A Numerical Study on Effect of Change in Longitudinal Center of Gravity on Planing Capability of a Coastal Patrol Craft: A Case Study, Sri Lanka Navy

DS Bogahawatte[1#], PMKC Chandimal[1] and LAKR Athukorala[2]

[1] Department of Mechanical Engineering, Faculty of Engineering, General Sir John Kotelawala Defence University, Sri Lanka
[2]Directorate of Naval Design, Sri Lanka Navy, Sri Lanka

#ds-bogahawatte@kdu.ac.lk

Abstract: *The pressure acts on the wetted surface area of the vessel always maintains the equilibrium with the weight of the vessel. The acting pressure comprises with two elements as hydrostatic, relates to buoyancy and hydrodynamic, relates to speed of the vessel. The authors involved in planned novel design of this monohull Coastal Patrol Craft with unknown capabilities of the dynamic behaviour with planing at initial stage. The research objectives were to, estimate the total weight, compare resistance for different LCG positions, and the dynamic wetted area comparison for different LCG positions, Effective power demand comparison for different LCG positions, dynamic trim comparison for different LCG positions, and planing capabilities for different LCG positions. Five different LCG positions were considered during the study to realize the craft's behaviour. According to the numerical approach, craft's behaviours explored with the change in LCG positions and anticipated effect on the resistance, effective power demand, dynamic trim, and planing capabilities. Based on the results, a small initial trim angle is required for the CPC to display optimal performance at speeds in the upper range of the planing regime. On the other hand, an initial trim by aft would increase the performance of the CPC at speeds lower than the planing region but would adversely affect the performance at higher speeds as the trim further increases due to dynamic behaviour. Further, this increase in trim at higher speeds would result in dynamic instability and be detrimental to the performance of the craft.*

Keywords: *Longitudinal Center of Gravity, Planing, Hydrodynamic Forces*

1. Introduction

The weight of a vessel is always balanced by the pressure acting on the wetted keel length developed by the vessel. This pressure is composed of two components: hydrostatic, related to the buoyancy, and hydrodynamic, related to the speed of the vessel. Many scholars classify the vessels according to the kind of pressure field acts during their steady motion:

i. Displacement vessels: if hydrostatic pressure is much higher than hydrodynamic pressure (Froude number of less than 0.4).

ii. Semi-displacement/semi-planing vessels: if hydrostatic and hydrodynamic pressure have the same order of magnitude (Froude number from 0.4-1.2)

iii. Planing vessels, if hydrostatic pressure is much lower than hydrodynamic pressure (Froude number beyond 1.2).

planing hull is a hull where its displacement is raised in the direction of the water surface mostly by hydrodynamic forces upon enough propulsive power and boat speed is maintained. Thus, hydrodynamic forces are more significant than hydrostatic components. In this scenario, the entire body of the hull performs like a lifting surface and generates the lift force against its weight as the boat speed increases. Upon the boat achieves the planing capability its bare hull resistance declines with the benefit of the reduced draft. Significant research on the hulls which bound to be planed was made by Baker and Millar (1912). Authors further studied the previous works by Sottorf (1932), Shoemaker (1934), Sambraus (1938), Sedov (1947), and Locke (1948) of constant deadrise prismatic planing planes hydrodynamic characteristics which operate with fixed trim, fixed mean wetted length, and constant speed of operation. The seminal studies on the planing hulls were made by Savitsky (1964). In this study, the authors embark on a comprehensive analysis of the hydrodynamic features of the Coastal Patrol Craft (CPC) with a proposed planing hull. The empirical formulae proposed by Savitsky were employed in this conceptual design with a proposed planing hull.

At present, the attractiveness of planing hulls in the applied research area has been developed with the help of developments in Computer Fluid Dynamics (CFD) and computational infrastructure. Authors examined the work of Su et. al.(2012) on hydrodynamic performance of the planing hulls with the employment of CFD software as a numerical approach. One step further, the work of Yu-Min et. al. (2014) hydrodynamic performance of a planing multihulls has been explored with the commercial CFD software.

The basic concept of planing could be depicted in Figure 1 below, which indicates the Pressure and Velocity distribution beneath a planing flat plate in a self-explanatory manner. The hydrodynamic pressure at stagnation point is very high, since all kinematic energy is converted into pressure.

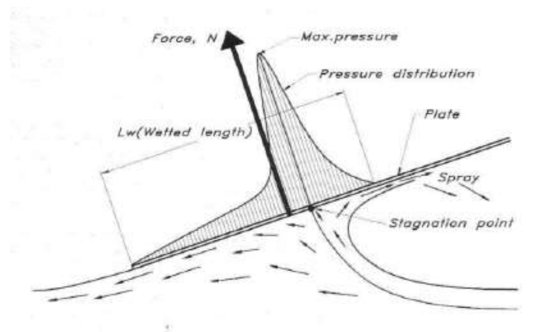

Figure 1. Pressure and velocity distribution beneath a planing flat plate

Source: (Larsson & Eliasson, 2000)

Figure 2 describes the Bow down moments (Pressure force, Appendage resistance, Frictional resistance), and Bow up moments (Thrust force). Accordingly hull automatically attain a trim angle cancelling all moments (i.e. net moment becomes zero). If a net moment to trim by bow occurs the trim will become smaller and the pressure force N moves forward until balance is achieved. If a bow down trim is applied, when craft at optimum trim angle, new trim becomes smaller, due to that hydrodynamic pressure is reduced. However, wetted surface is increased and the lift may be large enough. If it's not hull will sink down until hydrostatic pressure makes up for the loss.

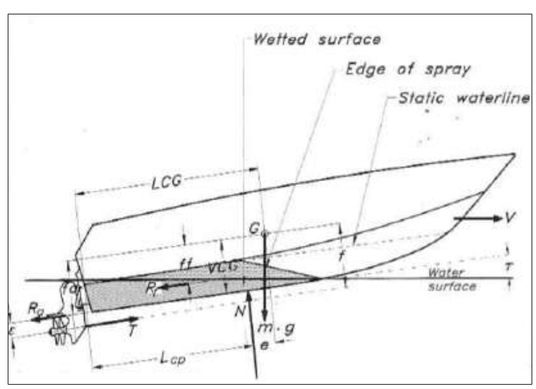

Figure 2. Forces on a planing hull

Source: (Larsson & Eliasson, 2000)

N: The pressure force (hydrodynamic and hydrostatic)

R_f: The friction force

T: Thrust Force

R_a: Resistance of the propeller drive (a denotes appendage)

G: Weight centre of gravity

ff: Lever arm for friction force

fa: Lever arm for appendage resistance force

e: Lever arm for pressure force

f: Lever arm for thrust

The Planing hulls could employ in numerous applications in marine transport including patrol boats, sea taxis, passenger carriers, and pilot boats. A major impact on Planing hulls could be observed in the racing boat industry.

Naval Architecture shall understand the 'Porpoising' phenomenon as a continued, tiresome motion, which leads a boat's bow to jump up and down from water, even at still waters. Negative affect are un-comfortability for fares, and loss of boat control, and even destruction to the construction of boat.

The Naval Architecture shall understand design criteria and promote the ability of boat planing as design input. The principal factors were found to be Displacement and Longitudinal position of Buoyancy and Gravity. The geometrical parameter named Longitudinal Center of Buoyancy (LCB) shall not change during the manufacturing stage if it was manufactured as per the blueprint. Yet the Longitudinal Center of Gravity (LCG) may perhaps be uncertain leading to general arrangement changes, material options, or supplementary burdens from the ship owner.

Due to the machinery selections at later stages and by naval architectural design changes in the boat could lead to an undesired loading state which might have an adversarial consequence on the boat's hydrodynamic performance. An unexpected initial trim (trim by forward) at the loading condition may prevent the boat from achieving its planing speed. Savitsky (1964) studies leading to LCG behaviours and subsequent development of formulas by him discuss, even if the initial trim could be brought to the desired status with extra ballast weight, this might deteriorate the hydrodynamic performance of the boat, as it leads to an increase in boats wetted surface area, thereby the increment in total hull resistance. Consequently, many authors discuss the phenomenon and came to lime light as many planing hulls remain agonized from the absence of planing capability for this simple reason.

The authors engaged in this novel design and, the dynamic behaviour with planing capabilities of the proposed craft was unknown at initial stages. Thus, it comprehends the research problem. More specifically authors extensively studied the proposed LCG positions for the designed Coastal Patrol Craft for Sri Lanka Navy as a planing hull. The objectives were to (a) estimate the total weight of the craft, (b) comparison resistance for different LCG positions, (c) the dynamic wetted area comparison for different LCG positions, (d) Effective power demand comparison for different LCG positions, (e) The dynamic trim comparison for different LCG positions, and (f) Planing capabilities for different LCG positions. Thereby this study included five different LCG positions (5.4 m, 5.6 m, 5.8 m at fore, 5.98 m at neutral, and 6.15 m at astern) to fully comprehend the study. This paper discusses the results of those tests (numerical approach) with their comparative influence on the change in the LCG position of the CPC.

2. Methodology and Experimental Design

The authors obtained the customer requirements from Director General Operation.

Then principal project proposal was submitted to the Ministry of Defence and National Planning Authority. Upon receipt of approval, the detailed design process of CPC (to be manufactured with Fibre Reinforced Plastic) was commenced. As per the SLN requirement, discarded steel hull of 'French Dvora' was used as the plug to develop these CPC moulds (Hull, Deck, and superstructure). Further, mould(s) were improved to cater habitability, transom for de-moulding requirements, decks to incorporate hatchers, and a custom wheelhouse was designed.

During the study the change to the LCG was considered keeping in mind that a significant change in the LCG would affect the other factors in the Ship Design Spiral such as stability, structural strength, and General Arrangement. Thus, these graphs are to be developed early in the design stage to select the most optimum LCG.

Once the hull mould was completed, the principal dimensions were obtained from the mould, and a lines plan was developed. The body plan of the planing hull used in the study is depicted in Figure 3 below. Then used the Rhino3D software to complete the 3D hull of the CPC, which was a necessity to import CPC dimensions/features for other software for the stability studies, hull drag, powering and structural design.

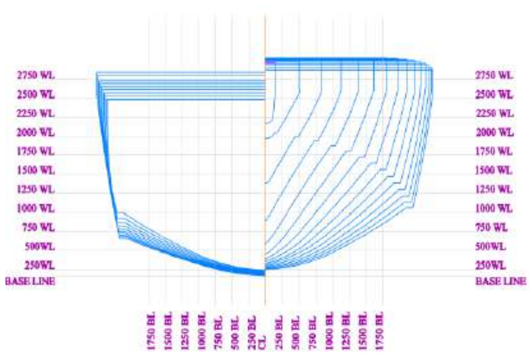

Figure 3. The body plan of the planing hull used in the study

The estimation of CPC weight and determining the principal features were the first step. In this endeavour, the concept of the Ship Work Breakdown Structure approach was employed. The basic equation for weight estimation of individual components using the ratiocination method is depicted as follows. Textbook formulas were considered (Enclosure 1) for different components to find corresponding coefficients. The principal coefficient estimations based on benchmarked parent hull is depicted at Table 1 below.

$$\text{New ship component weight} = \text{Parent hull component weight} * \frac{\text{New ship dimension}}{\text{Parent ship dimension}}$$

Table 1: Ratiocination values comparison

Description	CPC Ratiocination Values	Parent Boat Ratiocination Values
L (m)	15.76	13.50
B (m)	4.38	3.00
D (m)	2.79	1.40
Displacement (T)	27.50	10.40
SHP	2400.00	838.00
V (knots)	35.00	35.00
Cp	0.60	0.55
T (H) (m)	0.80	0.68
KW	21.50	5.7
LD	44.02	18.90

LB	69.03	40.50
L*(B+2D)	157.06	78.30
L*D*(2D+B)^2	4371.89	635.80
LBD^2*Cp	323.09	43.66
LD^2	122.94	26.46
L(B+D)	113.05	59.40
2*(D-H)*L	62.82	19.44
LBD/100	1.93	0.57
Crew	12.00	12.00

The weight, LCG, and Vertical Center of Gravity (VCG) derived from above approach and with data obtained from AutoCad and Rhino3D software were used as input data for Savitsky Programme to determine Hull Drag, Trim Angles, Effective Horse Power (EHP), etc. The basic inputs for the Savitsky Programme is depicted at Table 2 as follows.

Table 2: Input data for Savitsky programme

Length of Waterline	L_{WL}	15.767	m
Beam	B	4.380	m
VCG	VCG	1.469	m
Displacement	□	27,000	kg
Deadrise @ Transom	□□$_{T}$	12.000	degree
Deadrise @ Amidships	□□$_{)0(}$	21.000	degree
Distance to Amidships	L□$_{)0(}$	7.884	m
	□	2.724	degree
Angle of Thrust Line	□	5.000	degree
	f	0.305	m
Minimum Speed	V_{min}	7.000	knots
Maximum Speed	V_{max}	45.000	knots
Length Overall	LOA	19.059	m
Maximum Beam	B_{max}	5.000	m
Moulded Depth of Hull	□	2.850	m
Number of Propellers	N	2	

3. Results and Discussions

VCG, Transverse Center of Gravity (TCG), and LCG for each component weights were obtained from the General Arrangement plan and AutoCad drawings. The report was generated for three conditions (full load, arrival load, and lightship condition). The outcome was to finalize the CPC total weight, VCG, LCG, and TCG. The result for full load condition is depicted at Table 3 below. The position of the origin for the longitudinal moments is Transom.

Table 3: Total weight estimation

Weight Group	**Weight (T)**	**VCG (m)**	**Moment (m-T)**	**LCG (m)**	**Moment (m-T)**
Hull Weight	8.6	1.7	14.6	7.7	65.9
Engine Room	6.7	0.7	4.5	2.4	16.2
Aux Machinery Room	2.3	0.8	1.8	5.8	13.3
Berthing Areas	0.3	1.1	0.3	10.0	2.8

Wheel House and Galley	0.8	3.2	2.5	8.7	6.7
Flying Bridge	0.3	5.6	1.5	5.9	1.6
Deck	0.7	3.0	2.0	10.0	6.7
Full Load components	6.5	1.1	7.2	6.4	42.0
Sum	26.1		34.4		155.3
Full Load Weight	27.04	VCG (m)	1.47	LCG (m)	5.98

Note: According to SNAME margins for naval vessels or special ships following criterions were used.

i. Weight Margin - 5% added to the lightship weight

ii. VCG Margin - 0.5 ft added

Thereafter worked out a few LCG values (+) and (-) around the initial neutral value of LCG to understand the sensitivity of LCG for bare hull total resistance and other parameters. The results are depicted at Figure 4 below. It was evident with increase LCG additional drag in the form of hump is decrease at low boat speed (20 knots), yet adverse effect beyond 40 knots. Since CPC designed operate with 35 knots, minimum resistance below the planing regime was observed with LCG on or beyond neutral LCG.

Authors studied the steady dynamic wetted keel length comparison for different LCG positions and results are depicted at Figure 5. The power demands for the resultant LCG positions were compared as per the method described in ITTC Quality Manual 7.5-02. -05-01 and results are depicted in Figure 6. According to this association, the LCG on or near the initial neutral position seems to be the optimum case, an CPC hull needs to operate sub planing speeds as well as the beyond the planing speeds with minimum EHP.

Finally, the dynamic trim comparison for different LCG positions is depicted at Figure 7 below. It was evident, at neutral LCG or beyond it CPC display low trim angles and around 20 knots CPC depicts planing features for all LCG values.

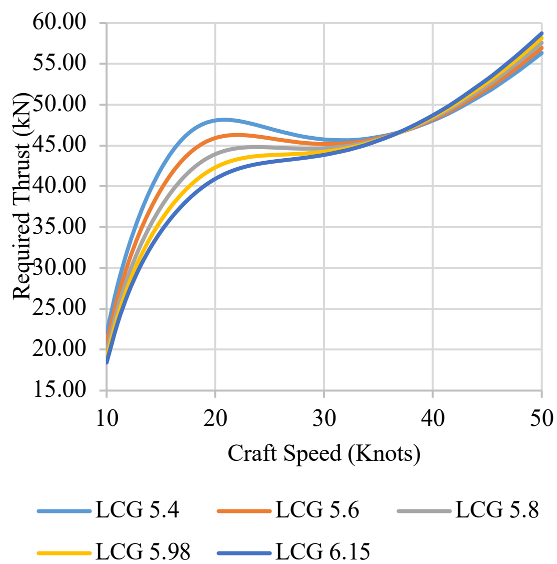

Figure 4. Change in Total Resistance with LCG Positions

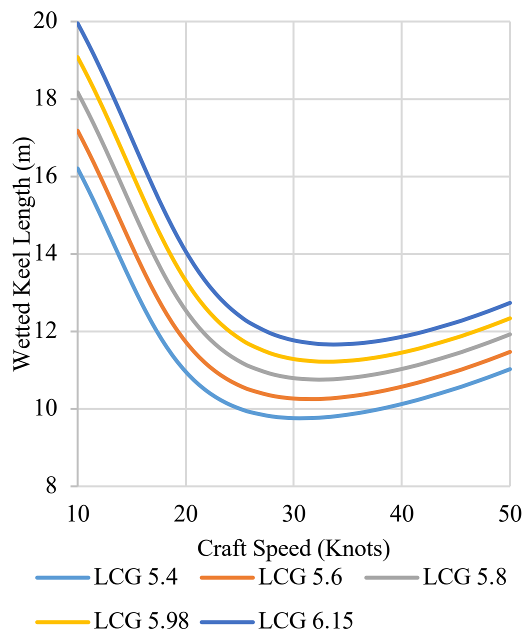

Figure 5. Dynamic wetted keel length comparison for different LCG positions

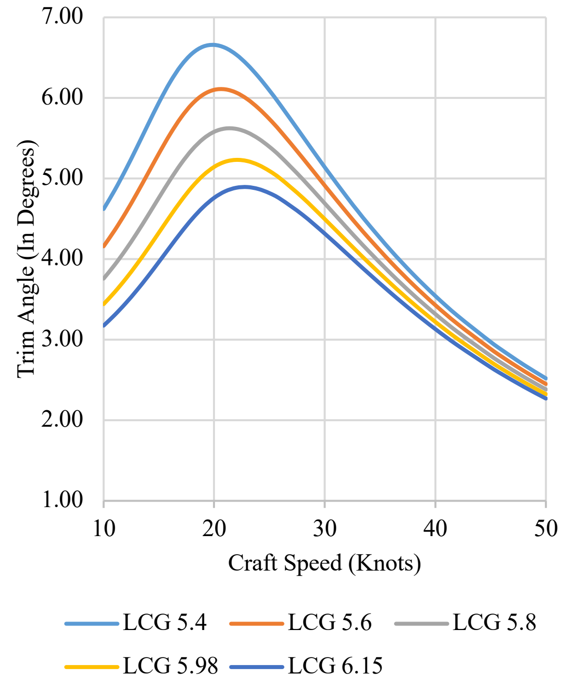

Figure 7. Change in dynamic trim angle with LCG

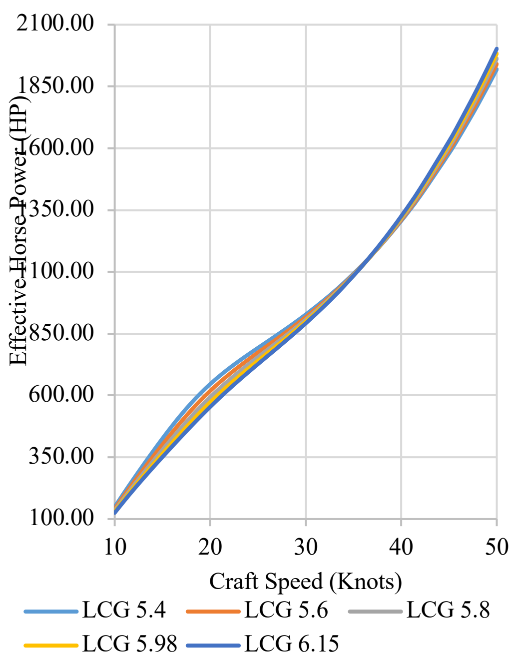

Figure 6: Effective Power Demand Comparison for Different LCG Positions

Authors then studied the Planing capabilities for different LCG positions with the spreadsheet written by Dingo Tweedie, October 2004. The various results are tabulated at Enclosure 2 to this article. It specifies the CPC speed which start Planing the craft. With increase of LCG from transom the speed required to plan the craft increases.

The NavCad commercial software with its database was used to validate the above outputs.

4. **Conclusion**

Authors explored the behaviour of monohull Coastal Patrol Craft with the change in craft LCG positions and anticipated effect on the resistance, effective power demand, dynamic trim and planing capabilities based on numerical approach. Authors worked out a few LCG values (+) and (-) around the initial neutral value of LCG to understand the sensitivity of LCG. Based on the results, a small initial trim angle is required for the CPC to display optimal performance at speeds in the upper range of the planing regime. On the other hand, an initial trim by aft would increase the performance of the CPC at speeds lower than the planing region but would adversely affect the performance at higher speeds as the trim further increases due to dynamic behaviour. Further, this increase in trim at higher speeds would result in dynamic instability and be detrimental to the performance of the craft. With the increase of LCG from transom the speed required to planing the craft increases. When LCG increases, to plan the craft, trim angles become large with higher speeds and cause dynamic instability a phenomenon called 'Porpoising'.

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Author Biographies

Captain, Dinuk Sakoon Bogahawatte, Charted Marine Engineer, perform as Head of Department at KDU. Last six year shouldered the responsibility of Manager Naval Boat Building Yard, Sri Lanka Navy. Graduated with BSc Eng (Hons) in Marine Engineering from KDU. Possess MBA from University of Moratuwa and Masters in Manufacturing Management from University of Colombo. Expert for Fast Attack Craft & Fast Missile Vessels fleet repairs.

Lieutenant Commander, PMKC Chandimal has graduated with BSc Eng (Hons) in Marine Engineering from KDU and also the Chartered Marine Engineer, perform as Lecturer (Probationary) at Department of Mechanical Engineering, KDU.

Lieutenant Commander, LAKR Athukorala has graduated from the United States Coast Guard Academy with a BSc. Eng (Honours) in Naval Architecture and Marine Engineering. Currently serves in the capacity of Staff Engineer Officer (Naval Architecture) at the Directorate of Naval Design, Sri Lanka Navy. Further, Visiting Lecturer on Marine Vehicle Design at the KDU since year 2020.