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Redesigning the Rudder for Nigat Boat

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ABSTRACT
Boat Nigat is a medium sized boat launched in December 2011, its maiden voyage in the Lake Tana to ferry passengers and goods across the lake. Nigat's rudder is an intuitive design and not manufactured to standard specifications, because of limited facilities in terms of designing and manufacture. Obviously it is difficult to predict controllability efficiency (characteristic) of the boat with the intuitively designed rudder. This paper proposes an optimized rudder design for Nigat based on an airfoil shape. The design presented here uses NACA 0012 airfoil shape for the rudder cross-section in order to improve its better performance. It is hoped that the design suggested herein can be used as a standard rudder design for use in other boats irrespective of the size of the boat.

KEYWORDS: *Rudder Design, Rudder Profile, Stock Diameter, NACA Profiles, Yacht Maneuvering*

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I. INTRODUCTION:

Lake Tana Transport Enterprise is a 70 year-old enterprise providing boat transport to local people and tourists travelling to the monasteries on Ethiopia's largest Lake Tana, covering 2,156sqkm.The enterprise started work with a couple of Italian-made boats. The defeated Italian army sank its boats while retreating from the area. Ethiopians recovered the boats and put them to civilian use shortly after. The company has experience of maintaining, rebuilt the body and changed its engine of the Italian made boats. Presently the company starts to build new boats for their own demand and customer. The first dual purpose boat which is constructed at Gorgora boat manufacturing yard, is Nigat Boat which can carry 135 people and 20 tons of cargo. The initial sketch was prepared by the company technicians having maintenance experience. To prepare the ketch they use the previous boats, of having one bigger and the other smaller carrying capacity and dimension. They assumed the relations to find sizes, thickness of different parts are interpolated linearly to find the dimension. In reality the relation may not be linear, hence the aim of this paper is to provide an optimum design for the currently used rudder which is designed by taking arbitrary shape and dimension [2]. Moreover the rudder and propeller arrangement is not having sufficient space so that, it has high vibration of the hull (transom) because of water propelled to the groove shaped part on the hull formed for increasing the propeller tip clearances.

To provide a better controlling means of the boat the rudder shape and arrangement of the propeller and rudder should be well designed. Controllability encompasses all aspects of regulating the ship's (boat's) trajectory, speed and orientation at sea, as well as in restricted waters where positing and station keeping are of particular concern. Controllability includes starting, steering at steady course, and turning, slowing, stopping and backing. For conventional boat, the two qualities of course keeping and maneuvering may tend to work against each other; an easy turning boat may be difficult to keep on course whereas a boat which maintains course well may be hard to turn. Fortunately, a practical compromise is nearly always possible.

Different standard shapes and arrangements of rudder are available for maneuvering of boats; the selection depends on the requirement of the boat.

The rudder effectiveness in maneuvering is mainly determined by the maximum transverse force acting on the rudder. Rudder effectiveness can be improved by:

- Rudder arrangement in the propeller slipstream
- Increasing the rudder area
- Better rudder type

Although extensive experimental studies have been extensively made on the rudder design there is no systemized or generalized rudder design process has been known until now [1].

The aim of this research is to fill this gap in the design and construction of boat rudder at Lake Tana Transport Enterprise. Up until now the Lake Tana Transport Enterprise located at the Gorgora boat manufacturing yard is not able to use an organized and scientific approach in the design and construction of the rudder. This paper attempts to replace the trial and error approach which may also be used as a guide in building rudders for future boat projects.

1.1 Factors Considered During Rudder Design:

Some of the general factors to be considered in rudder design process of most such as ship's maneuvering are performance, possibility of installing and removing propellers, steering gear capacity for rudder control, avoidance of erosion by cavitations, selection of a shaft diameter, weight of rudder, and lift capacity.

II. STEPS IN RUDDER DESIGN PROCESS:

Rudders should be installed so as to turn about 35 degrees from dead center in both direction and not over 40 degrees. More action than this can result in stalling, or an immediate loss of control, and a drastic increase in strain on the rudder, which could damage the rudder [1].

The general rudder design process can follow but not restricted the following steps Fig. 1

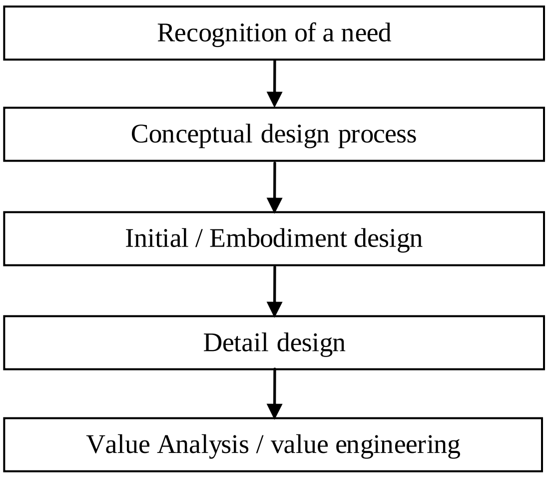

Fig 1 Rudder Design Process Outline

2.1 Recognition of a need:

Needs are identified at many points in a business or agency. Need usually arise from dissatisfaction with the existing situation; it may be to reduce cost, increase reliability or performance or just change because the public has become bore with the product.

Table 1: Basic dimension of Nigat Boat

Principal Data	
Overall length	20.75 m
Water line length	18.00 m
Beam	5.20 m
Draft	1.20 m
Capacity	20 tons
Self weight	55 tons
Number of propeller blade	5
Diameter of the propeller	1.05 m
Designed Speed	10 knot

2.2 Conceptual Design

One of the most important points of the rudder concept design process is that the draft should meet customer requirement given in Table 1.

2.3 Initial Design

Rudder initial design process is embodiment of results from the concept design. So, this process compares the economy or basic layout functions like rudder form or dimension. The rudder initial design is classified by decision of rudder profile, dimension, and assumption of steering gear capacity. Rudders may be either the unbalanced type, or designed with some degree of balance to make turning easier. On a balanced rudder, there will be a certain portion of the blade area forward of the rudder stock or pivot point which will decrease some of the force necessary to pivot the rudder. For this design the unbalanced type rudder is selected.

III. SELECTION OF RUDDER PROFILE

There are five kinds of rudder profile (Becker rudder standards): Flap, Twist, Schilling, NACA series and Kort Nozzle as it appears in Fig. 2. NACA lines are generally used when rudder type determined with no specific requirement of boat owners.

NACA lines are suitable in thin section for resistance, and in thick one for strength [1]. We have to select the appropriate NACA Profile rudder considering the drag and stall characteristics not affected greatly by the manufacturing quality; NACA 65, NACA 66 and NACA 67 have such limitation [3].

Hence, it is preferred to use NACA 0012 which provide high stall angle, the stall characteristics is gradual, less likely to cause cavitation and vibration. Among the NACA series aerofoil section, NACA0012 is used in boat rudder. The maximum thickness on this foil is found at a distance 30% back from the leading edge. The portion of the blade forward cannot be too great it will makes steering too easy as well as dangerous, with constant attention to the helm being required. Thin foil sections stall at lower angles of attack than thick sections NACA0012 is a good compromise. For these reasons NACA 0012 section has been chosen for the present design (Refer Table 3 for the coordinate of the portion of aerofoil).

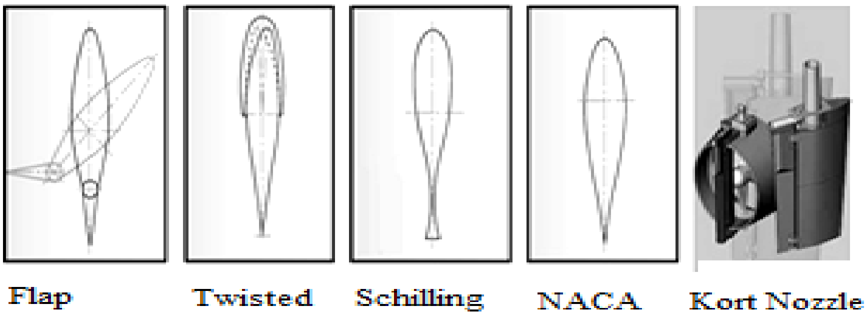

Fig. 2 Classification of Rudder Profile [1]

3.1 Selection of Rudder Form

There are four kinds of rudder fin arrangements as shown in Fig 3; Full spade, King Support rudder (KSR), Herus support and Semi spade. Among these the full spade rudder type is selected for this design, because it is relatively easy to manufacturing the rudder structure and can avoid gap cavitation. It consists wholly of movable part and it does not have a horn. In the full spade type arrangement, the mass loaded on rudder as well as the rudder mass is supported by one shaft.

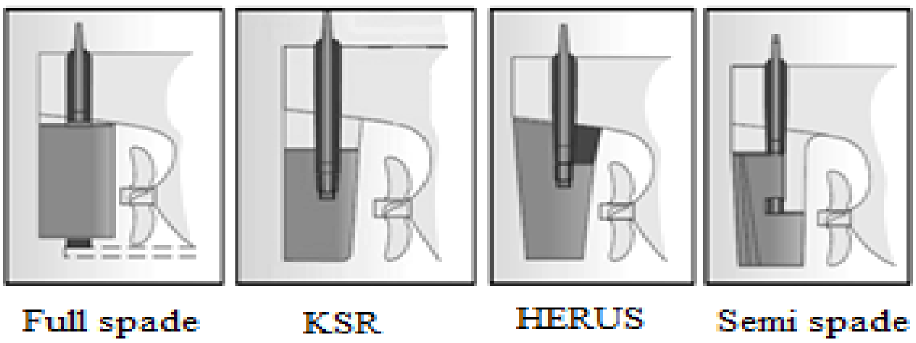

Fig. 3 Rudder-Fin Arrangements [1]

3.2 Rudder Dimensions and Manoeuvring Arrangement

Each ship or boat is to be provided with a maneuvering arrangement which will guarantee sufficient manoeuvring capability. The manoeuvring arrangement includes all parts from the rudder and steering gear to the steering position necessary for steering the boat [4]. Distance between rudder and propeller, distance between hull bottom and rudder, and influence of stern frame are to be considered when rudder design criteria is investigated. Distance between rudder and propeller should be designed considering cavitation, installing and removing the propeller. The distance between the rudder and the propeller is chosen such that the rudder is located just behind the propeller and close to it. In Fig. 4, if the interval between 'a' and 'b' gets larger, the vibration becomes smaller, and the performance of propeller propulsion improves greatly. It is recommended that the minimum clearances (Fig 4) between propeller astern frame or between the propeller and rudder not to be less than the following: [5]

a = 0.12 D [m] = 0.12 * 1.05 = 0.126 m
b = 0.20 D [m] = 0.20 * 1.05 = 0.210 m
c = 0.14 D [m] = 0.14 * 1.05 = 0.147 m
d = 0.04 D [m] = 0.04 * 1.05 = 0.042 m
Where
D – Diameter of propeller in [m]

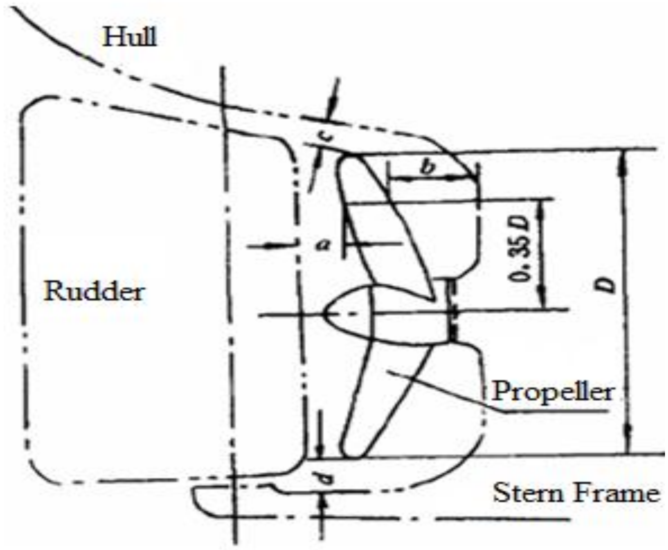

Fig. 4 Propeller clearances [5]

3.3. Rudder Detail Design Process:

Rudder detail design process re-examination of result of initial design, decision of rudder torque, layout for the rudder structure, form and dimensions. These are all determined during the process of rudder detail design. Also, if the information of rudder initial design has mistakes, the process of initial design has to be repeated; therefore, the process of rudder detail design can have course of feedback. The process of rudder design is comprised of making decision of rudder structure and rudder area.

a. Structural Details

Effective means are to be provided for supporting the mass of the rudder body without excessive bearing pressure. The hull structure in way of the rudder carrier is to be suitably strengthened. Suitable arrangements are to be provided to prevent the rudder from lifting.

b. Materials

In general materials having yield strength (σ_y) less than 200 N/mm^2 and a tensile strength (σ_t) of less than 400 N/mm^2 recommended for rudder stocks, pintles, keys and bolts.
The material used for the rudder stock and blade is medium carbon steel of yield strength 400MPa which is readily available in the market without any special order, may be used for the rudder construction.

c. Size of Rudder Area

In order to achieve sufficient manoeuvring capability the size of the movable rudder area should be determined and verified during the initial boat arrangement study. A good first step to use the 1975- Rules of Det Norske Variation for a minimum projected rudder area [6]:

$$A \geq \frac{dL}{100}\left(1 + 25\left(\frac{B}{L}\right)^2\right)$$

Where

A Movable rudder vertical projected area [m²]

L Length between perpendiculars [m]

B Beam [m]

d Draft [m]

$$A \geq \frac{1.2 * 18}{100}\left(1 + 25\left(\frac{5.20}{18}\right)^2\right)$$

$$A \geq 0.67$$

$$A = 0.70\ m^2$$

d. Rudder Force

The rudder force (F) is to be determined from the following formula: [5]

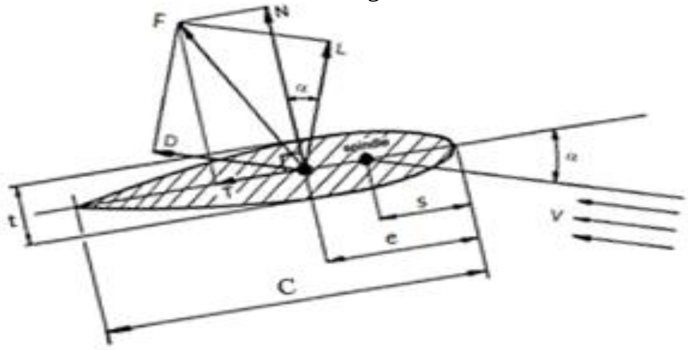

Fig. 5 Forces on a Rudder Section [3]

Where

C-Chord length, e-Total force acting point (center of pressure), F-Total force , N-Normal force, T-Tangential force, D-Drag force, α-Angle of attack, V-Velocity of the boat and t-Blade maximum thickness

$F = 132 * K_1K_2K_3AV_d^2$ [N]

Where:

F Rudder force [N]

V_d Design speed of boat [kn]

K_1 Coefficient, depending on the aspect ratio Λ

$K_1 = (\Lambda + 2)/3$, where Λ need not be taken greater than two [4]

Where $\Lambda = \frac{h_m{}^2}{A_t}$ [3] = $\frac{(1.05)^2}{0.7}$ = 1.57

A_t = Movable rudder area (A) + Area of a rudder horn, if any for our case no horn area

Hence, $A_t = A = 0.7m^2$

$K_1 = (1.57+2)/3 = 1.19$

h_m Mean height of rudder blade

K_2 Coefficient, depending on the type of the rudder and the rudder profile

Table 2: Coefficient K_2 [5]

Type of Rudder/ Profile	K_2	
	Ahead	Astern
NACA-00 Series	1.10	0.8
Flat Side Profiles	1.10	0.9
Hollow Profiles	1.35	0.9
High Lift Rudders	1.70	To be specifically considered; If not known: 1.7.

K_3 Coefficient, depending on the location of the rudder
K_3 = 0.8 for rudders outside the propeller jet
K_3 = 1.0 elsewhere, including also rudders within the propeller jet
K_3 = 1.15 for rudders aft of the propeller nozzle
It is taken from the above data K_2 = 1.10 and K_3 = 0.8
$F = 132 * K_1 K_2 K_3 A V_d^2$ [N]
$F = 132 * 1.19 * 1.10 * 0.8 * 0.7 * 10^2$
F = 9676 N

e. Rudder Torque
The rudder torque (T) is to be determined by the following formula: [4, 5]
T= FR [Nm]
Where:
R = (e - s) [m]; Referring fig 5.
R = C (μ − β) [m]
C = A/h_m = 0.7/1.15 = 0.610 m
μ Coefficient, 0.33 for ahead condition, 0.66 for astern condition.
The value μ = 0.66 is considered for the analysis
β = A_f /A = 0.3 from the position of large width of NACA 0012 along its chord (Refer Table 3)
A_f, being portion of the rudder blade area situated ahead of the centerline of the rudder stock
R = 0.610(0.66 – 0.30) = 0.220 m
For ahead condition, lever R is not to be taken as less than 0.1c [5]
T= 9676 * 0.220 = 2125 Nm

f. Rudder Stocks
The diameter D_t of rudder stock transmitting torque in way of the tiller is not to be less than that obtained from the following formula: [5]

$$D_t = 4.2 \sqrt[3]{\frac{T}{K_m}} \text{ [mm]}$$

Where
K_m material factor of rudder stock
$K_m = (\sigma_y /235)^{0.75}$ for $\sigma_y > 235$ N/mm²
$K_m = \sigma_y /235$ for $\sigma_y \leq 235$ N/mm²
$K_m = (400 /235)^{0.75}$ for $\sigma_y > 235$ N/mm²
K_m = 1.14

$$D_t = 4.2 \sqrt[3]{\frac{2125}{1.14}}$$

= 52.0 mm but to withstand the equivalent stress it should be raised to 60 mm
The diameter of rudder stock below the upper bearing (ι_{40}) is not to be less than that at the tiller.

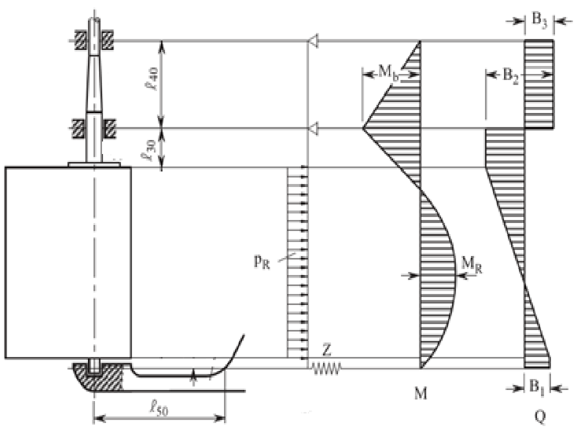

Fig. 6 Shear force (Q) and bending moment (M) diagram of rudder supported by sole piece [4]

For the diameter D_c of rudder stock in way of and below the lower bearing is not to be less than that obtained from the following formula:

$$D_c = D_t \sqrt[6]{1+\frac{4}{3}\left(\frac{M_b}{T}\right)^2}$$

Where

M_b Maximum bending moment of rudder stock from lower bearing to top of the rudder blade [Nm]

$M_b = 0.125\ F\ h_m$ [N.m] [4]

$M_b = 0.125*9676*1.15 = 1391$ N.m

Where h_m mean height of rudder blade

$$D_c = 60 \sqrt[6]{1+\frac{4}{3}\left(\frac{1391}{2125}\right)^2}$$

$= 65$ mm

When direct calculation is used for checking the rudder stock strength in way of below the lower bearing, the equivalent stress σ_e is not to be greater than 118Ks [N/mm^2]

The equivalent stress σ_e is to be determined by the following formula

$\sigma_e = \sqrt{\sigma_b{}^2 + 3\tau_t{}^2}$ [N/mm^2]

Where

$\sigma_b = \frac{10.2 M_b}{Dc^3} * 103$ [N/mm^2]

$\sigma_b = \frac{10.2*1391}{65^3} * 103 = 52$ N/mm^2 = 52 MPa

$\tau_t = \frac{5.1T}{Dc^3} * 10^3$ [N/mm^2]

$\tau_t = \frac{5.1*2125}{65^3} * 10^3 = 39$N/mm^2 = 39 MPa

$\sigma_e = \sqrt{66^2 + 3 * 39^2} = 85$ N/mm^2 = 85 MPa

For the increased rudder stock diameter the equivalent stress of bending and torsion is not to exceed the following value:

$\sigma_e = \sqrt{\sigma_b{}^2 + 3\tau_t{}^2} \leq \frac{118}{k_m}$ [N/mm^2] [4]

$85\ \text{N/mm}^2 \leq \frac{118}{1.14}$ [N/mm^2]

Hence 85 MPa < 103.5 MPa it is safe design which meets the material requirement.

g. Thickness of Rudder Blades

The structure of rudder bales is to be capable of effectively transmitting the subjected force into rudder stock, axis and pintle as to ensure the integral strength of the rudder blades.

The thickness of side (t_s), top and bottom plating of rudders is not to be less than that obtained from the following formula: [5]

$$t_s = 5.5 h_s\ \varphi \sqrt{d + \frac{F}{A} * 10^{-4}} + 2.5\ [\text{mm}]$$

Where h_s and h_l are respectively the short side length and the long side length of webs, in m, φ to taken as 1 if h_l/h_s be ≥ 2.5

$$\varphi = \sqrt{1.1 - 0.5\left(\frac{h_l}{h_s}\right)^2}$$

$\varphi = \sqrt{1.1 - 0.5\left(\frac{1.15}{1.15}\right)^2} = 0.77$

$$t_s = 5.5 * 1.15 * 0.77 \sqrt{1.20 + \left(\frac{9920}{0.7} * 10^{-4}\right)} + 2.5\ [\text{mm}]$$

$= 4.87*1.62 + 2.5$

$= 9$ mm

The thickness of bottom plating (t_b) of rudders is not to be less than that of the side plating of rudders i.e t_b = 9 mm.
Where vertical and horizontal webs are fitted within the rudders, the thickness (t_w) is not to be less than 0.7 times that of side plating of rudders but in no case to be less than 8 mm.
t_w = 9*0.7 = 6.3mm should be taken as 8mm
The thickness of nose plating (t_n) of rudders is not to be less than 1.2 times that of side plating of rudders, but need not be greater than 22 mm.
t_n = 1.2*9 = 11 mm
Internal surfaces of double plate rudders are to be efficiently coated with anticorrosive coating; and holes fitted with plugs made of non-corrodible metals are to be provided both on the top and bottom parts of the rudder for draining.

IV. VALUE ANALYSIS PROCESS OF DESIGN REVIEW:

Value analysis (VA) process of design review has provided major business returns. The key to realizing these returns is knowledge, of the customer requirements, the costs of the product, an in-depth knowledge of manufacturing process and the costs associated with failures due to poor or inadequate product design. All these inputs to the VA process are vital if decisions regarding product and process redesign are to yield lower costs and enhanced customer value.
Systematic review that is applied to existing product designs (rudder design) in order to compare the function of the product required by a customer to meet their requirements at the lowest cost consistent with the specified performance and reliability needed [7].

V. CONCLUSIONS:

This paper provides rudder design for Nigat Boat. The approach can be used as a generalized method of designing rudder in the empirical way.The design process includes customer requirement, conceptual design, initial design, detail design and the value analysis. In all the steps we have to check against to the set criteria and use feedback in order to optimize every step of the design process.The selected rudder arrangement for Nigat boat was full spade rudder blade arrangement, which is possible to manufacture with the existing facility of the workshop. The profile of the rudder is NACA 0012 which avoids stall and separation under all operating conditions. Hence it is possible to have a better control over the boat to helms man and course stability.

VI. RECOMMENDATION:

The welding of the plates and connection with the rudder shaft should be analyzed critically to withstand the given torque/ working condition. Modeling and simulation of the rudder using commercially available Finite element software will also important to see different parameters how it influence the controllability of the rudder.

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Table 3: N.A.C.A. 0012 (upper half portion coordinate to form the profile of the symmetrical blade profile)

S/N	X Coordinate	Y Coordinate	S/N	X Coordinate	Y Coordinate	S/N	X Coordinate	Y Coordinate
1	1.00000	0.00126	19	0.38566	0.05853	37	0.11544	0.04924
2	0.94801	0.00833	20	0.36489	0.05914	38	0.10515	0.04767
3	0.89900	0.01460	21	0.34501	0.05958	39	0.09521	0.04600
4	0.85274	0.02020	22	0.32596	0.05987	40	0.08561	0.04421
5	0.80903	0.02523	23	0.30771	0.06000	41	0.07633	0.04229
6	0.76769	0.02974	24	0.29020	0.06000	42	0.06735	0.04023
7	0.72855	0.03381	25	0.27340	0.05985	43	0.05866	0.03802
8	0.69146	0.03747	26	0.25728	0.05958	44	0.05026	0.03562
9	0.65627	0.04076	27	0.24178	0.05919	45	0.04212	0.03301
10	0.62287	0.04371	28	0.22689	0.05867	46	0.03424	0.03013
11	0.59112	0.04636	29	0.21257	0.05804	47	0.02660	0.02690
12	0.56094	0.04871	30	0.19879	0.05730	48	0.01920	0.02316
13	0.53220	0.05080	31	0.18552	0.05646	49	0.01203	0.01860
14	0.50483	0.05263	32	0.17275	0.05551	50	0.00508	0.01231
15	0.47874	0.05423	33	0.16044	0.05446	51	0.00168	0.00717
16	0.45384	0.05561	34	0.14858	0.05331	52	0.00000	0.00000
17	0.43007	0.05678	35	0.13713	0.05205			
18	0.40737	0.05775	36	0.12610	0.05070			

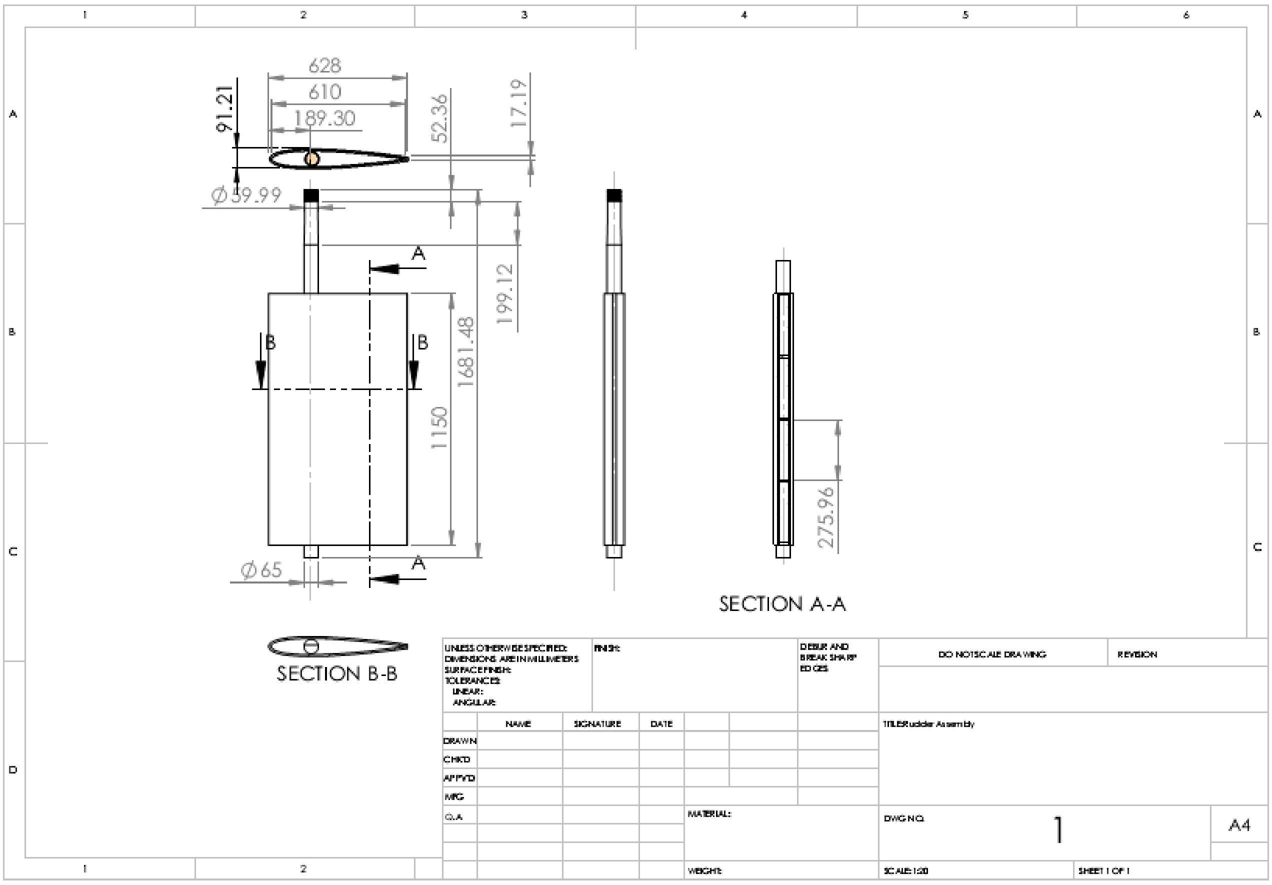

Fig. 7 Assembly Drawing of the Redesigned Rudder for Nigat Boat