. The results from the simulation shows that fishtail rudder has higher lift coefficients and can produce better manoeuvring performance than that of conventional rudder.**

***Index Terms*—CFD study, Fishtail, Ship Maneuverability, Rudder.**

I. INTRODUCTION

Rudder is the most important hydrodynamic control surface on a ship to control the horizontal motion of a ship. The important function of the rudder is to develop a force with respect to its orientation and motion relative to water. Trading through shipping is increasing day by day demanding more ships resulting in crowded marine traffic. For better operation of these waterways the maneuverability of vessels should be improved. This can be achieved by increasing the performance of rudders of marine vehicles. Now a days the size of ships is also increasing with demand posing naval architects new challenges in design of rudder and maneuverability of ship. Maneuvering ability of a ship plays a vital role in preventing accidents in a seaway especially in restricted waterways like harbours, canals etc. For better maneuverability of ships rudders with high lift coefficients have been sought. A rudder to a ship is like a tail to a fish. It is known that fish has excellent maneuvering capabilities, so depending upon this fact innovative rudders of fish tail designs were developed.

Consider a rudder immersed in viscous fluid at an angle of attack to the uniform flow velocity. In this condition a vortex street is formed around the rudder which produces additional velocity when this velocity is added to the stream velocity it gives an effect of drag force because of decrease in the total velocity, due to pressure difference between the sides of the rudder a lift force is produced. And because the fluid is viscous there exists frictional force, this frictional force acts tangentially to the surface of the rudder. The total hydrodynamic force on the rudder tends to act a single point called center of pressure (*CP*) [1].

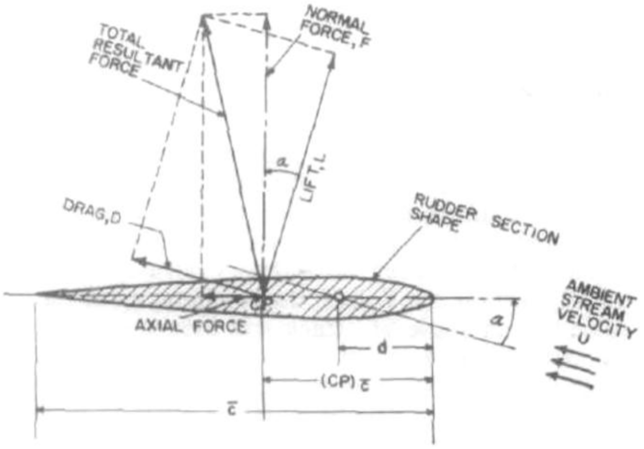

Fig.1. Rudder force components

To know the characteristics of rudder like lift and drag coefficients at various angles of attack there are various methods like experimental, computational and analytical methods. Although experimental methods give accurate results it has become the second choice for the designers with the advent of computer technology because experimental methods are time consuming and costly whereas the computational results are reliable and can be achieved easily.

In this work a comparative study of lift generation and maneuvering performance of conventional rudder and fish tail rudder is done to predict which one suits better on a particular ship in this case a bulk carrier in the preliminary design stage itself and to check whether it satisfies the maneuvering criteria prescribed by International Maritime Organization (IMO).

II. PROCEDURE

A. Overview

The procedure began with estimating the size and geometry of the rudder. For this purpose firstly area of rudder is calculated using *Det Norske Veritas* (DNV) classification society rules, equation (1). Depending upon this area and geometric aspect ratio, the dimensions of chord (*C*) and span (*S*) are estimated.

$$A_r = \frac{L \times T}{100}\left[1 + 25 \times \left(\frac{B}{T}\right)^2\right] \qquad (1)$$

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B. Conventional Rudder

National Advisory Committee for Aeronautics (NACA) 0018 section is used as the shape of section of conventional rudder. The area of rudder is estimated to be 35.25 m^2 and geometric aspect ratio is taken to be 1.5. The rudder is considered to be rectangular. Therefore the chord length and span of rudder is approximated to 3.3758 m and 5.0638 m respectively.

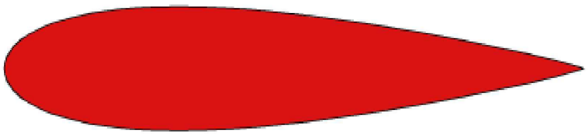

Fig .2. Section of Conventional rudder

C. Fishtail rudder

In this study the fishtail rudder section is generated by making changes to NACA 0018 section such that the maximum width is located at 20% of chord length from head, taper to 80%, concave to 90% and flare to 100% [2]. The maximum thickness of section is similar to that of NACA 0018 and trailing edge thickness is taken to be 0.08*C* [2]. This rudder is also considered to be rectangular. Here the chord length and span of rudder are approximated to 3.21 m and 4.81 m respectively.

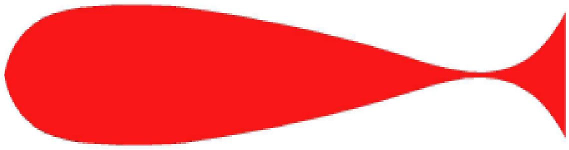

Fig 3. Section of fishtail rudder

D. Computational model

A cuboidal domain whose dimensions are 12 m x 8 m x 6 m respectively was created in AutoCAD. The important aspect while generation of domain is to ensure that, the walls has little effect on disturbance of flow around the rudder, for this to achieve the length of domain must be at least three to four times the chord of rudder [4]. The head of rudder is placed at a distance of 1.5 m from the inlet.

Ansys Mesh tool is used for the meshing of computational domain. Non Uniform unstructured mesh elements have been used to divide the domain into small control volumes. Mess structure has been designed denser in the vicinity of the rudder and gradually the elements size increases as it moves away from it. Such an approach enables simulations run economically.

The analysis is done using Ansys Fluent 14.0 software. The flow around the rudder is assumed to be pressure based, steady, non-viscous and incompressible. *K-ω SST* model is used as turbulent model for this setup. It is a two equation eddy viscosity model which has become popular in recent times [6].

The velocity at the inlet is given as 6.2 m/s or 12 knots. The boundary conditions are given in Table.1.

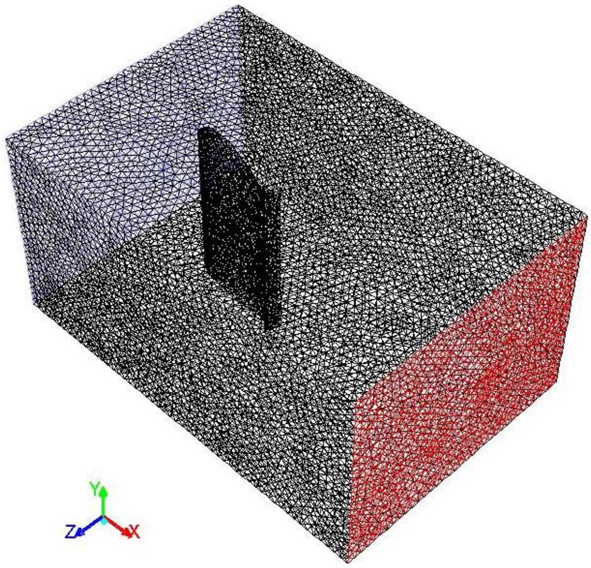

Fig.4. Meshed Computational domain

Table.1. Boundary conditions of computational domain

Boundary	*Type*
Left	Velocity inlet
Right	Pressure outlet
Rudder profile	No slip wall
Remaining sides	No slip wall

E. Calculating maneuvering performance

The evaluation of these two model rudders effect to the ship maneuvering performance was determined by using Clark's equations, [3]. In this computation the rudder models were installed on the ship whose details are given in appendix. Steady turning test was performed to evaluate ship maneuvering performance. Fig.5 describes the model of turning test, in which the ship was initiated turning by rotation of rudder for various angles i.e., 10°, 20°, 30° and 35° respectively. Here the performance of the ship could be predicted by measuring Steady Turning Diameter (*STD*), Tactical Diameter (*TD*), Transfer (*Tr*) and Advance (*Ad*) in the turn for any rudder angle. Turning test is mainly divided into four stages. The first stage of preparation which at this stage the ship moves straight from rest until it reaches the desired speed. At this stage there is no rudder turning, this stage ends when rudder starts turning. The second stage begins when the rudder has rotated to form the desired angle and terminates when the ship direction is about 90° to the original direction. The third stage begins when the rudder has reached the maximum angle, and ends when the ship has rotated to 180°. And in the last stage the ship turns around with a fixed radius and is referred as steady turning phase.

IMO has set certain standards of ship maneuverability and every ship must satisfy these standards in order to sail. The standards of turning test are that Advance (*Ad*) must not be greater than 4.5 times the length of ship and Tactical Diameter (*TD*) must not exceed 5 times the length of ship [7].

The maneuvering simulation program was developed based on Clark's equation in which the lift coefficient is required as input. The hydrodynamic coefficients of maneuvering are calculated using set of equations (2).

$$Y_{\dot{v}}' = -\pi.\left(\frac{T}{L}\right)^2 \times \left[1 + 0.16 \times C_b \times \left(\frac{B}{T}\right) - 5.1 \times \left(\frac{B}{L}\right)^2\right]$$
$$Y_v' = -\pi.\left(\frac{T}{L}\right)^2 \times \left[1 + 0.4 \times C_{b\times}\left(\frac{B}{T}\right)\right]$$
$$Y_{\dot{r}}' = -\pi.\left(\frac{T}{L}\right)^2 \times \left[0.67 \times \left(\frac{B}{L}\right) - 0.0033 \times \left(\frac{B}{T}\right)^2\right]$$
$$Y_r' = -\pi.\left(\frac{T}{L}\right)^2 \times \left[-0.5 + 2.2 \times \left(\frac{B}{L}\right) - 0.08 \times \left(\frac{B}{T}\right)\right]$$
$$N_{\dot{v}}' = -\pi.\left(\frac{T}{L}\right)^2 \times \left[1.1 \times \left(\frac{B}{L}\right) - 0.041 \times \left(\frac{B}{T}\right)\right] \quad (2)$$
$$N_v' = -\pi.\left(\frac{T}{L}\right)^2 \times \left[0.5 - 2.4 \times \left(\frac{T}{L}\right)\right]$$
$$N_{\dot{r}}' = -\pi.\left(\frac{T}{L}\right)^2 \times \left[\frac{1}{12} + 0.017 \times C_b \times \left(\frac{B}{T}\right) - 0.33 \times \left(\frac{B}{L}\right)\right]$$
$$N_r' = -\pi.\left(\frac{T}{L}\right)^2 \times \left[0.25 + 0.039 \times \left(\frac{B}{T}\right) - 0.56 \times \left(\frac{B}{L}\right)\right]$$

Here $Y_{\dot{v}}'$, $Y_{\dot{v}}$, $Y_{\dot{r}}'$, $Y_{\dot{r}}$, $N_{\dot{v}}'$, $N_{\dot{v}}$, $N_{\dot{r}}'$, $N_{\dot{r}}$ are non-dimensional hydrodynamic coefficients. Hydrodynamic coefficient which is related to rudder force is the value of Y_δ' and it can be calculated by equation (3).

$$Y_\delta' = \left(\frac{A_r}{T\times L}\right) \times \left(\frac{T}{L}\right) \times \left(\frac{dCl}{d\delta}\right) \times Cl \times \left(\frac{c}{u}\right)^2 \quad (3)$$

Here Cl is the lift coefficient and c is a flow velocity on rudder surface. Here $\left(\frac{dCl}{d\delta}\right)$ represents the slope of lift curve of rudder and is given by equation (4).

$$\frac{\partial Cl}{\partial \delta} = \frac{0.9\times 2\pi\times a}{57.3\left[\left(\cos\Omega\times\sqrt{\left(\frac{a^2}{\cos^2\Omega}+4\right)}\right)+1.8\right]} \quad (4)$$

The rudder position is assumed a half of ship length after of amidships, non-dimensional rudder moment N_δ' can be calculated by equation (5).

$$N_\delta' = 0.5.\ Y_\delta' \quad (5)$$

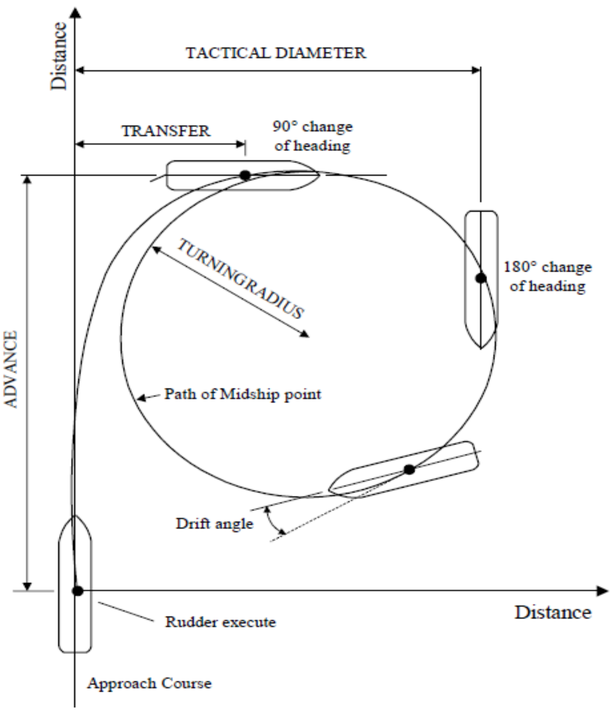

Fig.5. Modelling of turning test

The STD of the ship can be calculated by equation (6) from [1].

$$STD = \left(\frac{L}{\delta}\right) \times \left[\frac{\left(Y_v' \times N_r' - N_{v'} \times (Y_r' - m')\right)}{N_v' \times Y_\delta' - Y_{v'} \times N_{\delta'}}\right] \quad (6)$$

Here m is mass of ship and δ is rudder angle. The other parameters which indicate the maneuvering performance such as Ad, TD and Tr can be approximated by set of equations (7) from [3].

$$\frac{TD}{L} = 0.14 + 1.0 \times \left(\frac{STD}{L}\right)$$
$$\frac{Ad}{L} = 1.1 + 0.514 \times \left(\frac{TD}{L}\right) \quad (7)$$
$$Tr = 0.375 + 0.531 \times \left(\frac{TD}{L}\right)$$

III. RESULTS AND DISCUSSION

A. *Lift generation*

In this study Computational Fluid Dynamic (CFD) simulations of Conventional rudder and fishtail rudder at 0°, 10°, 20°, 30°, 35° are shown, which gives us a visualization of pressure field around the rudder. Fig.6 and Fig. 7 shows that the pressure difference between the sides of rudder increases with increase in angle of attack. This implies that pressure force increases with increase in angle of attack.

Table.2. Lift and drag coefficients of conventional and fishtail rudders

Angle of attack (δ)	*Lift Coefficient (Cl)*	*Drag Coefficient (Cd)*
Conventional rudder		
0	0.00011	0.01484
10	0.29665	0.03942
20	0.67775	0.13235
30	0.9506	0.2602
35	0.87543	0.30561
Fishtail rudder		
0	0.0016	0.08845
10	0.3055	0.1186
20	0.68649	0.2247
30	1.0596	0.4212
35	0.96645	0.5142

Table.2. shows the variation of lift and drag coefficient with increase in angle of attack. It is observed that the lift coefficient of fishtail rudder is significantly higher than that of conventional rudder, this is because additional pressure force is generated on the surface of fishtail rudder due to its converging and diverging nature of rudder surface along the flow and this can be observed from the Fig. 7. It is also observed that the drag coefficient of fishtail rudder is also much higher than that of conventional rudder which is obviously a con of fishtail rudder. The reason behind it that due to huge variations on surface along the flow, more pressure force is generated which has a component in the drag force direction.

From Fig.8, the lift coefficients of conventional as well as fishtail rudder takes a dip after 30° and nearly at 35° due to stalling of rudder. Most of the marine rudders have stall angle in this region, so for this reason IMO has limited the rotation of rudder to a maximum of 35° on either sides of rudder.

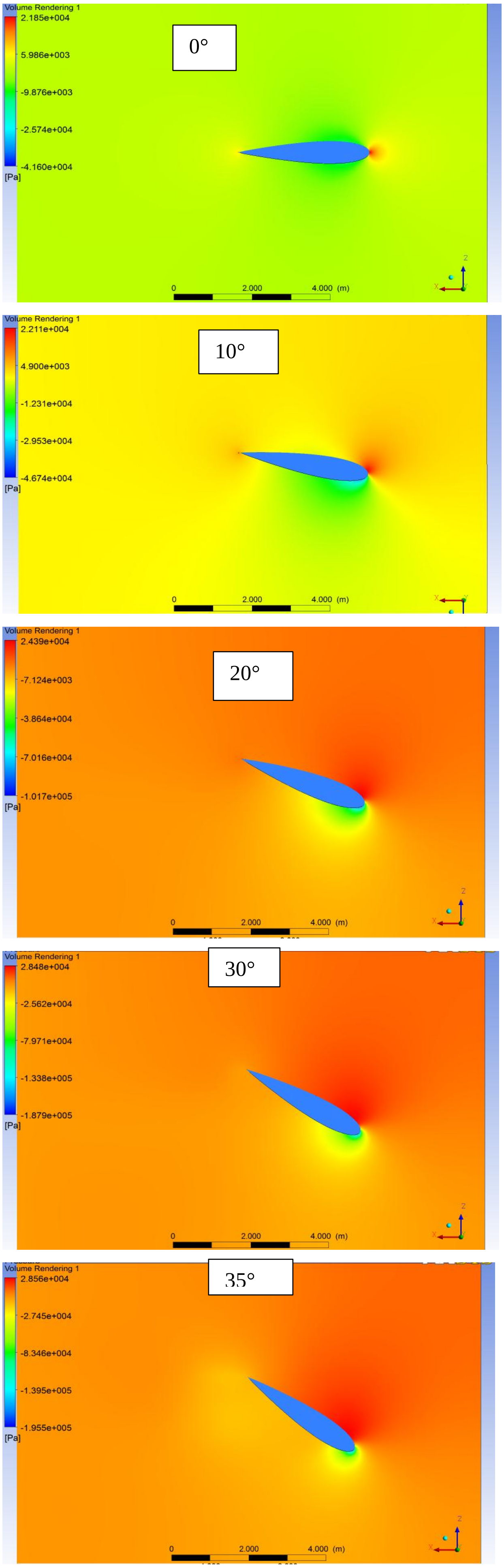

Fig.6. Pressure distribution around conventional rudder

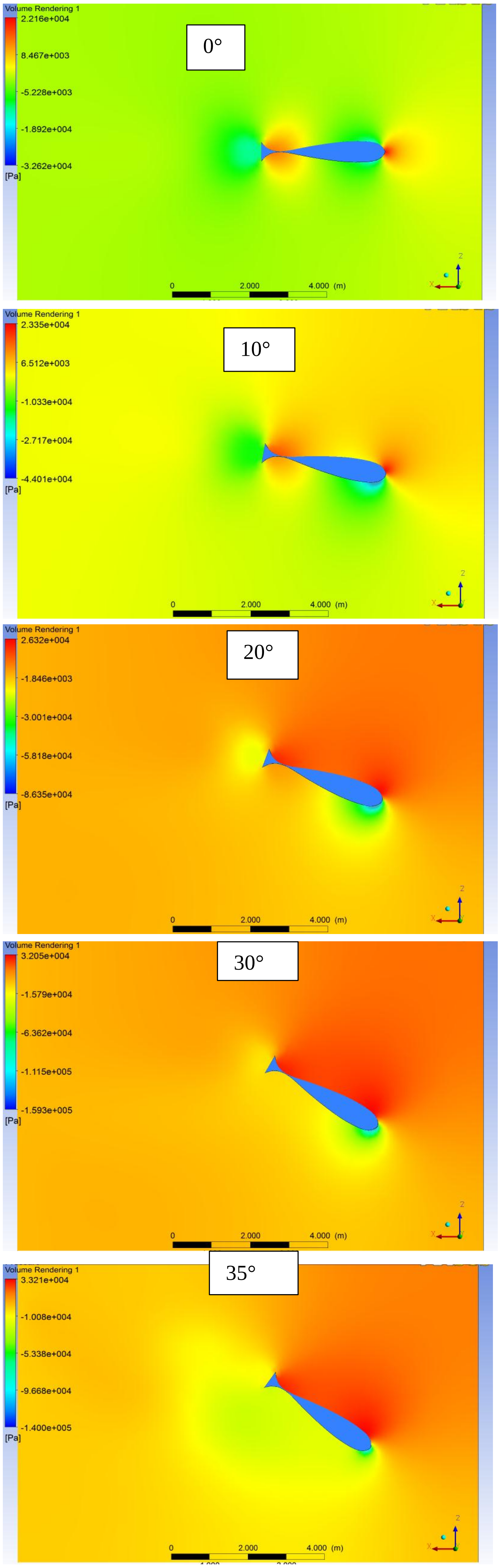

Fig.7. Pressure distribution around fishtail rudder

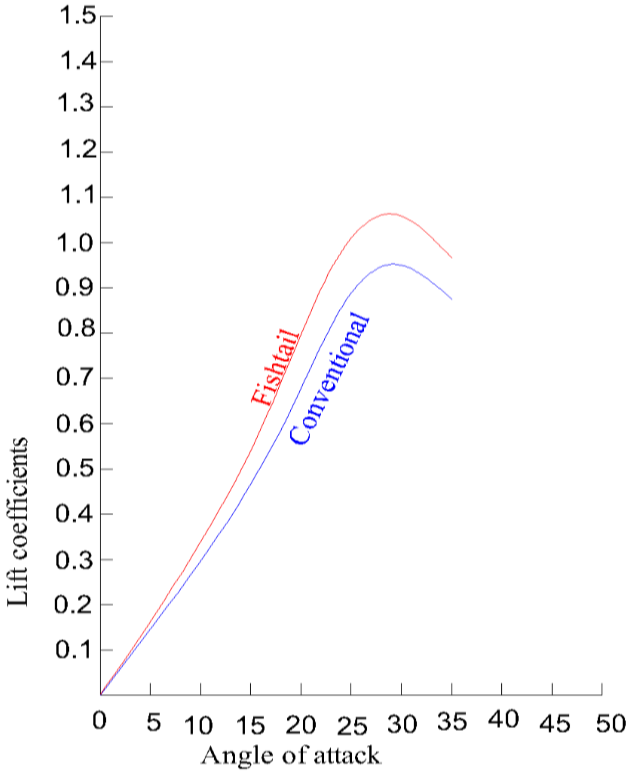

Fig. 8. Lift coefficient vs. angle of attack

B. *Maneuvering performance*

From Table. 3, it is clear that both the rudders satisfy the criteria set by IMO for safe maneuvering practice as the Advance is much lesser than the 4.5 times the length of ship and *TD* is not exceeding 5 times the length of ship.

It is quite evident from data that fishtail rudder has better maneuvering properties than that of conventional rudder as all the parameters like *STD*, *TD*, *Tr*, *Ad* of fishtail rudder are significantly lesser than that of conventional rudder which indicates the superiority of fishtail rudder over conventional rudder in terms of maneuverability.

Table.3.Turning test results of conventional and fishtail rudder

Angle of attack (δ)	*STD(m)*	*TD(m)*	*Ad(m)*	*Tr(m)*
Conventional rudder				
0	-	-	-	-
10	516.77	541.97	476.57	355.28
20	106.62	131.82	265.76	137.50
30	45.38	70.58	234.28	104.98
35	43.08	68.28	233.09	103.75
Fishtail rudder				
0	-	-	-	-
10	404.00	429.20	418.61	295.40
20	91.71	116.91	258.09	129.58
30	39.35	64.55	231.18	101.78
35	37.68	62.88	230.32	100.89

IV. CONCLUSION

In this paper it is shown that fishtail rudder generates more lift force and maneuvering capabilities than a conventional rudder but it is also observed that the drag is also much higher in case of fishtail rudder, so it is actually a compromise between better maneuvering capabilities and power efficiency. In cases if ship is operating in areas like narrow canals, harbours and other high marine traffic regions where maneuvering of ship is of paramount importance the fish tail rudder can be a better substitute to conventional rudder.

APPENDIX

A. *Details of Ship and Nomenclature*

L - Length of Ship – 180 m
B - Breadth of ship – 32.2 m
T – Mean draft of ship - 10.9 m
C_b – Block Coefficient of ship – 0.82
m – Mass of Ship (Displacement) – 53,175 Tonnes
A_r – Area of rudder – 35.25 m^2
Ω - Sweep angle of rudder - 0°
a- Geometric aspect ratio – 1.5
m' – Hydrodynamic mass coefficient – 0.00001779
c- Speed of ship

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