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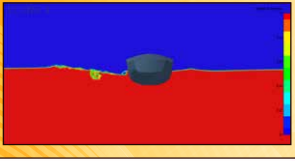

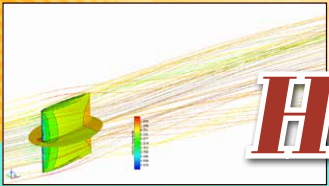

Assessing Ship Heeling Moments

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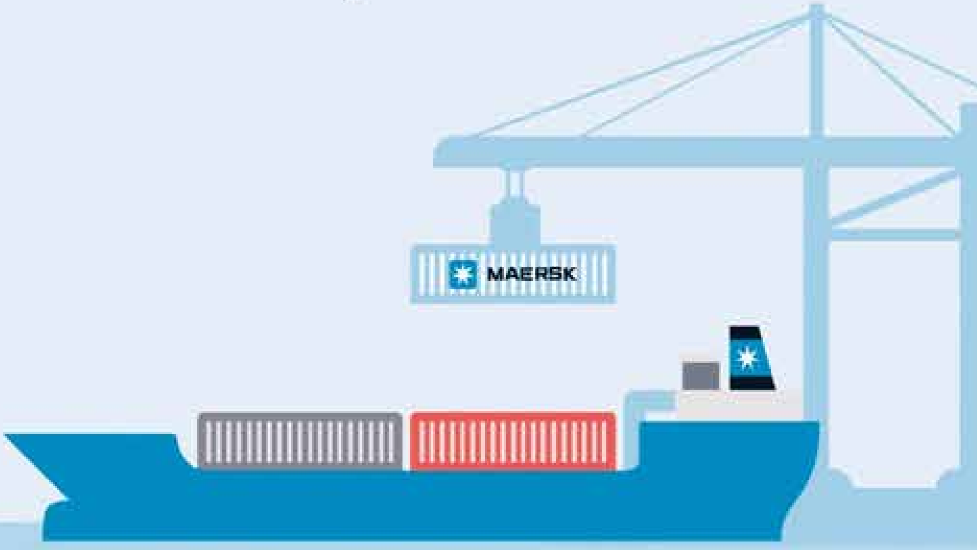
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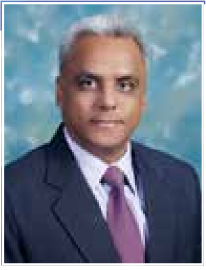
EDITORIAL



There is no unhappiness like the misery of sighting land
again after a cheerful, careless voyage.
– Mark Twain

The Shipbuilding conversation continues. The second edition of the Shipbuilding cluster hosted by Indian Maritime University (IMU) with the Andhra Pradesh Maritime Board saw the minor yards and representatives from the AP Government amongst other industry personnel. While there were echoes of woes from the first edition, there was convergence on a few actions. Cash flow problems, supply chain issues and rigid ways of doing business featured again. However, a few realisable ideas were also floated: creation of a repository of ships and other crafts designs; standardisation (further than those available now) of inland vessel designs (objective: safe craft designs), establishing conduit/corridors with ancillary suppliers (try to fit into the hub around the port model; industrial parks hosting maritime industries); repair facility availability (if possible inside the ports; allocation of repair berths… workable?). There were discussions on how shipbuilding sector was backed and fostered in the South Korean landscape since 1960s, the Japanese approach of not letting any tonnage to go unbuilt away from the country etc. There were open discussions on award of contracts by nominations, quality control issues, dependence on defence orders and its monopsonic character, failed yards, container shortages etc. It was a re-revelation that containers built in India face serious quality issues under Classification checks. The AP Industry representative was convinced that the sector has issues affecting AP also and assured that there will be succour.

India's miniscule shipping tonnage has aging vessels between 15-20 years (global average: about 15). Apparently, over half of this present fleet needs replacement and this itself provides a reason to go for commercial shipbuilding. And if the 30+ yards in India can address this need, we will have our hands (read: yards) full for the next 10-15 years (leave alone building ships for other countries).

With defence builds becoming a regular feeder, ship repairs of the Indian built vessels will happen in the country's shores. The capacity for repairing merchant vessels (ours and others') can be built around this vertical. Reports working on these conservative estimates indicate a potential of 60-75 million CGT (Compensated Gross Tonnage) for commercial and defence builds. Furthermore, shipbuilding, being one of the highest multipliers, will create more jobs and hence mitigate the malady of unemployment. Sounds exciting and doable also.

From the two cluster meetings, the feeling was that the sector is being looked into and listened to also. If not a euphoria, there is hope that commercial/cargo ship building will look up in the coming years. The need to elevate the takeaways of such forums to the policy makers was also apparent and in that IMU and the industry, both have a responsibility. The vision under the 2030-2047 horizons should inspire on this count. Else, the misery of sighting land (and the yards, in this case even without sailing the seas) might just prevail.

* * *

In this issue…

The first article is on ship's heeling moments. A naval architecture study looking at the vessel's stability when rudder is moved to hard over positions is presented by Dauson Nyonyi et al. The study concludes that multiple factors such as vessel design, hull form, trim, operational draft, cargo loading conditions would influence a vessel's overall stability, especially during these hard manoeuvres. Vessels carrying livestock and similar shifting cargoes would need such considerations. This is an easy read for a practicing marine engineer with interest in naval architecture.

* * *

And we follow this with the Part B of the Deep Dive discussions continuing from last issue. Herein Dr. Veda focusses exclusively on the developments in deep-ocean human-occupied scientific submersibles. It is to be appreciated that these submersibles have facilitated humans to explore the ocean depths safely and effectively. The article traces the development of the submersibles and their relative merits as time progressed. The history of the HOV (Human Occupied Vehicles) makes an interesting reading. The other absorbing part is on design factors and development of these hadal machines. The design factors, communication systems and the umbilical arrangements between the submersible and the mother vessel make the rest of this educative write-up.

* * *

We move on to a material article. Jyotsna Kalpana et al., discuss hybrid composites. Fibres are longer when compared to their cross-sectional dimensions and synthetic and natural fibres have been employed in many applications. Hybridised combinations fare better. The study looks at the thermal behaviour etc., of jutton and glass fibres the fillers being boron carbide and graphene. The description of the composite preparation and other requirements make it educative. The results prove that such applications can be beneficial to marine applications also.

* * *

Technical Notes carry easy-to-understand noting on the mathematical construct of PID algorithm by Ankush Sharma. Under Heritage Hourglass, Soumya Pai presents a historical essay on Larin, a form of currency, which was prevalent during the 16th-17th Centuries.

MER Archives has a few interesting features, as always and one Transaction on marine residual fuels. This has knowledge merit for those preparing for the examinations and otherwise also.

* * *

And we wish to share that we are working on two thematic issues one on the AI & ML and another related to the poles. We invite your thoughts and articles on these.

Meanwhile here is the November issue with the Season's Greetings.

Dr Rajoo Balaji
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Assessments of Ship Hull Heeling Moments Caused by Rudder Turning Manoeuvres

Dauson Nyonyi, V.V.S. Prasad, Giri Rajasenkar

Abstract

The rudder is an integral component of the steering mechanism on the ship which is designed to alter the course of the vessel and it affects the stability of the ship especially at sharp manoeuvres. This study investigates the effects of the forces induced by rudder on ship heeling, focusing on how rudder angles and ship speeds contribute to heeling moment, mainly in passenger and livestock vessels. Using Maxsurf and OriginLab software, under controlled conditions, simulations were performed to analyse stability of the vessel. Based on the results, a non-linear relationship between rudder forces and heeling angles was found, with maximum stability up to a 73.6° heeling angle. Beyond this angle, the risk of capsizing is higher, especially in vessels which have sensitive cargo configurations.

The study indicates that during manoeuvring an effective changing of rudder angles and speed is important. It also highlights the need for improvement in design considerations of shipbuilding which helps in prevention of instability. These findings are crucial for ship operators and designers, offering practical recommendations for mitigating risks in maritime operations. Further research is suggested to explore the impact of environmental factors such as wind and wave forces on ship stability.

Key words Lift force, Drag force, Transverse force, Heel Angle and Angle of attack

1. Introduction

One of the important part of the steering system of a ship is Rudder. It is useful in changing the direction of a vessel during navigation. Traditionally, its role is to maintain or change the heading of a ship. During some operational scenarios involving sharp or high-speed turns, rudder movements compromise the ship's stability by inducing a significant heeling. This even leads to capsizing under extreme conditions. This phenomenon is very much relevant for vessels which have sensitive cargo configurations, like passenger and livestock carriers, where even small shifts in balance can have critical consequences [5].

For naval architects and marine engineers, interactions between rudder angles, ship speed and heeling moments is a key area of interest. Understanding these interactions is very important for ensuring the safe operation of vessels in varying sea conditions. Especially in an industry where maritime accidents such as capsizing can result in significant loss of life and property. Balancing effective manoeuvring and maintain the stability of the ship during turns induced by rudder is one the biggest challenges.

Due to rapid advancements in simulation technology, better models and ship behaviour analyses under different conditions are being done by researchers. Tools like Maxsurf and OriginLab are used by researchers to simulate the forces acting on a ship's hull during rudder manoeuvres. This provides insights into the relationship between rudder angles, vessel speed, and the resulting heeling moments [3]. This capability is very important in identifying operating parameters which are safe and in improvement of design considerations to enhance the ship's stability [17].

This study focuses on examination of effects due to forces induced by rudder on ship hull heeling, particularly under controlled conditions that exclude external environmental factors like as wind and waves [6]. This research explores the non-linear relationship between rudder forces and heeling moments [2]. And it also focuses on the increase in significant risk of capsizing when heeling angle increased beyond a critical value [2]. By doing this, **it provides practical recommendations for ship operators and designers to mitigate the risks associated with sharp turns and improper cargo management,** especially in vessels that are more susceptible to instability [1, 9].

> **During some operational scenarios involving sharp or high-speed turns, rudder movements compromise the ship's stability by inducing a significant heeling**

This research is expected to the contribution of safer design practices and operational strategies in the shipping industry due the criticality of stability in maritime operation [4]. Additionally, It highlights the requirement for future research in exploration of influence of factors like environmental conditions on heeling moment and overall stability of the ship during rudder manoeuvres [7, 19].

2. LITERATURE

2.1 Hull Turning forces

The forces produced by the rudder are one of the essential parts of a vessel's ability to turn in water and, without a doubt, play a significant role in vessel turns. Activation of the rudder generates side forces that create turning or deviation away from a straight direction. While such turning forces are vital for navigation, they can cause heeling (the tilting of the vessel) of the vessel. The forces are dynamic and depend upon the rudder's angle, the ship's speed, and the distribution of the weight aboard the vessel.

Research has suggested that at the beginning of the turn, the rudder forces act below the ship's centre of gravity, which in turn causes the vessel inboard heel. An inboard heel lasts only for a short period because the action forces of the moving vessel make it exert outboard centrifugal force which causes the ship to heel inboard [5]. Some of the many determining factors which may include the speed of the ship, the angle of the rudder, radius of the turn mainly dictate these quantities [1, 19]. The heeling moment increases with these factors therefore posing a threat to the equilibrium of the vessel if not well balanced. **The angle between the rudder and hull determines the development of the turning force.**

The lift and drag forces are crucial in the hydrodynamics developed while water flows along the hull and rudder faces. These forces have significant impacts on the manoeuvring as well as the stability of the vessel. A greater rudder angle builds higher lateral forces that enhance the heeling moment [2]. However, these may also cause significant heeling when the vessel is sailing at a high speed or if there is an uneven distribution of the load—even more so in vulnerable kinds of vessels, like carrying passengers or livestock [6].

Most of the preceding research was focused on geometric properties of rudder design and the interaction with the hull during turning manoeuvres [9]. These studies showed nonlinear effects of changes in rudder angle and velocity on the turning moment experienced by the ship. With increasing rudder angle, the force applied

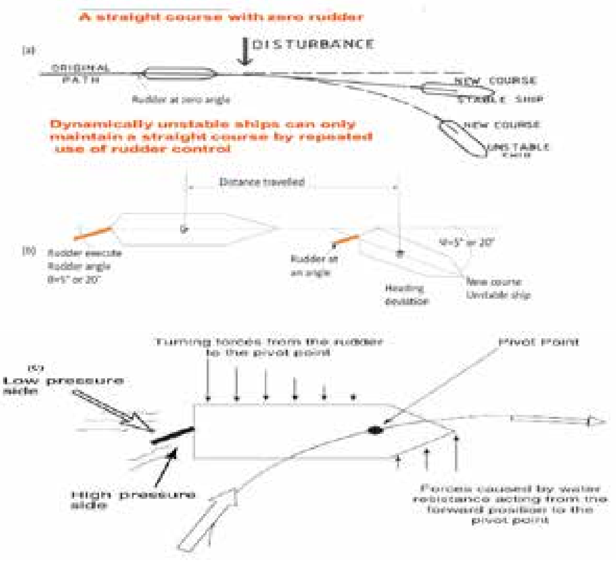

Figure 1 (a-c) Deviation of Vessel from its straight course

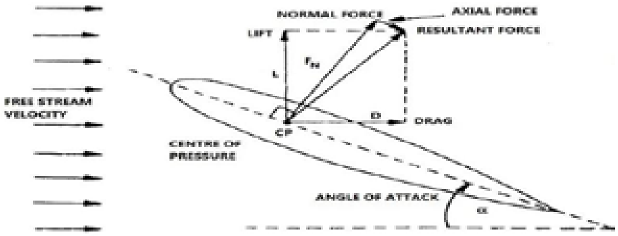

Figure 2 Force component on the Rudder

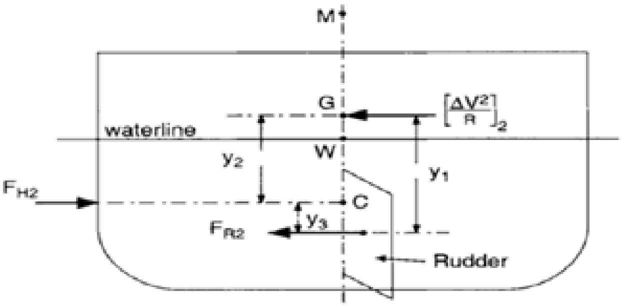

Figure 3. Hull heel due to rudder-induced forces.

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to the hull tends to be much larger and stability tends to reduce slightly if uncompensated [3, 17].

Results clearly indicate the need for prudent assessment of rudder forces in the ship design and its operations, especially in the case of those vessels more prone to instability. A deeper appreciation of the interaction between forces at work on the rudder and those on the hull would more effectively help naval architects and engineers develop better strategies aimed at maintaining hull stability in sharp turns and quick evolution.

The paper further emphasizes the need to incorporate forces on the rudder as one of the fundamental elements of ship design and operational procedures, especially for ships prone to instability with greater variability. Increased insight of the relationship between the rudder forces and hull configuration will allow naval engineers and architects to conceive of more effective ways towards the achievement of stability in sudden turns and high-velocity manoeuvres.

2.2 Build-up of forces on Rudder surface due to water streamlines

The uniform water flow from propeller thrust, characterized by a velocity V**,** is directed towards the rudder section at a certain angle of attack α **[4,17].** Because of this, hydrodynamic forces like the normal force (F_D) and the perpendicular lift force (F_L) acting against the flow direction show up on the rudder, as shown in **figure 2.** Equation (1-2) represents the hydrodynamic force and its associated components.

Figure 4 Capsize of MV. Nyerere boat at Lake Victoria (Tanzania)

Drag force $(F_D) = F\cos\alpha,$ but $F = KAV^2$, and $k = 580$, (1)

$F_D = 580AV^2\cos\alpha$, $A =$ Rudder Angle of attach and $V =$ velocity of the water

Drag Coefficient $(C_D) = \frac{F_D}{0.5A_r\rho V^2}$, $A_r =$ Rudder Area, $\rho =$ Water density, V = ship speed

Lift Forces $F_L = F\sin\alpha$, but $F = KAV^2$, and $k = 580$, (2)

$F_L = 580AV^2\sin\alpha$

When Taking consideration hull moments about ship centre of Buoyancy C, then for an angle of heel Φ, as the resulting of rudder moments and forces consider **figure 3.**

Hydrostatic moment = Centrifugal moment + Rudder force moment [4]

$$\{F_{H2} \times y_2\} = \{T_{CF} \times y_2\} + \{F_{R1} \times y_1\} \qquad (3)$$

Where, $F_R =$ Force developed from the rudder, $F_H =$ Transverse forces is the hydrostatic and $T_{CF} =$ Transverse centrifugal forces $= \left(\Delta\frac{V^2}{R}\right)$, $R =$ Estimated radius of Turns

$$T_{CF} = \{F_{h2} \times y_2\} - \{F_{R1} \times y_1\} \qquad (4)$$

From eqns. 3 and 4 it can be seen that the increase of rudder forces at speed of the vessel (velocity of thrust from the propeller) reduces the Transverse moment forces which lead the increase of the Transverse centrifugal forces which automatic detonate the ship hull to heel at an angle [6]. This proves that rudder can be utilized as a roll stabilizer by utilising the heeling moment it produces as a stabilizing moment in roll [4,9].

The manoeuvring performance has received little attention during the designing stage of a Merchant ship [5,10]. This has sometimes resulted in very poor

Description	Rudder area (Ar)	Max. Rudder Angle. (deg)	Number of Rudder Balanced	Lifting coeff. (C_L)	Drag coeff. (C_D)	Vessel speed (Vs)	Turning Radius (R)	Wake Fraction (w)
Unit	m^2	(θ°)	-	-	-	Knots	m	
Value	24.6	35	1	0.696	0.892	28	306	0.26

Table 1 Rudder particulars

Measurement	Displacement (t)	Draft Amid Ships (m)	WL Length (m)	Beam max on WL (m)	Wetted Area (m^2)	Block coeff. (Cb)	Max Sect. area coeff. (Cm)	Water-plane area coeff. (Cwp)	VCB (m)	KB (m)	BMt (m)	KMt (m)
Value	8031	6.537	102.13	17.6	2496.5	0.667	0.97	0.902	3.795	3.795	5.02	5.8

Table 2 Vessel Hydrostatic particulars

manoeuvring qualities and in some cases resulting in marine causalities (capsizing of MV. Nyerere [12], IMO MSC/Circ1053). Designs are relied upon while human ship handling abilities are also considered. This can be disturbed by human error [10,14] as **figure 4 (a-b)** shows.

3. METHODOLOGY

This study was conducted under controlled conditions in steady waters and external environmental factors like wind were excluded from consideration. **This study is focused on a general cargo vessel operating in open-sea, deep-water conditions, with the ship fully loaded, and cargo assumed to be properly secured to minimize variability in the stability analysis.** To examine the effects of rudder-induced forces on the ship's stability, the rudder angle was systematically varied between 0° and 35°, specifically towards the starboard side, adhering to the Colreg Part B Rule 14, which governs conduct during head-on situations at sea.

Research has suggested that at the beginning of the turn, the rudder forces act below the ship's centre of gravity, which in turn causes the vessel inboard heel

Throughout the study, the vessel's speed was maintained at a constant 20 knots to ensure consistency in the data and to isolate the influence of rudder angles on the ship's heeling and stability. By holding all other variables constant, this methodology allowed for an accurate assessment of the ship's response to rudder-induced forces and provided a controlled setting for analysing heeling moments at different rudder angles and under full load conditions.

3.1 Method

According to the specific characteristics of the vessel, ship's heeling angle was simulated systematically and analysed. To simulate real-world passenger positions, vessel was fully loaded with distributed weights across various positions. Before seas trials, ship's upright stability is assessed to make sure the baseline stability under static conditions. This provides a reference point for evaluation of effects of forces induced by the rudder during manoeuvres.

The detailed specifications of the vessel and its rudder were documented in **Tables 1 and 2.** The Key parameters like rudder area, maximum rudder angle, vessel speed, and turning radius are outlined in the tables. These data points formed the basis for the sea trial experiments. In these experiments, vessel underwent controlled manoeuvres. It involved sharp turns to both the port (left) and starboard (right) sides. The rudder command inputs were derived from the ship-specific data presented in **Table.1.** It made sure that the manoeuvres represent the typical operational conditions.

By utilizing the rudder parameters outlined in **Table 2,** the ship's heeling angle, moments, and forces were monitored and recorded during the experiment. These parameters provided critical insights into the vessel's behaviour during turning manoeuvres. It allowed for a detailed analysis of the forces that influence the stability of the ship. The results offer a comprehensive understanding of how rudder-induced forces impact heeling and overall vessel performance, particularly under sharp directional changes.

3.2 Simulation

The simulation was conducted in two phases to assess the stability of the ship and its hydrodynamic behaviour under different conditions

Phase 1 Upright Hydrostatic and Large-Angle Stability Simulation

In the first phase of the simulation, the upright hydrostatic stability of the ship is investigated under full loading conditions. This simulation is performed to assess the ship's stability when fully loaded. And to ensure that ship could maintain an upright position under static conditions. In addition, large-angle stability is also studied to determine how the vessel responds when subjected to extreme heeling angles. This provided insights into ship's maximum stability thresholds under heavy load.

Phase 2 Hydrodynamic Manoeuvrability Simulation

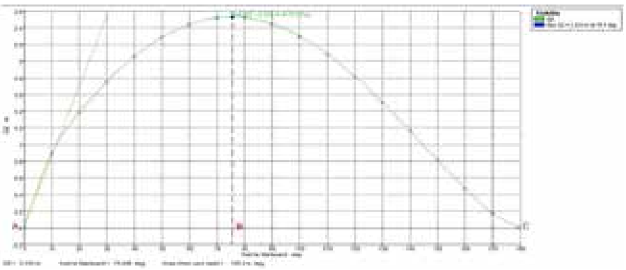


Figure 5 Stability Curve

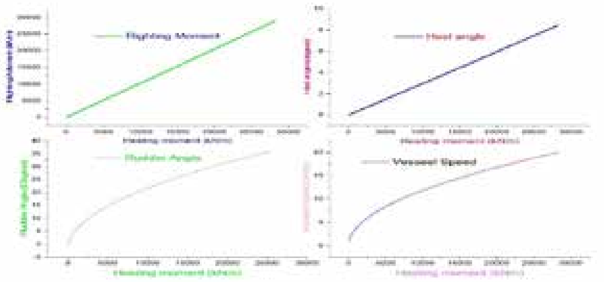


Figure 6. Heeling moment vs Heel angle and Rudder angle

The second phase of the study is to focus on the ship's hydrodynamic manoeuvrability. It is done by examining how changes in the rudder angle affected its behaviour at a constant vessel speed. The rudder angle was adjusted systematically, and the ship's response to these changes was closely monitored to capture the dynamics of turning and stability under real-world operational conditions.

During this phase, key parameters such as the ship's heeling angle, heeling moment, rudder forces, centrifugal forces, and centripetal forces were recorded. During sharp manoeuvring conditions, previous mentioned parameters are analysed. This helped in understanding their impact on the stability of the ship. Relationships between rudder angle, ship stability and the various forces acting on the vessel are plotted using data collected from simulation. These graphs provide insights into how forces reduced by rudder can influence the overall performance of the ship, mainly during turning manoeuvres at constant speed.

> **One of the main reasons for this course deviation of the ship is rudder drift angle, which is defined as the angle between the tangent to the ship's route and its centreline**

3.2.1 Hydrodynamic Vessel stability

The most direct method to track a ship's stability across a range of heel angles is to generate a curve that correlates the righting lever (GZ) to the angle of heel. During the study, the rudder successfully steered the ship by maintaining an angle of attack with respect to the water flow passing the hull, consistent with previous findings [13]. Ship's deviation from its main course, as illustrated in **Figure 1,** results in the development of a hull heeling angle. One of the main reasons for this course deviation of the ship is rudder drift angle, which is defined as the angle between the tangent to the ship's route and its centreline [7].

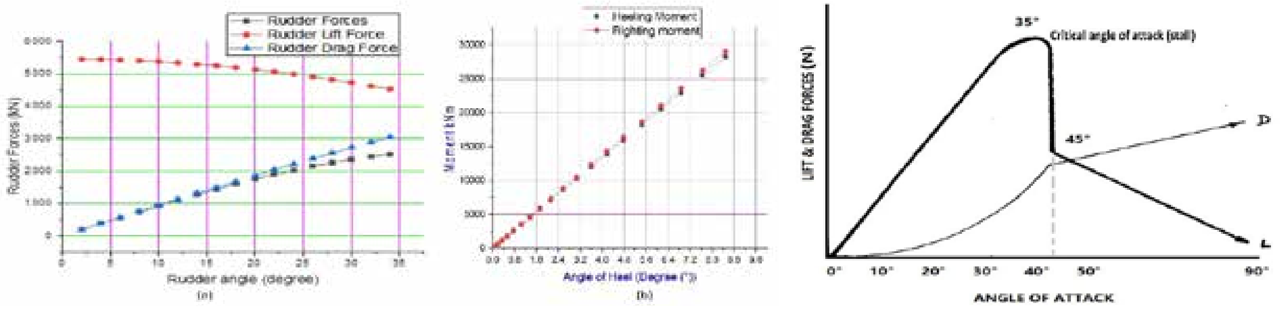
As shown in **Figure 5,** The static stability data which is collected is used to plot a graph which illustrates the relationship between the righting lever (GZ) and the angle of heel. When ship reaches its maximum heeling angle of 73.6. The maximum righting lever, GZ_{Max}, was recorded at 2.56 meters [16]. This GZ_{Max} value represents the largest static heeling moment required to return the ship to its upright position.

The maximum heeling moment which the ship can sustain without capsizing is calculated by multiplying the maximum righting lever GZ_{Max} by the ship's displacement weight (Δw). Beyond the maximum heeling angle of 73.6°, the righting lever (GZ) decreases significantly. This indicated a marked decline in the ship's ability to right itself. As shown in **Figure 5,** at the point where the GZ curve intersects the horizontal axis, the curve approaches vanishing stability at 180°. The range of stability for the vessel, from upright to the point of vanishing stability, spans from 0° to 180°. This supports the findings presented in **Figure 5.**

3.3 Ship heeling moment

When the vessel achieves its maximum speed and the rudder is turned to starboard side at its constantly increasing the angle of attack, the weight distribution is transferred from one side to the other. This shifting of weight is monitored to assess any potential changes in the initial metacentric height (GM) during the turn [11]. A known drawback of the rudder is its tendency to induce heeling moments during these manoeuvres, which affect the ship's overall stability [12]. **The vessel continues to diverge from its initial course until the rudder is returned to its neutral, centreline position, restoring the ship's heading. This deviation occurs due to the significant application of lateral force on the rudder.** This force is applied below the point where the ship rolls. This results in both rolling and yawing moment. These moments contribute to the overall heeling effect on the vessel. As shown in **Figure 6,** interactions between the hull's heeling moment, ship speed, righting moment, rudder angle, and hull heel angle are recorded and then plotted. The data reveals the complex relationship between these forces, illustrating how the rudder-induced forces influence the ship's stability during sharp turns.

3.4 Rudder Forces



(b)

Figure 7 (a-b) Rudder Forces

The basic reason for installation of a rudder on a ship is have assistance to keep the vessel on a straight course and for steering. It is useful in making controlled variations in direction of the vessel while maintaining the predetermined speed [18]. To achieve this, a lateral force is generated due to rudder for correction of any deviation from the intended path. Vessel's direction is changed by altering the streamline of water around the rudder. It is done by generation different forces drag forces, lift forces, and normal forces.

The maximum heeling moment which the ship can sustain without capsizing is calculated by multiplying the maximum righting lever GZ_{Max} by the ship's displacement weight (Δw).

As shown in **Figure 6 (a-b),** the magnitude of the lift and drag forces for a given rudder and ship speed varies with the change of angle of attack of the rudder. This study recorded several rudder forces. The results are plotted in Figure **7(a-b). Figure 7(a-b)** depicts the relationships between forces such as drag, lift, normal forces, and transverse forces.

Both lift and drag forces are increased when the rudder angle is increased. Their maximum is reached when rudder angle is at 38°. After 40°, the lift force starts to lower while the drag force continues to rise. This results in the stalling of the ship. To avoid this, rotation of the rudder is generally limited to 35° to maintain steering and prevent stalling conditions.

In **Figure 8,** the coefficients of rudder forces are illustrated. They are drag, lift, normal and transverse force coefficients. The lift coefficient is particularly sensitive to the ship's directional stability, which is affected by the rudder angle. The hull will slowly deviate from the initial path when the rudder is turned to port or starboard to change the course of the ship. As mentioned before, the corresponding force coefficients for varying rudder angles of attack are also depicted in **Figure 8.** These illustrations provides insight into how the effectiveness of rudder is changed with its angle and speed of the ship.

4.0 RESULTS AND DISCUSSION

The extensive studies on the ship's stability revealed that it remains stable up to a heel angle of 73.6°, with a maximum GZ value of 2.56 meters, **Figure 5.** It is also observed that both the righting moment and heeling moment are increased as the heeling angle increases, as shown in **Figure 6. But the relationship between rudder angle, vessel speed, and heeling moment is nonlinear.**

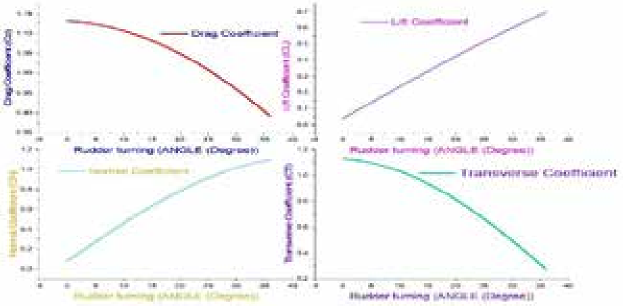


Figure 8 Rudder Force Coefficient

In **Figure 7,** following are observed:

1. The lift forces increase steadily with the rudder angle
2. The Lift forces reach their peak at a rudder angle of 38°
3. After Lift forces reach their peak, vessel experiences a 'stall' condition
4. And the lift force drops sharply

Simultaneously, when the rudder angle of attack increases a moderate increase in drag forces is seen. As shown in **Figure 8,** the lift force coefficient increases with the rudder angle, while the drag coefficient shows a corresponding decrease. Based on the findings, **it is evident that a vessel is less likely to lose stability only due to the heeling angle caused by the rudder unless there are other destabilizing factors present.**

Special caution is to be exercised for passenger and livestock carriers. Because, these vessels are particularly vulnerable to even small heeling angles. Even a relatively small heeling angle of about 5° can induce hydrodynamic instability and potentially leading to capsizing. This risk was similarly reported in the capsizing incidents of M/V Nyerere on Lake Victoria [12] and M/V Queen Hind (IMO 7920675) [10, 14], where improper load distribution and external factors contributed to catastrophic loss of stability.

5.0 CONCLUSIONS

A ship is said to have directional stability when, after being deviated from its initial straight course by external forces such as wind or waves, it eventually returns to its original heading. Although the vessel may not follow the exact same path during recovery, it remains aligned with the intended direction. To maintain this stability and ensuring that the ship stays on a straight course, effective control of the rudder angle is needed.

The interaction between large rudder angles and high-speed rudder forces, which can destabilize the vessel, is studied in this research. It is evident that when extreme rudder forces are applied at high speeds can induce instability in the vessel. This results in potentially deviating the ship from its course or to experience excessive heeling.

Based on the findings of this research, it is concluded that multiple factors like design shape of the vessel, hull form, trim, operational draft, cargo loading conditions influence a vessel's overall stability. For maintaining the stability and to ensure safe navigation of a vessel, especially in high-speed and challenging operational conditions, previous mentioned factors must be carefully managed.

6.0 FUTURE RESEARCH

For future research, its far crucial to discover the overturning moments experienced by using diverse types of vessels in various operational situations. Taking cues from the study, other effects of sea conditions, which includes currents, winds, and waves, on a ship's stability and manoeuvrability are also to be taken cognisance of. By analysing how these environmental elements influence vessel design, we can gain a more comprehensive understanding of the forces affecting overturning moments.

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Author contributions

Dauson Nyonyi contributed to the manuscript formulation, experimental data collection, and authored the work, while Dr. Giri Rajasenkar evaluated the content and offered suggestions for improvement. Prof. V.V.S. Prasad was crucial in revising and supervising the text, giving final approval, and taking responsibility for the entire content.

Conflict of Interests

The author(s) have stated that they do not have any known conflicts of interest related to the research, writing, and/or publishing of this work.

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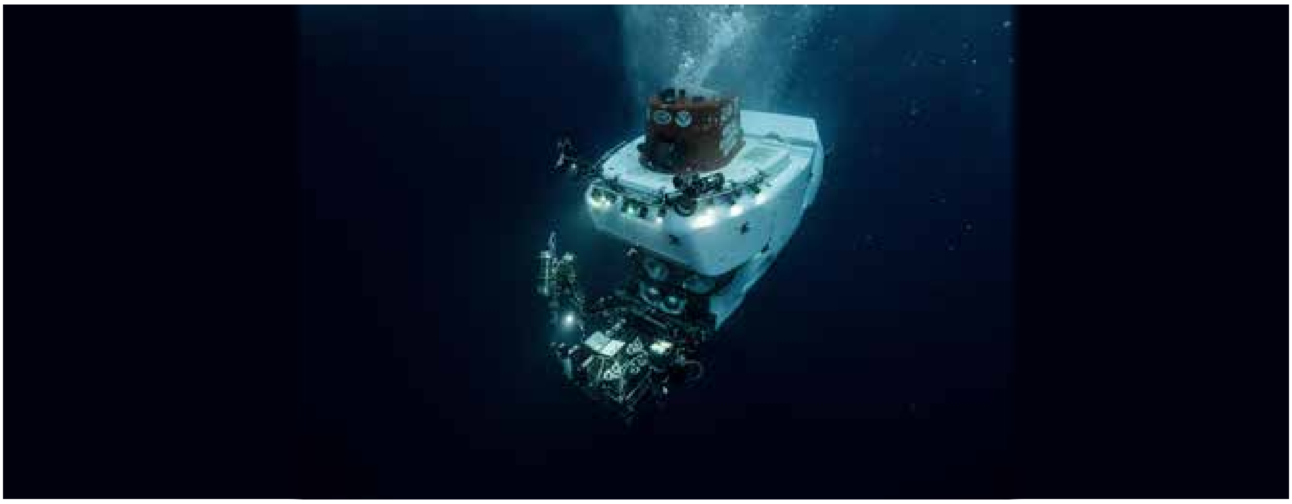
Technological Maturity of Deep-ocean Human Diving Systems – Part B



N. Vedachalam

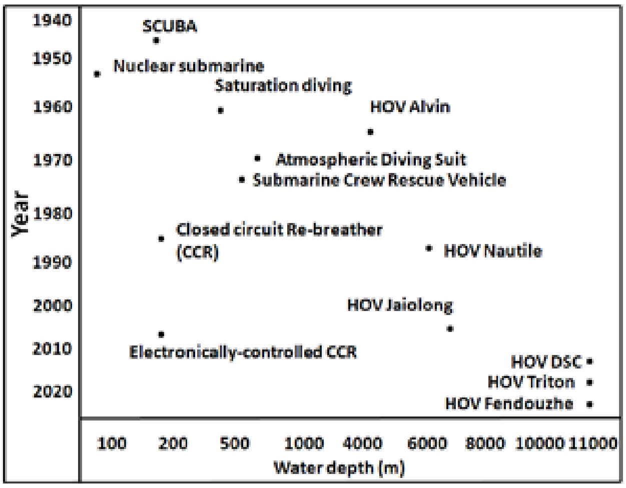
Introduction

Despite the fact that the ocean covers ~70% of Earth's surface and plays a critical role in supporting life on our planet, from the air we breathe and the food we eat to weather and climate patterns, our understanding of the ocean remains limited. Rigorous ocean observations and documentation of biological, chemical, physical, geological, and archaeological aspects allow us, collectively, to protect ocean health, sustainably manage our marine resources, better understand our changing environment, and enhance appreciation of the importance of the ocean in our everyday lives. There are multiple technological challenges in exploring the deep-oceans characterised by high ambient pressure, low temperature, absolute darkness and salinity that prevent access to global positioning systems and radio signals. These hostile environmental conditions make deep-ocean human missions equally or even more complex than space missions. The challenges involved are evident from the fact that only a few have descended to the deepest part of the oceans (~11 km deep Mariana Trench) compared to twelve people who have landed on the moon. Part A (previous part) of the article discussed the significant technological advances since the 1940s till date in the areas of underwater breathing systems, saturation diving, and distressed submarine crew rescue vehicles. This part (Part B) discusses exclusively on the developments in deep-ocean human-occupied scientific submersibles that have made it possible for humans to safely and effectively explore the deep-oceans including its true mysteries, living and non-living resources.

Evolution of Deep-ocean human occupied vehicles

Human Occupied Vehicles (HOVs) have the advantages of taking scientists to deep-ocean for carrying out high-resolution bathymetry, geological surveys, search activities, salvage operations, engineering support for underwater construction, biological sampling, habitat analysis and carry out in-situ experiments. Scientists can continuously obtain real-time and in-situ data, design experiments and perform fine operations based on actual dynamics in real-time compared to other remotely operated (ROVs) and unmanned robotic vehicles (AUVs) and systems **(Table.1).**

The first human dive in the deep-ocean took place in 1930 when William Beebe and Otis Barton descended to a depth of 245m in a bathysphere (and then to 923m in 1934) near Bermuda. The bathysphere comprised of a pressure-resistant cast steel sphere housing humans with view ports, and equipped with life-support system, basic instrumentation and communication systems **(Figure.1).** It was suspended from the ship using a steel cable and



underwater positioning of the bathysphere was achieved by adjusting the cable length and by re-positioning the surface mother ship (MOSHIP). Subsequently there have been hundreds of HOVs built that have turned out to be important stepping stones for next generation HOV. In 1960, as a significant milestone, Jacques Piccard and Don Walsh descended to10.9km down in the Swiss-designed, Italian-built bathyscaphe Trieste **(Figure.1).** Reaching the bottom of the Challenger Deep, the lowest point of the Mariana Trench in the Pacific Ocean, they were the first people to achieve full-ocean depth.

Further technical developments greatly expanded the operating range and improved the operational efficiency of the HOVs used in scientific research. After the 1st generation HOV Alvin, the 2nd generation HOV that were centred on the development of a lighter pressure-resistant hull for the crew, improved power supply for propulsion, and establishment of reliable systems are shown in **Table.2** and **Figure.2.** These HOV are certified for human occupancy by agencies forming part International Association of Classification Society (IACS) including the American Bureau of Shipping (ABS), Germanischer Lloyd, Det Norske Veritas (DNV) and operational guidance were given by International Marine Contractors Association (IMCA).

Table.1. Comparative capabilities of underwater robotic vehicles

Feature	ROV	AUV	HOV
Endurance	Unlimited	Limited	Limited
Spatial capability	Limited	>10s of kms	< 10s kms
Connectivity	Tethered	Untethered	Untethered
Intervention capability	Limited	Maturing	Well-proven

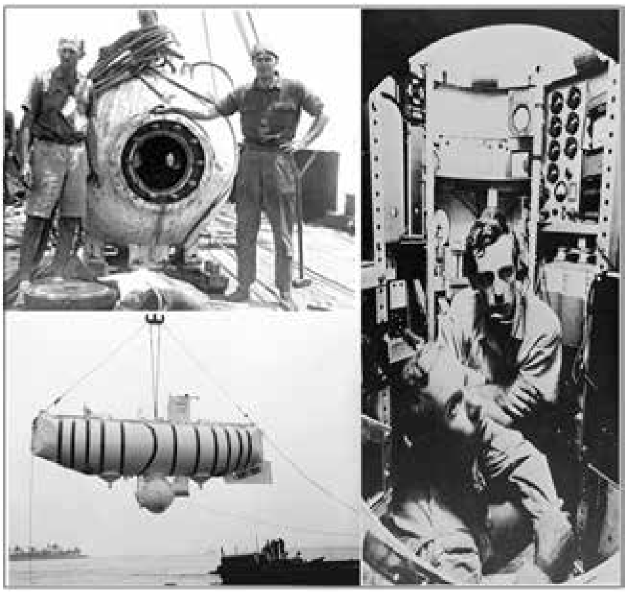


Figure.1. View of first generation HOVs

Hadal-depth HOVs

Following the historic descent of Jacques Piccard and Don Walsh, no human submersible dives occurred over the next 50 years, and exploration was based on the descents of the remotely operated vehicles, ROV Kaiko in the 1990s and early 2000s and the hybrid ROV (HROV) Nereus in 2009. These unmanned robotic expeditions offered new insight into some of the specific organisms that live at the bottom of the Challenger Deep. Inspired by the discoveries, post-2008, significant interest was shown in the development of 3rd generation hadal depth human submersibles.

There are 37 known hadal trenches in the global ocean, the 9 deepest are located along the western

Figure.2. Deep-ocean HOVs across the world till-date

Table.2. Evolution of HOVs post-1960

Year built	HOV	Country	Depth rating
1964	Alvin	USA	4500m
1985	Nautile	France	6500m
1990	Shinkai	Japan	6500m
	MIR	Russia	6000m
2002	RUS	Russia	6000m
2009	CONSUL	Russia	6000m
	Jiaolong	China	7000m
2012	Deep Sea Challenger	Australia	11000m
2019	Triton	USA	10925m
2020	Fendouzhe	China	10909m
2021	New Alvin	USA	6500m
2024	Matsya (being built)	India	6000m

arc of the Pacific Ocean. Among them, the Philippine, Mariana, Tonga, Kermadec, and Kuril-Kamchatka Trenches are deeper than 10000m. They are the least explored habitat but one of the last frontiers on our planet. The map was generated by Mengran Du et al using the ETOPO1 database and Generic Mapping Tools software. White colour shows areas with water depth > 6000m. Dark red colour highlights areas with water depths >9000 m in hadal trenches, which are exclusively located in the Pacific Ocean. Values in small boxes show the maximum depth, the total area, the age of the subduction lithosphere, and the total flux of particulate organic carbon in each hadal trench. Yellow, blue, green, and red dots represent four different clusters of hadal trenches, which are grouped on how geographically distant each hadal area is from all other hadal areas **(Figure.3).**

Human Occupied Vehicles (HOVs) have the advantages of taking scientists to deep-ocean for carrying out high-resolution bathymetry, geological surveys, search activities, salvage operations, engineering support for underwater construction, biological sampling, habitat analysis and carry out in-situ experiments

The *Deep Sea Challenger (DSC)* and *Fendouche* hadal-depth HOVs recorded depths of 11000 and 10800m respectively, in 2009 and 2012. The Five Deeps Expedition by *Triton* submersible was the first to reach the deepest point in each of the Earth's five oceans including the Puerto Rico Trench (8376m) in the Atlantic, South Sandwich Trench (7434m) in the Southern Ocean/Antarctica, Java Trench (7192m) in the Indian Ocean, Challenger Deep (10925m) in the Pacific (which is the deepest place in the planet), and Molloy Deep (5550m) in the Arctic. The expedition covered 87000 km in 10 months. As a tool for geographic exploration, the *Limiting Factor* is one of the most uniquely-capable, piloted vehicles in seafaring history. The HOV *Matsya6000* indigenously designed and developed by India's MoES-NIOT focuses on increased human safety and reliable performance shall have 10 distinct features . This would include redundant power, control, positioning and data telemetry systems, on-board pressure-balanced oil-filled lithium-polymer batteries, human-rated ballast drop-weight configuration, rapid emergency location cum rescue system, bio-vest for near real time crew health monitoring, submersible

Figure.3. Hadal trenches over the world's ocean

Figure.4. Landers used by Triton (L) and DSC (right)

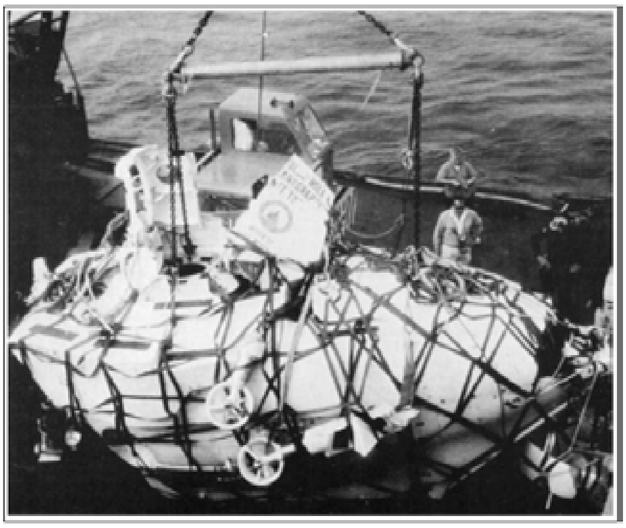


Figure.5. Alvin recovered after 1 year since it is lost in 1968

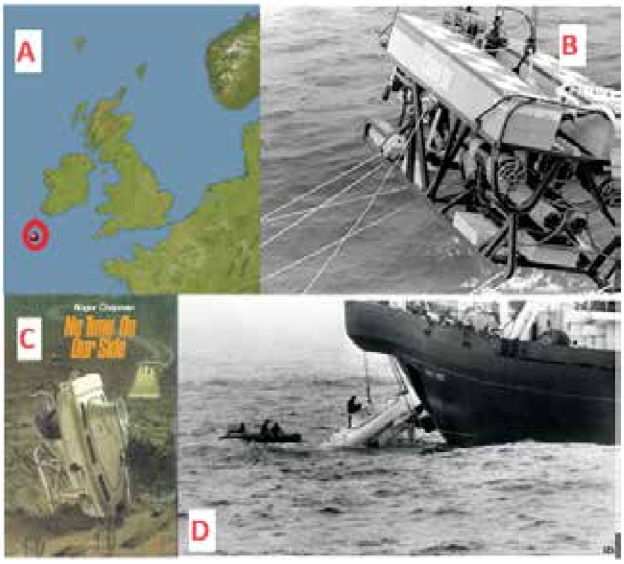


Figure.6. Rescue of *Pisces III* submersible during 1973

on-board/ship-based digital-twin assistance for supporting safety-critical operations and sub sea surface parking capability, identifies itself as the 4th generation deep-ocean submersible.

In hadal-depth submersibles, precise underwater navigation is achieved using a system of underwater modems. Once the target exploration site is located, the landers are deployed in freefall **(Figure.4)** and are then followed down by the submersible. The Limiting Factor submersible is equipped with two modems that are tracked using another two surface modems installed on the support vessel and a support ship, which can then triangulate from at least two of the three landers (Skaff, Closp and Flere) that are deployed prior to the submersible dive.

> **Inspired by the discoveries, post-2008, significant interest was shown in the development of 3rd generation hadal depth human submersibles**

Unsafe events and lessons learnt to improve safety

Hitherto, deep-ocean HOVs have encountered few accidents. The have given significant inputs in evolving guidelines for safety-centred design and operations. Alvin was the first generation deep-water HOV built by Woods Hole Oceanographic Institution (WHOI) of the United States in 1964. Between 1965 and 1968, Alvin logged ~300 dives, which included finding the lost H-bomb in deep-water off-Spain, the discovery of the hydrothermal vent (believed to be intimately connected to the evolution of life on Earth) environment at the Galapagos Rift in 1977 and filming the Titanic in 1986 along with ROV Jason. In 1968, during a retrieval operation by vessel Lulu, handling cables got snapped and water entered the personnel sphere through the open hatch and Alvin plunged to the sea bottom at 1515m water depth. It was later salvaged in 1969 **(Figure.5)** and since then Alvin has been in operation (with a retrofit) having completed >5000 dives.

During 1973, the 76h multinational effort in the successful rescue of the 2-crewed (Roger Mallinson and Roger Chapman) deep-ocean submersible *Pisces III* trapped on the seabed and lying upside down (due to flooding of its compartments) at a depth of 480 m, 240 km off-Ireland **(Figure.6a)** in the Celtic Sea is the deepest successful submarine rescue in history. At the time of accident, *Pisces III* (which was laying a transatlantic telephone cable) had 64h of oxygen storage left. The synergised effort that involved Controlled Underwater Recovery Vehicle (*CURV-III*), *Pisces II & V* submersibles **(Figure.6b)** and multiple ships explained by Chapman in his book titled *No Time on Our Side* **(Figure.6c)** can be appreciated from the fact that only 12 minutes of oxygen was remaining when *Pisces III* was rescued to the sea surface **(Figure.6d).** This was possible as they decided to allow the CO_2 in the air to build up beyond the normal 40 minutes to conserve O_2, which resulted in lethargy and drowsiness for both of them.

During 2023, *Titan*, a deep-ocean submersible **(Figure.7b)** operated by Ocean Gate, imploded during an expedition (with 5 occupants) to view the wreck of the Titanic in the North Atlantic Ocean off the coast of Newfoundland, Canada **(Figure.7a).** After the submersible had been missing for 4 days, ROV Odysseus 6000 **(Figure.7c)** from Pelagic Research Services (with Vessel Horizon Artic) discovered a debris field containing parts of Titan, about 500m from the bow of the Titanic, recovered the debris and returned to St. John's harbour **(Figure.7d).** The entire pressure hull consisted of two titanium hemispheres with matching titanium interface rings bonded to the 142 cm internal diameter, 2.4-metre-long carbon fibre-wound cylinder. Investigations revealed that failure of the carbon-fibre hull was the most likely cause of the implosion, given that no large pieces of carbon fibre are known to have been recovered. The incident which spread shock waves in the deep-ocean HOV sector showed the

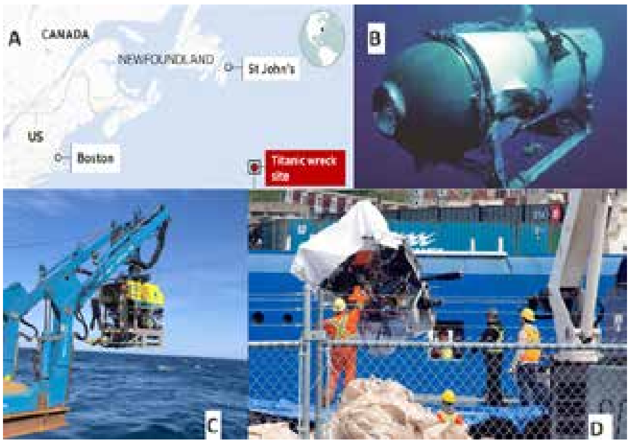


Figure.7. Salvage of Titan submersible during 2023

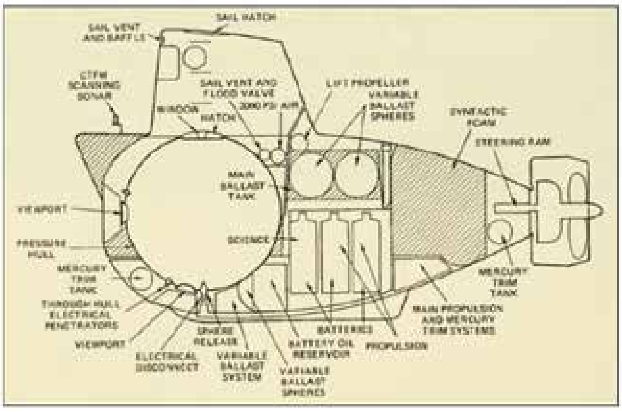


Figure.8. Subsystems of a HOV

importance of certification and the need for appropriate regulatory frameworks.

Design of HOVs

The overview of typical deep-water HOV is shown in **Figure.8.** The major systems include the pressure-rated personnel sphere for human occupancy, equipped with an entry hatch and acrylic view ports. They house the systems required for the control of the HOV, communication aids and life-safety systems required for the crew. Electro-optical penetrators enable electro-optical communication from the exo-structure systems. The propulsion system comprises of batteries and thrusters to enable the vehicle manoeuvrability in multiple degrees of freedom (DoF), variable buoyancy enabling systems comprising of pumps and compressed air bottles for descend, traverse, and ascend operations, navigation systems for position determination and safe vehicle manoeuvring, Ship-HOV communication and data telemetry systems, manipulator arms to perform tasks, frame covered with hydrodynamic fairing, emergency surfacing systems, entanglement release and emergency recovery systems.

The HOV Matsya6000 indigenously designed and developed by India's MoES-NIOT focuses on increased human safety and reliable performance shall have 10 distinct features

The challenges in the design of the HOV operating in the harsh deep-ocean environment are mapped in **Figure.9.** The thickness of these pressure-rated enclosures should be sufficient to overcome these axial and circumferential stresses caused by the external hydrostatic pressures (e.g. 606bar at 6000m water-depth). The design of the pressure-rated enclosures should consider the operating ambient temperature variations, shape, dimensions and weight limitations, material of construction, fabrication properties, creep properties under external hydrostatic pressure, cyclic pressurising effects, collapse strength, elastic-plastic behaviour, internal heat dissipation requirements, safety factor and corrosion allowance.

The design of the spherical personnel sphere for human occupancy is carried out based on the design rules of IACS agencies such that the overall out-of-roundness (OOR) < 1 % of the nominal inside diameter and local shell tolerance of < 0.5% of the nominal outside radius, else it poses penalty on increased overall shell thickness and weight. As a design Vs Operational trade-off, deep-water battery-powered HOV weighing ~20t (with a maximum speed of 3 knots) which could be launched and retrieved from a MOSHIP carry three persons in a titanium alloy personnel sphere of ~2m diameter, with human life-support systems and battery energy capable of supporting 12-18h of normal operations and for 96h during emergency.

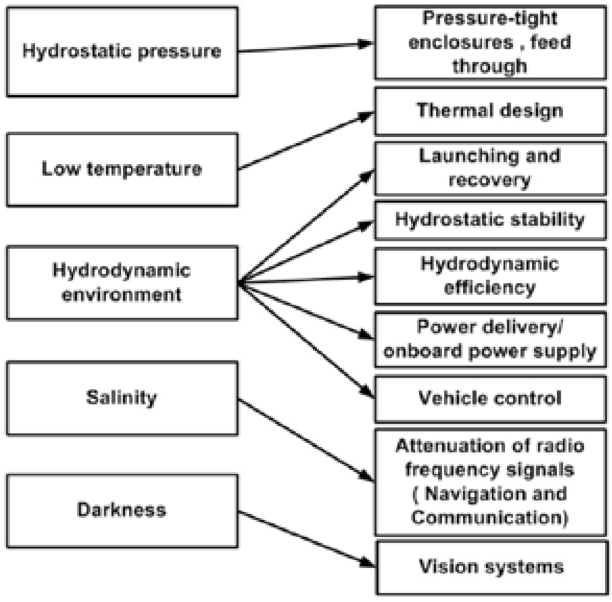


Figure.9. Challenges in realising deep-ocean HOV

Design, operational challenges and recovery of HOVs

Safety-centred system engineering

The system engineering of HOV has to address the key operational challenges including HOV ascending failure, personnel sphere (human cabin) water entry, personnel sphere oxygen support system failure, imprecise navigation system, ship-HOV communication outage, hard landing on the seabed, collision with forward objects and manipulator entanglement with sea floor objects. Safe launching and retrieval of the deep-water HOV in the dynamic offshore environment is a major challenge.

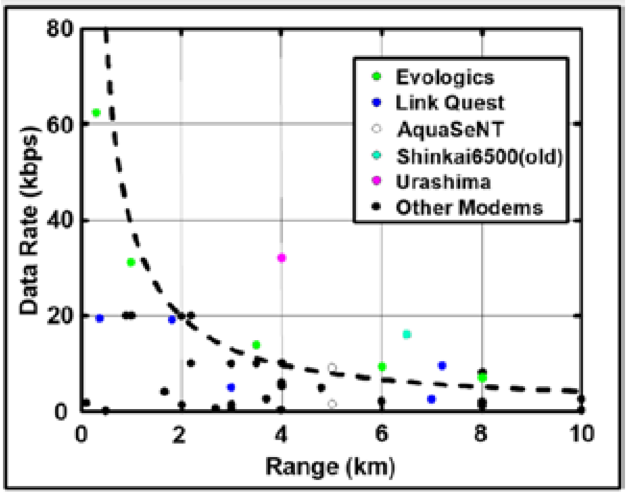


Figure.10. HOV slant range Vs achieved telemetry data rates

Due to the limited battery endurance and the life support systems, the HOV is normally taken on-board the MOSHIP to the deployment location. Once the HOV is launched on the sea surface, the HOV shall be off-hooked from deployment slings by the divers. Once it surfaces after the mission, the slings shall be hooked to the HOV for retrieval back into the MOSHIP. The design of these systems has to consider the dynamic loads during various sea states.

The IACS agencies provide clear guidelines for the design of HOV including the structural design of the personnel sphere, vehicle hydrostatic stability and personnel sphere human life support systems (during a normal operating period of 12 h and emergency endurance of 96 h). The emergency power supply, communication between the HOV and the deployment vessel, emergency drop weight systems during unavailability of the service drop weights, emergency jettisoning systems for enabling ascent of during loss of vehicle buoyancy or entanglement with the sea floor objects and procedures for emergency retrieval of the submersible from the deep-ocean using submersible hooks with ship-based deep retrieval line are also considered.

The IACS agencies provide clear guidelines for the design of HOV including the structural design of the personnel sphere, vehicle hydrostatic stability and personnel sphere human life support systems (during a normal operating period of 12 h and emergency endurance of 96 h)

Importance & limitations in HOV-MOSHIP communication

An Underwater Acoustic Telephone (UAT) is an important component of HOV. According to IACS rules, periodic voice communication (every 15min) between the HOV and MOSHIP is essential to ensure the health of the crew and HOV. In the absence of voice communication, the HOV shall initiate the ascent to the surface. The operational slant range of present UATs are limited to 12kms slant range for an electrical power of 300W. The first acoustic analogue modulation based (8-11kHz) single side band submarine communication system was developed in the US by the end of World War II. In the early 80's, the underwater communication systems based on digital signal processing (DSP) and Frequency Shift Keying (FSK) principles was developed by WHOI and MIT. FSK relies on simple energy detection (non-coherent detection), and thus offered robustness to channel impairments, its bandwidth utilisation is not efficient.

During 90's phase shift keying (PSK) and quadrature amplitude modulation (QAM) were used as they offered more bits/sec per Hz of occupied bandwidth, but required a receiver that can track the channel and compensate for the time-varying multipath and phase distortion (coherent detection). Recent acoustic telemetry modems with hemispherical beam patterns and optimised for vertical and slant channels operating in 4-14 kHz range offer adaptive communication data rates of ~6 kbps up to 12km **(Figure.10).**

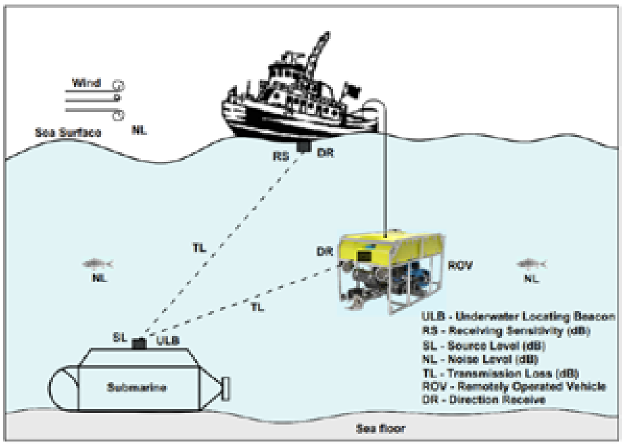


Figure.11. ASL of the DISUBB using ULB and directional receiver

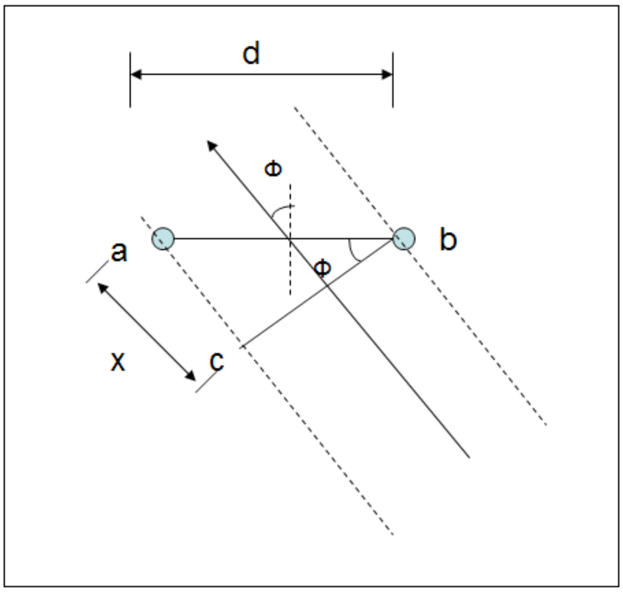


Figure.12. Bearing angle measurement between DISSUB & DR

Table.3. Capability of commercially DR

Parameter	Specification
Frequency Range	8-45 kHz
Bearing accuracy	5º
Bearing resolution	2º

Locating the distressed HOV

The methodology adopted by locating the distressed HOV (DISSUB) using a ROV is shown in **Figure.11.** HOVs are equipped with Underwater Locator Beacon (ULB) that emits a 10ms pulse signal once per second at 37.5 kHz, which is detectable at distances up to 2 km, based on the ocean state and seafloor bathymetry. A primary lithium battery serves as a power source for the ULB. The ULBs are designed based on the International Maritime Organization (IMO) guidelines MSC.333 (90) and MSC.163 (78) with a depth-rating of 6000m and omni-directional acoustic source power of 160 db.

> *“Ambient noise includes acoustic spectrum from below 1 Hz, to well over 100 kHz”*

Directional Receivers (DR) capable of detecting the ping produced by the ULB are designed for mounting on Remotely Operated Vehicles (ROV), Autonomous Underwater Vehicles (AUV) and towed bodies. The DR measures the relative bearing angle to zero-in on the DISSUB-located ULB. The relative bearing of the DISSUB is the clockwise angle from the heading of the DR (onboard ROV) to a straight line drawn from the DR to the ULB. The principle of determining the bearing angle is described in **Figure.12,** in which the phase difference of the incident wave front at the DR array (comprising of multiple transducers) is measured. In the figure d is the distance between the DR transducers, x is the extra distance travelled by the wave front to reach transducer “a” after reaching transducer “b”. If α be the phase difference between wave front reaching a and b, λ is the wavelength, the bearing angle is calculated based on the time difference of arrival between the hydrophones separated by distance d.

$$\Phi = \sin^{-1}\left(\alpha * \left(\frac{\lambda}{2}\right) \pi * \mathrm{d}\right)$$

Once a ULB is detected, multiple search passes with a DR are needed to adequately triangulate the location of the DISSUB-ULB.

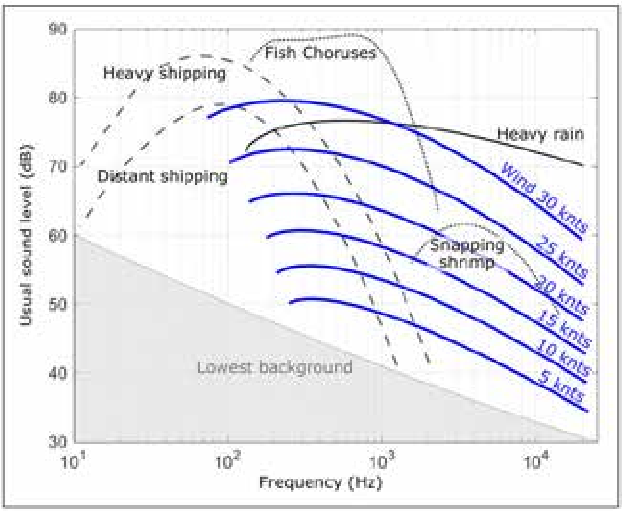


Figure.13. Sources of ambient noise in the ocean

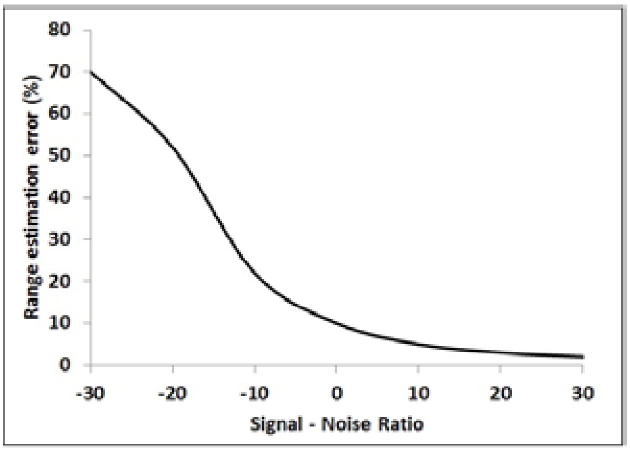


Figure.14. Range accuracy with SNR

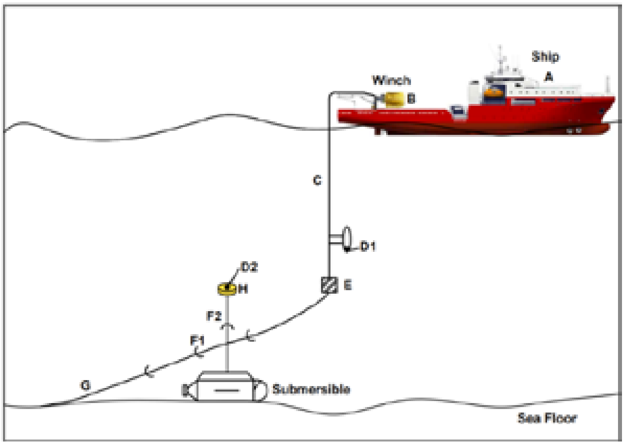


Figure.15. Concept of deep-ocean human submersible recovery

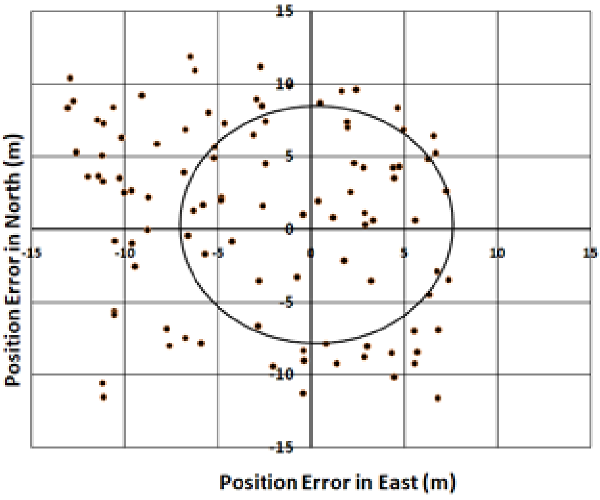


Figure.16. Performance of acoustic positioning system at 6km depth

The importance of SL, TL and NL in the successful detection of the ULB signal from a HOV is shown in the rendering **(Figure.12).** The rendering represents an ULB search with detector based on ship and ROV. For the fixed SL and geo-boundaries, detection capability is better for an ROV-based DR, as the signals experiences lower TL and subsea is characterised by lower ambient noise. In case of ship-based receiver, signals experience higher TL and the sea surface is characterised by higher ambient noise. The characteristics of commercial grade ULB and TPL are summarised in **Table.3.**

Influence of ambient noise during localisation of HOV

Ambient noises play an important role in the effectiveness of locating the HOV. Ambient noise includes contributions from many natural and anthropogenic sources. Ambient noise includes acoustic spectrum from below 1 Hz, to well over 100 kHz. It includes three constituents including wide-band continuous noise, tonal and impulsive noise. These combine to give the continuum of noise against which all acoustic receivers detect as the target signals.

Impulsive noise is transient in nature and is generally of wide bandwidth and short duration. It shows peak amplitude and repetition rate. Continuous wide-band noise is normally characterised as a spectrum level, which is the level in a 1Hz bandwidth. This level is usually given as intensity in decibels (dB) relative to a reference level of 1 µPa. Tonal are very narrowband signals and are usually characterised as amplitude in dB re 1µPa.The ambient noise level is variable and is dependent on the location and the environmental conditions. The component of ambient noise, which represents the NL is shown in **Figure.13.** It depicts the frequency and noise levels caused by heavy precipitation, near and distant shipping, wind (5-30 knots), shrimp and fish choruses.

As indicated in **Figure.14,** the signal-to-noise ratio (SNR) at the DR is an important factor that determines the accuracy of the range estimation. At higher ambient noise levels, the range estimation inaccuracies could be up to 70% and at lower noise levels, the range accuracies could be much better, even better than 5%.

Recovering a seafloor stranded HOV

In spite of reliable and safety-centred design, the possibilities of the deep-water HOV getting stranded on the seafloor due to the failure of the emergency systems and entanglement could not be ruled out. One of the methodologies adopted for the rescue of the stranded deep-ocean HOV is depicted in **Figure.15.**

During normal operations, the HOV will be transported on-board the MOSHIP and deployment at the survey location. Once the HOV descends to the location and starts the survey, the MOSHIP keeps following the HOV. When the HOV is stranded, the HOV pilot releases a buoy (H) which has hooks (F2) and acoustic pinger (D2). The MOSHIP (A) with a winch-would (B) long wire rope (C) and equipped with another acoustic pinger (D1), dead weight (E), hooks (F1) and a trailing deep recovery line (G) shall be lowered from the MOSHIP winch. The state-of-the-art acoustic positioning system D1 and D2 provides a position precision with a Circular Error Probability (CEP50) of ±15m between the HOV at 6000m water-depth and the MOSHIP **(Figure.16).** Maneuvering the MOSHIP around HOV results in the entanglement of the HOV hook F2 and once of the deep recovery line hooks (F1) and the HOV could be lifted back to the MOSHIP. The operation could be achieved quickly with ROV support.

Conclusion

Deep-ocean research in extreme environments is inseparable from human wisdom, knowledge, experience and judgment, which makes manned missions special compared to intelligent robot technologies such as Remotely Operated Vehicles and Autonomous Underwater Vehicles. Safe and reliable technologies are the prime requirement for enabling manned deep-ocean missions. Over the past eight decades, since the start of the technical diving using Self-Contained Underwater Breathing Apparatus for exploration in shallow waters, reliable and safe deep-ocean diving technologies such as saturation diving, submarine crew rescue vehicles and deep-ocean human scientific submersibles have made humans capable of reaching hadal depths including the 11km deep Mariana Trench, the deepest part of the global ocean. It is beyond doubt that the continuing technological evolution shall help human explore and support sustained exploration of the vast oceans for the benefit of the generations to come.

ABBREVIATIONS

ABS	American Bureau of Shipping
AUV	Autonomous Underwater Vehicle
DF	Direction Finder
DR	Directional Receiver
DISSUB	Distressed Submarine
DNV	Det Norske Veritas
DOF	Degree of Freedom
HOV	Human Occupied Vehicle
IMCA	International Maritime Contractor Association
IMO	International Maritime Organization
MOSHIP	Mother Ship
NL	Noise level
OOR	Out of Roundness
PLB	Personal Locator Beacons
ROV	Remotely Operable Vehicle
SL	Source Level

SNR	Signal to Noise Ratio
TL	Transmission Loss
TOA	Time of Arrival
UHF	Ultra-High Frequency
ULB	Underwater Locator Beacon
WHOI	Woods Hole Oceanographic Institution

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Stability and Thermal Behaviour of Hybrid Composites for Marine Applications with Graphene and Boron Carbide Nano Fillers

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ABSTRACT:

This article gives an investigation into the morphological analysis of boron carbide nano filler and thermal behaviour of the hybrid polymer composite used in marine applications. As reinforcements, hybrid nanoparticles comprising of boron carbide and graphene nano platelets were used. For laying the composites, the VARTM technique was used with the composition of hybrid nano-material taken as 0, 0.25, 0.5 and 1 vol. % of Gr and B_4C and the samples were testing for thermal properties as per ASTM standards. The samples prepared have been subjected to various testing's and the results are reported. Prior to the preparations of composites, the polymer is mixed with surface modified nanomaterial and stability tests were conducted to assess uniform dispersion the aid of U.V. spectroscopy, and the outcomes showed that the samples had been exceptionally uniform over a period of time. It is determined that the thermal behaviour of hybrid composites, which include 1% B_4C and Gr, shows more improved properties than base. But the multi-layered samples with 0.5% Gr and B_4C also showcased encouraging properties like thermal effusivity, specific heat and thermal resistance. This paper presents an overview of thermal properties and use of polymer matrix composites in the marine industry.

Keywords: Stability, Boron Carbide (B_4C), Scanning Electron Microscopy (SEM), Morphological Analysis, Thermal Properties, Marine applications.

1. INTRODUCTION:

The growth of composites and their applications in manufacturing is a brilliant development in the history of materials. Composites are used in numerous fields with mechanical and biological backgrounds for unique applications. When two or more materials with different properties are mixed, a composite material is created. The presence of particles in a composite material adds to its mechanical properties, which include hardness, tensile and flexural strength. Depending on the type of matrix, composites can be categorised into 3 types: Metal matrix composites, ceramic matrix composites, and polymer matrix composites. Especially in the marine sector, polymer matrix composites are used in the construction of marine vehicles (ships, boats, yachts, etc.) and equipment. Marine systems and structures include the hull and shipbuilding industries (ship and submarine masts, propellers, and interior parts), the offshore applications industry (gas pipelines, tendons, and support structures), and the renewable energy sector (turbine devices and rotor blades). The importance of lightweight design is increasing day by day in vehicles used in land, air, and sea transportation. Today, the increase in the value of both safety and energy savings causes research on composite materials to intensify in the marine sector. It is advantageous to use composite materials in many parts so that negative environmental effects such as corrosion, biological pollution, seawater aging, and hydrostatic pressure cause minimal damage to marine structures. With the developments in composite science, the level of use of these materials is increasing in the marine sector, as in every other field.

1.1 About polymer composites:

Polymer matrix composites (PMCs) are composite materials in which a polymer matrix is strengthened by including high-strength fibres or particulate elements. The incorporation of the polymer matrix and reinforcing materials yields a composite material that demonstrates improved mechanical, thermal, and occasionally electrical characteristics in comparison to the separate constituents. **The properties of polymer matrix composites are determined by three constitutive factors: the type of reinforcements (particles and fibres), the type of polymer and the interface between them.** Nowadays, these composites are used in various sectors such as automotive, marine, aerospace and many others due to their high specific stiffness and strength.

Especially in the marine sector, polymer matrix composites are used in the construction of marine vehicles (ships, boats, yachts, etc.) and equipment.

Fibre-polymer composites, also known as fibre-reinforced polymer (FRP) composites, are composite materials consisting of a polymer matrix reinforced with high-strength fibres. These composites combine the favourable properties of both the polymer matrix and the reinforcing fibres, resulting in materials with enhanced mechanical, thermal, and sometimes electrical characteristics.

A fibre is characterised by the fact that its length is much greater compared to its cross-sectional dimensions. The properties of the matrix, the fibre and its interface significantly influence the properties of composites. Fibres in polymer composites can be either synthetic/man-made fibres or natural fibres. Commonly used **synthetic fibres** for composites include glass, aramid, carbon fibres, etc., while natural fibres include jute, banana, cotton, flax, hemp, etc. Depending on the application, there are different types of glass fibres, e.g. E-glass fibres for electrical applications, C-glass for corrosive environments and S-glass for structural applications and high temperatures. Glass fibres are available in various forms, including continuous fibres, chopped fibres and woven fibres. When the fibres are derived from natural sources such as plants or other living organisms, they are referred to as **natural fibres**.

The properties of some of these fibres can be found in **Table 1.** Composites made from the same reinforcing material may not perform better because they are exposed to different loading conditions during their lifetime. To solve this problem, hybrid composites are the best solution for such applications. A hybrid composite material is a combination of two or more different fibre types, where one fibre type compensates for the deficiency of another fibre type. The concept of hybridisation offers the designer the flexibility to tailor the material properties according to the requirements.

1.2 Nano-composites:

Fibre-reinforced polymer nanocomposites (FRPNCs) are a sophisticated type of composite materials in which durable fibres are incorporated into a polymer matrix that is additionally strengthened with nanoscale fillers or nanoparticles. The utilisation of both macroscopic reinforcement (fibres) and nanoscale reinforcement (nanoparticles) enables the augmentation of mechanical, thermal, and barrier properties to a greater extent than what can be achieved with traditional fibre-reinforced polymer composites. These composites can be categorised as unintercalated, interposed, exfoliated, and are produced using various techniques such as intercalation of polymer, in-situ polymerisation, and melt compounding. Biomedical Nano-composites are specifically designed for dental treatments, bone tissue engineering, and drug delivery in cancer treatments and wound dressings. Moreover, the optical properties of composite materials can be improved by embedding a transparent matrix material. Certain Nano-composites, including CNTs,

Table 1. Physical properties of various fibres.

Type of Fibre	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	Density (g/cm^3)
Megass	292	17.5	----	1.26
Willow	221	11.5-18.2	-----	0.61-1.12
Musa Paradisiac	501	13.2	5.93	2.32
Coir	178	4.4-8.1	30.5	1.21
Gossypium	564	5.52-13.63	8.1-9.2	1.41-1.62
Linum	1039	28.62	2.72-3.32	1.52
Cannabis	690	73.1	1.61	1.47
Corchorus	392-778	26.52	1.51-1.82	1.20
Hibiscus Cannabinus	935	53.5	1.62	----
Agave Sisalana	521-643	9.41-23.1	2.1-2.51	1.61
E-glass	3412	73.4	------	2.51

Graphene and its oxides, and MoS2/ Graphene, have shown promising optoelectronic properties for photonic applications.

a. Graphene:

Graphene is an allotrope of carbon, composed of hexagonally arranged carbon atoms in a layered structure. A single layer of carbon atoms isolated from the bulk graphite structure is called "graphene". The carbon atoms in a graphene layer form three robust in-aircraft bonds per atom, which in turn ends in the formation of a hexagonal planar layer with a honeycomb-like atomic association.

> **Polymer matrix composites (PMCs) are composite materials in which a polymer matrix is strengthened by including high-strength fibres or particulate elements**

b. Boron Carbide:

B_4C possesses a range of notable properties, including a high melting point, a high hardness, a low density, exceptional deterioration and rusting confrontation, and more. Currently, this material is garnering significant attention in the field of nano-composites research owing to its distinct somatic, chemical, and electric characteristics, which position it as a foremost challenger amongst the constituents with potential for high-performance applications [53–65]. The micro-sized performance applications [53–65]. The micro-sized boron carbide powder is sourced from a specialised supplier and subsequently transformed into nano-sized particles.

1.2.1 Study on natural Fibre based Polymer Composites:

Natural-based polymer composites have been used more frequently in recent years because of their many benefits, including biodegradability, flexibility, availability, affordability, and light-weight nature. Many studies have been carried out by researchers to improve the mechanical properties of these composites. Gowda et al., for instance, found that composites made of jute fibres have stronger properties than those made of wood. In unsaturated polyester resin, Chawla and Bastos investigated the impact of fibre volume fraction on the mechanical characteristics of untreated jute fibres. According to Schneider and Karmaker[], composites made with jute fibres have better mechanical qualities than those made with kenaf fibres.

1.2.2. Study on non-natural Fibre based Polymer Composites:

A significant extent of research has been conducted by numerous researchers on polymer composites based on artificial fibres. *Huang et al.*(20) investigated the impact of water absorption on the mechanical properties of glass/polyester composites. It was determined that the breaking strength and tensile strain of the composites gradually decreased with increased immersion time in water, as the bonding between the fibre and matrix weakened. *Yuan et al. (21)* examined the reinforcing effects of modified jute fibre on the mechanical properties of timber-flour/polypropylene composites

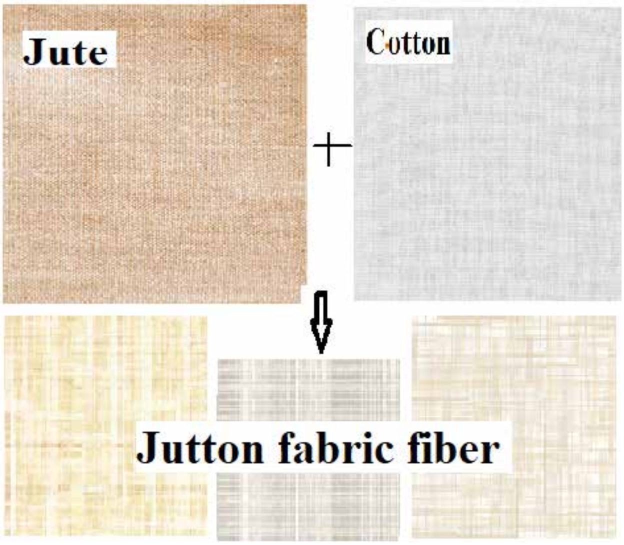


Figure:1. 50:50 Jute and Cotton Fibre (Jutton fibre)

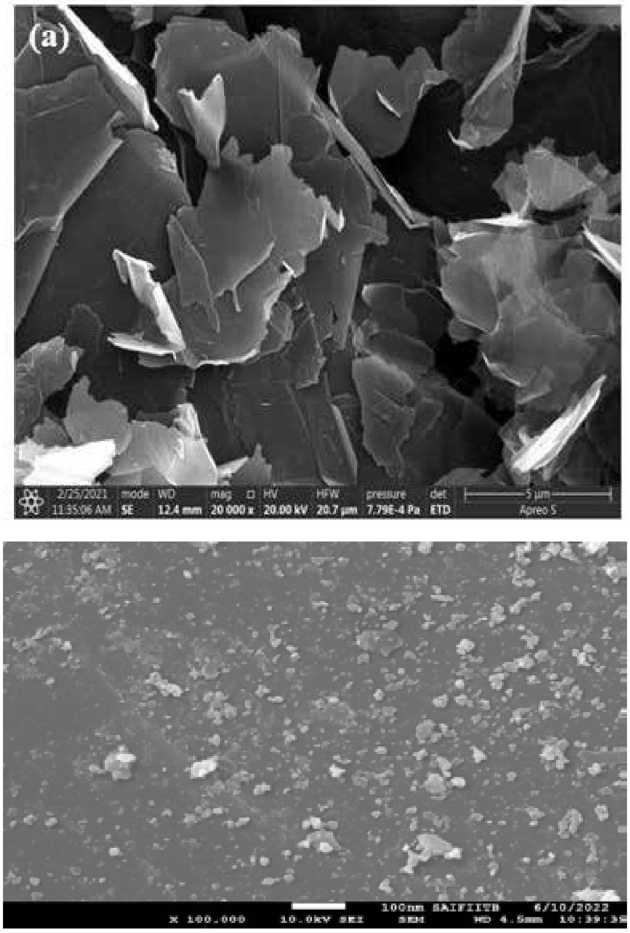


Figure.2. FESEM images of a) graphene b) B4C nano

and discovered that the addition of Kevlar fibre enhanced the mechanical trends of the materials. Wang et al.'s studies (22) into the mechanical traits of composites strengthened with woven Kevlar and fiberglass found that the sort of fibre utilised had a great impact on the fibres mechanical behaviour. At the same time as Cho et al. (23) seemed into the mechanical conduct of carbon fibre/epoxy composites, they discovered that the composites reinforced with nanoparticles had better mechanical traits, along with better shear and compressive strengths.

The resilience of the interface between the polymer matrix and nanofillers is crucial during the creation of nanocomposites

1.2.3 Impression on Hybrid Fibre based Polymer Combinations:

Hybrid fibre composites are composed of a mixture of natural and/or synthetic fibres, that may encompass highly-priced materials including glass, carbon, and boron fibres. Several studies have examined the mechanical behaviour of hybrid composites based on different fibre combinations, along with jute and oil palm fibre or glass and jute. Those investigations have proven that using hybrid structures can effectively beautify the tensile and dynamic mechanical performance of composites because of stepped forward fibre/matrix interface bonding. Moreover, remedies such as the conduct of jute cloth were determined to enhance the performance characteristics. Notch sensitivity has also been studied in untreated woven jute and jute-glass cloth reinforced polyester hybrid composites, with jute composites showing higher sensitivity than jute-glass hybrids. The impact of stacking sequence on mechanical features has additionally been experimentally investigated in interlaced jute and glass material bolstered polyester hybrid composites.

1.2.4.Dispersion of Nanomaterials in polymer:

Achieving uniform dispersion of nanoparticles within the polymer matrix is crucial. Agglomeration of nanoparticles can lead to uneven properties and compromise the performance of the nanocomposite. Modifying or functionalising nanoparticles on the surface can increase their stability in the polymer, leading to better dispersion. The compatibility of nanomaterials with the polymer matrix can be improved by applying surface treatments or coatings. This is achieved by utilising surfactants, coupling agents, or other chemical treatments to alter the surface energy and facilitate greater dispersion. These agents can help stabilise the nanomaterials in the polymer matrix and prevent agglomeration. The dispersion stability of nanomaterial's in the polymer prior to preparation of fibre reinforced polymer nanocomposites is a vital step. To assess the stability, UV Visual spectroscopy is normally employed.

1.3 Present work and Novelty:

This research aims to examine the investigation, evaluation, and thermal behaviour of jutton/glass fibre-strengthened epoxy hybrid composites with Nano fillers such as graphene and boron carbide. The study investigates the impact of B_4C size, with and without surface modification, on thermal properties. Additionally, the morphological and thermal behaviour as well as the stability of the composite polymer were analysed using micrographs. Jutton fibres offer several benefits, including improved performance, enhanced durability, and thermal resistance, quick drying, reduced shrinkage, and cost efficiency.

Figure:3. Experimental Setup

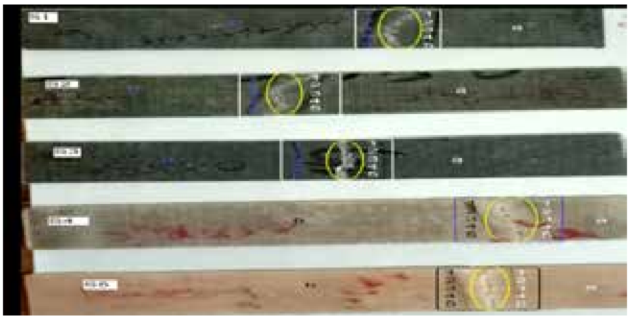


Figure:4. Composite Specimens

2 Materials and Methods:

This phase provides an overview of the processing information for the composites and the experimental procedures conducted to characterise and test the composite specimens. The raw materials utilised in this study are

Moreover, thermosetting resins like polyester and epoxy can end up brittle if they're not properly strengthened in the course of the curing process

2.1 Materials:

Reinforcements / fibres: Jutton fibres (Jute + Cotton), Glass fibre

Matrix / Resin: Epoxy (LY556) with hardener (Hy951)

Nano-fillers: Boron Carbide, Graphene

Type of method: Stability, Surface modification.

Fabrication Technique: Vacuum Bagging Technique

The bast fibre with the highest production extent is jute, which is likewise one of the most low-cost natural fibres. Jute plants can grow up to 2–3.5 m in height; however, their fibres are brittle and feature low extension to break due to their high lignin content material (12–16%). However, jute fibres have less resistance to moisture, acid, and UV light. On the other hand, cotton fibres are soft, cool, and can hold water 24-27 times their own weight. They are also resistant to abrasion, wear, and high temperatures. A visual representation of diverse varieties of jute fibres is shown in the figure.

Jutton fibres are acquired from plant life and are a mixed form that comprises fibres of jute and cotton.

At present, in the jute sector, it has been used and improved to a satisfactory level for use in diverse regions, particularly ground coverings, technical textiles, household textiles, handicrafts, etc. It emphasises combining and growing the best qualities while at the same time minimising the wicked qualities of the fibres. Mixing jute with cotton fibre may be an acceptable process of jute diversification, with the aid of which value-added merchandise may be produced. As a result, the techniques of softening and mixing have established a new class of jutton-based products. S2 Glass offers substantially greater power than conventional glass fibre, better fibre durability, modulus of resistance, impact deformation, and green processing. This has the capacity of composite parts to face up to high stages of concern and flexural fatigue. Epoxy LY556 is Araldite LY556 is a medium-viscosity, unmodified epoxy base on bisphenol-A. It possesses tremendous mechanical properties and resistance to chemical compounds, which can be modified within wide limits by way of the use of HY951 hardener as well as fillers. Epoxy LY556, which specifies LY as bisphenol-A, and 556 is a five-viscosity code, five-performance grade. 6-curing time(seconds).

Nature of Epoxy resin LY-556:

1. Visual issue - self-evident, light yellow fluid
2. Viscosity@ 250 C - 10000-12000 MPa
3. Thickness , 250 C - 1.15-1.20 gm/cm3
4. Streak factor - 1950 C

What's more, hardener HY951 which indicates HY as Araldite and 951 is nine-thickness code,5-execution code,1-relieving time(in seconds). homes of hardener HY-951:

1. Thickness = 0.95 gm/cm3
2. Liquefying factor = 120 C (lit.)
3. Edge of boiling over = 266-2670 C (lit.)
4. Water solubility= Dissolvable
5. Streak point = 143.330C

2.2. Characterisation:

2.2.1 Scanning-Electron-Microscopy (SEM)

It is used to study the morphological characterisation of the composite and powder particles. SEM images

Table:2 Thermal property values for composite

Sample / Properties	Thermal Effusivity(e) in $Ws^{½}/m^2$-K	Sp. Heat (C_p) in j/kg-k	Thermal Resistance (R_a) in kg-k /j
Base	1.08365	8.7581	1.92466
0.25% [Gr+B4C]	3.26902	6.32727	3.08466
0.5% [Gr+B4C]	5.5274	6.1758	3.9985
1% [Gr+B4C]	4.3029	5.0981	5.1264

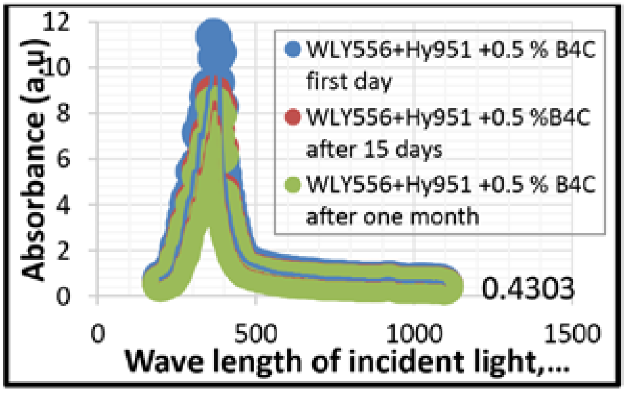


Figure.5. Absorbance vs. Wavelength of incident light

have been taken of synthesised boron carbide during the milling process, with variations in timing. As the dimensions of the matters approached the nanoscale and the percentage of fragments on the surface decreased relative to the total number of molecules, the properties of the substances changed. The figure shows smaller, more uniform, spherical particles, as well as heavily agglomerated debris within the powder.

2.2.2 Surface modification:

The hybrid composites [14, 22] have been extensively studied and it has been found that the composites with a jutton-to-glass ratio of 3:2 exhibit superior thermal properties, including thermal conductivity and thermal effusivity, compared to untreated jutton composites. To further enhance these properties, the jutton and glass fibres are exposed under varying intensities of UV radiation. The UV-pre-treated jutton and glass fibre (3:2) composite, at the most optimal intensities, demonstrates the highest thermal properties when compared to untreated jutton and glass-based hybrid composites.

2.3 Preparation of the Composite

2.3.1 Preparation of polymer and its stability:

The stability of polymer dispersed with nanomaterials as reinforcements is a crucial aspect that determines the performance of nanocomposites and their suitability for various applications. Proper dispersion of nanofillers within the polymer matrix is crucial. The clustering of nanoparticles can result in non-uniform characteristics and jeopardise the stability of the nanocomposite. Methods such as sonication and melt mixing are frequently used to attain homogeneous dispersion. The resilience of the interface between the polymer matrix and nanofillers is crucial during the creation of nanocomposites. Enhancing the interfacial adhesion between the matrix and the filler is crucial for effectively transferring stress, hence enhancing the mechanical characteristics and stability of nanomaterials. The ultra-sonication technique affects the surface and structure of nanoparticles and prevents the agglomeration of particles to form solid fluids. Adequate dispersion of short Jutton-glass fibres in a resin can be achieved without sonication. However, due to the clinginess of graphene and boron carbide, the degree of dispersion of graphene and B_4C in the resin mixture can be improved by sonicating a suspension of nanoparticles. The reasonable dispersion is much greater and effects the size of the Nano powder agglomerates.

Table:3 Peak Absorbance

S.No	Days	Peak Absorbance (a.u)
1	1st Day	11.345
2	After 15 Days	8.845
3	After One month	8.403

2.3.2 Assessment of stability of polymer dispersed with nanomaterials

To assess the stability, UV Visual spectroscopy is normally employed. UV-Visible (UV-Vis) spectroscopy is a method employed to evaluate the durability of nanoparticles in polymers before creating polymer nanocomposites. UV-Vis spectra are collected in order to observe any alterations in the absorption characteristics of the polymer that is distributed with nanoparticles. The UV stability assessment primarily focuses on the UV range, which spans from 200 to 400 nm. UV-Vis spectra can detect absorption bands linked to the polymer and nanomaterials included within it. Alterations in these bands can signify the clustering and sedimentation of nanomaterials. Prior to subjecting the polymer dispersed with nanoparticles to UV radiation, a baseline UV-Vis spectra of the parent polymer is acquired. This spectrum functions as a benchmark for comparison and aids in the detection of any alterations in the absorption properties of the material.

2.3.3 Preparation of composite with vacuum bag method:

Vacuum bag moulding is a highly effective technique utilised in composite manufacturing to produce laminated structures. This technique applies pressure to the laminate throughout its action cycle, serving various purposes.

- Efficiently removes any trapped air among the layers of fabric.
- Compacts the layers of fibres, ensuring sturdy bonding between them and preventing any distortion at some stage in the preparation system.
- Facilitates reducing humidity ranges.
- And most importantly, the vacuum bagging technique complements the integration of the fibre and resin in the composite.

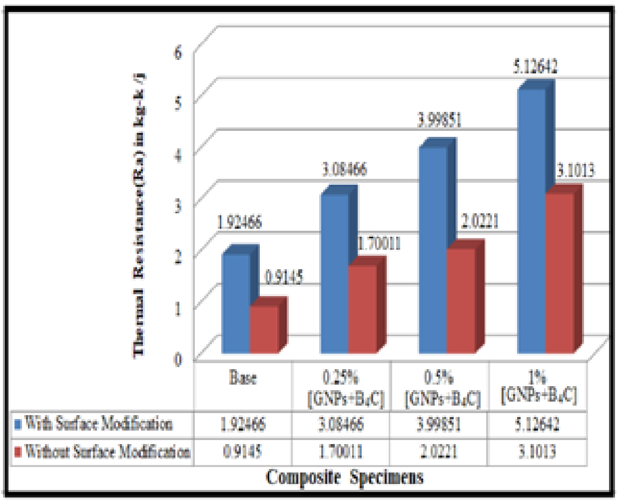


Figure:6 Thermal Effusivity for various composite

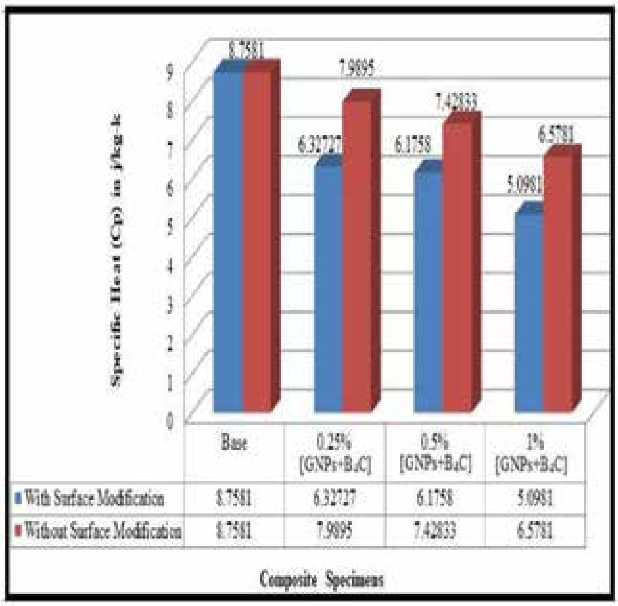
The key to accomplishing those advantages lies in maximising the ratio of fibre to resin. It is vital to observe that the reinforcement within the fabric industry. Moreover, thermosetting resins like polyester and epoxy can end up brittle if they're not properly strengthened in the course of the curing process. If there is extra resin inside the laminate, it'll showcase extra habitations of the resin as opposed to the desired composite. Conversely, if there is too little resin, areas in which the reinforcement is dry will have susceptible spots. To optimise the resin content, it is essential to absolutely saturate the entire reinforcement with resin while minimising any excess content. The essential principle in the back of the vacuum bagging technique is to "squeeze out" any excess resin so as to obtain a maximised fibre-to-resin ratio.

2.4 Thermal properties:

Numerous studies on thermal properties of different polymer nano composites have already been conducted in the last decade but investigations on melting temperature, glass transition temperature, thermal conductivity, and thermal expansion coefficient of the nano composites were found to be most pivotal.

a. Thermal Effusivity(e) :

The thermal diffusivity and effusivity are both composite material properties that contain the qualities: density, conductivity and specific heat capacity. The thermal effusivity is a measure of a materials ability to exchange thermal energy with its surroundings. Thermal effusivity (also known as thermal inertia) describes the heat storing or dissipating capacity of a given material and has units of ($Ws^{1/2}/m^2K$). It is used to describe the one-dimensional heat transmission between two closely associated and touching objects. Even if two different materials are at the same ambient temperature, the material with the higher thermal effusivity will "feel cooler" and the material with the lower effusivity will "feel warmer" to the touch. The thermal diffusivity of a material is a measure of how fast the material temperature adapts to the surrounding temperature.



	Base	0.25% [GNPs+B$_4$C]	0.5% [GNPs+B$_4$C]	1% [GNPs+B$_4$C]
■ With Surface Modification	8.7581	6.32727	6.1758	5.0981
■ Without Surface Modification	8.7581	7.9895	7.42833	6.5781

Figure.7. Specific Heat of composites

3 Results and Discussion:

The obtained solid laminates are cut as per ASTM standards, and various characteristics are being analysed. Stability tests for the resin samples with various volume percentages of nanoparticles were performed, and the results were analysed

3.1 Polymer and its Stability:

Figure. 5 shows the absorbance vs. wavelength of incident light of the epoxy-B4C substance. If the wavelength of incident light increases, the absorbance in the respective substance reaches its maximum value and then decreases as shown in **table 3.**

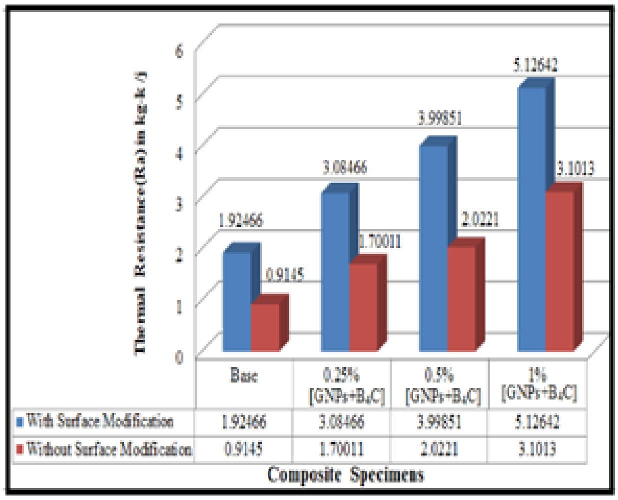
3.2: Thermal Properties on Composite Specimen:

3.2.1 Thermal Effusivity (e):

The thermal effusivity test was performed randomly on the surface of each sample, and mean values were reported. Thermal effusivity is found for different samples at various temperatures. **Figure.6** shows the relation between thermal effusivity and samples with and without surface modification. The thermal property values for composite.

It clearly showed that the base specimen exhibits the lowest thermal effusivity, i.e., $e=1.0863\ Ws^{1/2}/m^2\text{-}K$ and the 0.5% (GNP+MWCNT) with and without surface modified sample exhibits the highest thermal effusivity, i.e., $e=5.5274\ Ws^{1/2},/m^2\text{-}K$ and $e=4.12801\ Ws^{1/2},/m^2\text{-}K$.

Materials with high thermal effusivity can quickly absorb heat, which can make them less likely to reach their ignition temperature because they can dissipate heat rapidly.



	Base	0.25% [GNPs+B$_4$C]	0.5% [GNPs+B$_4$C]	1% [GNPs+B$_4$C]
■ With Surface Modification	1.92466	3.08466	3.99851	5.12642
■ Without Surface Modification	0.9145	1.70011	2.0221	3.1013

Figure.8. Thermal Resistance for composite samples

Also, a material of high thermal effusivity, allows heat to spread quickly through the material. This can prevent localised hotspots that could lead to ignition.

3.2.2 Specific Heat (Cp):

Figure.7, shows the relation between specific heat and samples. In this, it is evident that the specific heat of the 1% (GNP+ B_4C) sample has decreased significantly. The sample 1%B_4C +GNP has attained the lowest value of 2.5781 j/kg-k compared to other samples.

3.2.3 Thermal Resistance (Ra):

The addition of GNPs and B_4C nanoparticles on the hybrid composite, due to the strong filler/matrix and good particle dispersion, which led to an efficient thermal stress regulator, will considerably increase the samples' thermal resistance. As per the results, beginning with a composite specimen without nanofillers, the thermal resistance is 1.4986 kg-k/j, and the sample containing 1% B_4C +GNP shows a high thermal resistance of 4.1264 kg-k/j, as shown in **Figure.8.**

CONCLUSION:

This research focuses on marine applications of polymer matrix composites. Composite materials, which are used instead of traditional materials due to their many advantages, are also widely used in the marine sector. In addition, studies on hybrid composites are continuing. With the development of design, analysis, and manufacturing methods, it will be possible to manufacture more economical, reliable, and durable materials with different components. In this way, the application area of composites will increase, and their properties in the places of use will be further improved.

Based on the results and discussion, it can be concluded that

- The stability of the particles is uniform, as evidently showcased in the absorbance, i.e., if the wavelength of incident light increases, the absorbance in the respective substance reaches its maximum value and then decreases.
- Thermal properties like thermal effusivity and thermal resistance, improved when embedded with GNPs and B_4C nano-fillers.
- The specific heat decreased with an increased percentage of GNPs nanoparticles with B_4C.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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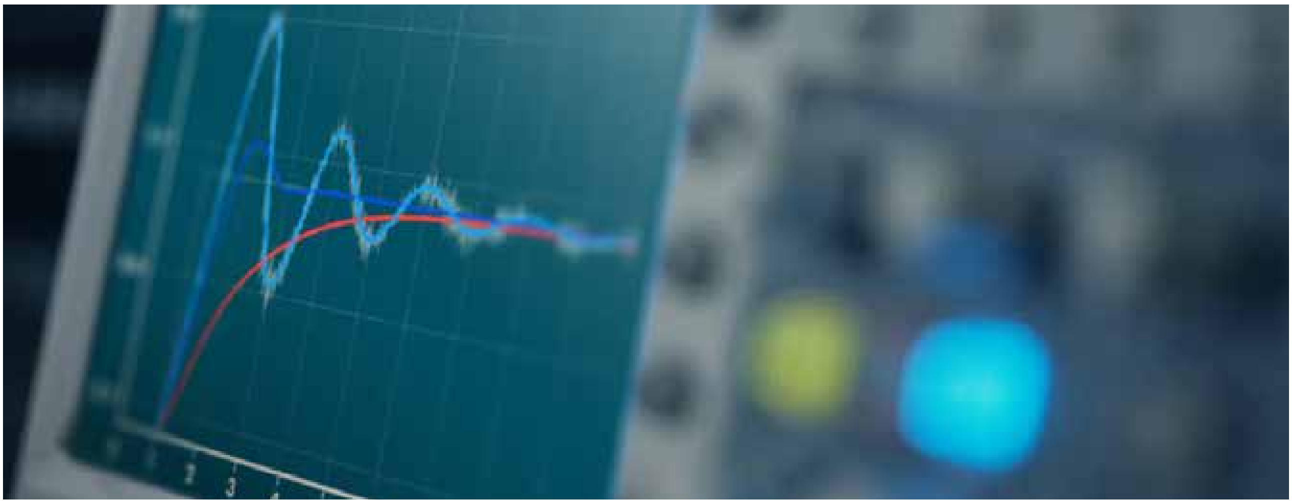
The Effect of P, PI AND PID controllers on Stability, Accuracy and Speed of Response in a Process control system



Ankush Sharma

Abstract/Summary:

The main purpose to design a control system is to achieve accuracy in the parameters but not at the cost of stability. Also, how much time the controller is taking to correct the error or eliminate the offset is of great importance. Therefore, control systems are designed to make process accurate, stable and fast. PID controllers are the widely used in continuous types of control system to achieve stability, accuracy and fast speed response. However, if the tuning of Proportional band, Integral time and Derivative time is not under the range then either the system will become unstable or it may have error. This paper presents the consequences of improper tuning of P-I-D values and how do we improve these parameters.

Keywords: Process control system, continuous control system, PID controllers, Proportional Band, Reset Time, Rate Time.

I. INTRODUCTION

In industrial processes, it is always required to maintain parameters like temperature, pressure, flow, level, viscosity, etc. within the specified range. These process parameters must be accurate for safety and economical operations. Any variation of these parameters from the desired or set value will generate error and it needs to be controlled immediately. The disturbances and load variations in the system gives error. Sensors or transducers continuously monitor the process and controllers try to control the deviation between set value and actual value. However, if controllers are not properly tuned, it will affect the stability and speed of response of the whole process.

For example: For efficient and complete combustion, fuel oil must have correct viscosity. On ships, residual or heavy fuel oil is used which is generally of high viscosity. It is not possible to use such type of highly viscous fuel for combustion and therefore its viscosity is controlled by passing it through steam. If steam flow rate is not regulated properly, then flow of steam either makes viscosity too low or too high. It will damage the liner, piston crown, exhaust valve, etc.

From the above example it clear that tuning of controller is of so much importance. PID controllers are the most common type of controllers for such type of applications where precise monitoring is required.

II. MODES OF CONTROLLERS

Based on the control mechanism, the action of controllers is divided into two groups. Each control mode has its advantages and disadvantages.

A. On-Off Mode:

On-Off mode is also known as Discrete or Two position mode. It is the simplest type of control action where

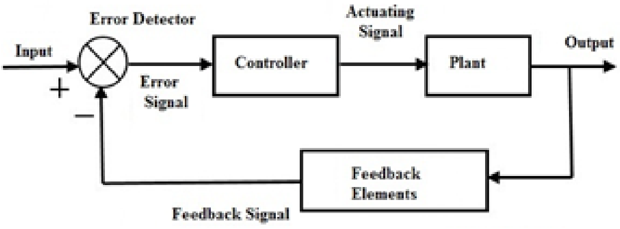


Figure. 1. Elements of Close Loop Control System

controller is either generate 0% output or 100% output. It means the final control element is either fully open or fully close.

Such type of control mechanism is widely used where precise monitoring is not required. In domestic applications like home heating, cooling, refrigeration, water geysers etc., On-Off systems are used. These systems are easy to use, simple design and are cost effective, but not meet the requirements in industries. Therefore, their use is limited to domestic applications only.

Sensors or transducers continuously monitor the process and controllers try to control the deviation between set value and actual value

B. Continuous Mode:

Continuous mode is also commonly known as Modulating controller. The control action is continuous here i.e. the output can have any value from 0% to 100%. It means final control element, which is mostly a control valve, may have any position between fully open to fully close.

Such type of control modes is required in industries where continuous monitoring and precise control is needed. In continuous control, there are three modes on which the whole control action takes place.

1. Proportional Action
2. Integral Action
3. Derivative action

Depending on the applications, we can use either P action or PI action, PID action.

III. THEORY OF PID CONTROLLERS

PID is most suitable algorithm used in a process control system. It has three basic modes of operation. In a close loop control system, the input for a controller is the error between set value and actual value. And the output of the controller is known as Actuating signal. PID control action basically defines the relation between input and output of the controller.

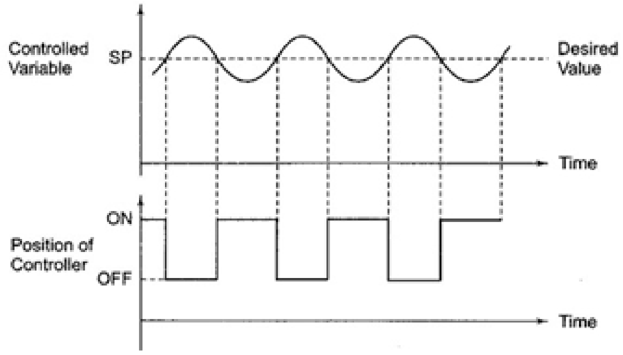


Figure. 2. Response of On-Off Control System

1. **P-Action:** P-Action is nothing but the amplification of error signal. It is the minimum action used in close loop control system where Actuating signal is proportional to the error signal. It is used to adjust the gain settings or Proportional band settings. Mathematically,

$$e_a(t) \propto e(t)$$

$$\text{or, } e_a(t) = k_p \times e(t)$$

where, $e_a(t)$ = Actuating signal

$e(t)$ = error signal = SP- MV

and k_p = Proportional gain

Also, $k_p = \frac{1}{Pb}$

Pb is the proportional band and it is defined as the percentage change in the measured value required to give a 100% change in the output. It has no unit and measured in percentage. Most of the controllers have P-band settings to adjust the P-action. Incorrect tuning of Pb will make system either very sensitive or insensitive.

Case 1: If $k_p = 1$, then $e_a(t) = e(t)$ i.e. actuating signal is equal to error signal. It means if error signal increases, actuating signal also increases. If error signal decreases, actuating signal also decreases. But, if error signal becomes constant then actuating signal also does not change, no matter how much the error is. P action responds only for the change.

Case 2: If $k_p = 0$ or minimum, then $e_a(t) = 0$. It means if gain of the controller is very low then the system is not responding and become insensitive.

Case 3: If k_p = infinite or maximum, then $e_a(t)$ = infinite. It means if the gain of the controller is very high then the system is highly sensitive and become unstable.

According to the above three cases, it is clear that Band settings are very important to make system stable. By decreasing the P-band, accuracy is improved but system will become more unstable. However, if we increase the P-band, stability is improved but accuracy is deteriorating.

The value of P-band is selected in such a way that controller is able to sense any disturbance in the system and respond for that change but final control element should not start hunting.

If we use P-only control action, there will be some degree of offset (sustained deviation) depending on the settings of P- band on Proportional gain.

2. **P+I -Action:** Integral action is also termed as Reset action and used to remove the offset. Integral controller is defined as the controller where actuating signal is proportional to integral of error signal. In P+I control action, both proportional and integral action are used together. Mathematically,

$$e_a(t) \; \alpha \; e(t) + \int e(t)$$

or, $$e_a(t) = k_p \, e(t) + ki \int e(t)$$

where, k_p = Proportional Gain and k_i = Integral gain

$$k_i = \frac{1}{Ti}$$

T_i is the reset time or integral action time. It is the time taken for the controller output to change due to the integral action to equal the output change due to the proportional change and measured in either minutes or seconds.

From the above equation it is clear that, integral gain and integral action time are reciprocal with each other. In P-only control action integral time should be maximum or ideally infinite. Small integral time will make integral action fast and removes the offset quickly. But too small T_i will make system again unstable and increased Overshoot. Too large integral time will make system stable, accurate but very slow. Also, on increasing the reset time will decrease overshoot.

PID control action basically defines the relation between input and output of the controller

As it is mentioned above that if error is constant, then output of P action is also remains constant no matter how high the error is. However, in I- action, output of controller is changing linearly with time with magnitude zero at time zero. If both P and I actions are used together, then at time zero magnitude of actuating signal is equal to error signal and increases linearly with time until the error becomes zero or output signal reaches to the its 100% value (20 mA in electronics circuits and 15 psi in pneumatic signal.). The slope of actuating signal depends on reset time settings.

3. **P+I+D -Action:** Derivative action also termed as Rate action and used to make system response fast and stable. Derivative controller is defined as the controller where actuating signal is proportional to rate of change of error signal. In P+I+D control action, all three proportional, integral action and derivative action are used. Mathematically,

TABLE I. Effect on System Performance by increasing PID actions

Parameter	Accuracy	Stability	Speed
Increasing k_p	Improves	Deteriorate	Increase
Increasing T_i	Improves	Improves	Decrease
Increasing T_d	No impact	Improves	Increase

$$e_a(t) \; \alpha \; e(t) + \int e(t) + \frac{d}{dt} e(t)$$

or, $$e_a(t) = k_p \, e(t) + k_i \int e(t) + k_d \frac{d}{dt} e(t)$$

where, k_p = Proportional Gain

k_i = Integral gain

or, $$k_i = \frac{1}{Ti}$$

k_d = derivative gain

or, $k_d = T_d$

T_d is derivative time or rate time and it is defined as the time of derivative action. In P only control action and P+I control action, derivative time is to be kept zero. Derivative time is also measured in minutes and seconds. Rate action cannot used without P or I action because if error is constant then output of D- action becomes zero.

Rate action has no impact on accuracy of the system. Neither it increases the error nor it decreases the error. Only it helps to make system fast and stable which are the disadvantages of P+I action. However, if wrongly used, derivative action can also make system unstable. Too large value of T_d will cause hunting.

IV. EFFECT OF PID CONTROLLERS ON SYSTEM PERFORMANCE

For any control system there are three performance parameters which need to be control. These parameters are Accuracy, Stability and Speed of response. Proper tuning of PID control action is required to maintain the performance of any control system. But change in demand, load variations and improper values of proportional band, integral time and rate time will disturb all these three parameters.

There are different methods of tuning of PID controllers like Ziegler-Nicholas method, Cohen-Coon method, trial method, etc. Although, trial method is very time consuming but it is the easiest process to get stability, accuracy and fast response and maintenance engineers can easily tuned the controller on board. The other methods need mathematical modelling of the system to get desired values of P, I and D actions. Further, the values of P, I and D are not fixed for all applications.

Initially at the beginning of tuning process, keep Proportional band maximum, reset time infinite (∞) or at the maximum value and rate time zero. This is said to be P-only control action and in this condition the system is insensitive. Now, start decreasing P_b in large steps due to which system will start sensing the disturbances and respond for the change. However, if P_b is too small, sensitivity will improve, offset also decreases but it may cause hunting. Therefore, one should keep the value of Pb at which system will respond for the error and there will be no hunting of the control valve.

For any control system there are three performance parameters which need to be control. These parameters are Accuracy, Stability and Speed of response

Once the system becomes stable with P-only control action, then now introduce integral action by keep the reset time minimum. At the minimum value of reset time, system will cause hunting and overshoot is also increases. As reset time increases in small steps, overshoot starts decreasing and offset is completely eliminated. However, the accuracy will achieve in longer time. So, in P+I controller, maintenance engineer has to compromise between system stability and speed of response. Ideally reset time should be little bit high to achieve ideal response.

Although, in most of the applications P+I controllers are sufficient to achieve all system performance parameters but the application where demand and load variations are very frequent, in such cases derivative action has to be introduce to get fast response. In order to remove P+I controller's slow response in case of a sudden change in loading conditions, derivative action is added to the controller which make the process response fast and stable.

To introduce derivative action with P+I controller, rate time should increase in small steps. If rate time is increase too large, then system cause hunting.

V. CONCLUSION

From the above discussion, it is concluded that PID is the most suitable algorithm for achieve accuracy, stability and fast response on any control system if values of proportional band, reset time and rate time are tuned properly. If any one of the values is increased or decreasing, then performance parameters are also disturbed. In that case, either system will stop responding or will cause hunting.

Not only accuracy, stability and speed of response will be affected but the parameters like rise time, peak time, settling time, overshoot will also change.

VI. APPLICATION OF PID COTROLLER

Although PID controllers are widely used in industries and have number of applications. Here, few of them are discussed in brief.

1. **Viscosity control of Fuel Oil used in Marine Diesel engines:** The viscosity of heavy fuel oil used in Marine diesel engines is very high. There is a complete control system which measures the viscosity and correct it before its burning. Viscotherm or Viscometer is used to measure viscosity and transmit the actual viscosity to the P+I controller. Any deviation of actual value from the desired value of fuel viscosity will generate the error and based on the tuning of Pb and T_i, controller will regulate the steam supply valve. If tuning of Pb and T_i is incorrect then viscosity of oil will be either too high or too low. In both conditions, combustion is incomplete.
2. **Jacket cooling water temperature control system:** Similarly, the temperature of Jacket of Main engine on ships in controlled by fresh water. However, the temperature of fresh water is increasing due to continuous circulation and it is controlled by Sea water. P+I+D controller is used in this application to maintain the temperature of fresh water with the help of sea water inside a cooler. If the temperature of freshwater is already within the range then, fresh water bypassed the cooler through a 3-way valve. However, if temperature of fresh water is very high then, it will inject the cooler. It means, depending on the temperature, P+I+D controller will regulate the flow rate of fresh water.

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Larin: The Fish-Hook Currency of the Indian Ocean Littoral

Soumya Pai

Coins, a type of currency, have allured humanity since they were cast about 2700 years ago and their story interweaves with the story of mankind. They served the purpose of being a token of value and a symbol that replaced the barter system. A study of this means of exchange i.e. currency, is known as Numismatics, which provides a fascinating glimpse into the economic and cultural history of civilisations. Within the wide time span of 2700 years several small and large kingdoms rose and fell. Many of the minted coins that provide evidence of art, society, economy and technology of the said period and also aid in understanding the historical and political dynamics of the region. Power which is generally alluded in terms of politics alone is also relational to the riches and economy.[1] Trade was one of the mainstays of a kingdoms economy and coins were the medium that denoted the magnitude.

Trade in the Indian Ocean was an interplay of multiple networks of economic exchanges conducted beyond localised zones.[2] It spanned across many regional civilisations, each with its distinct commercial infrastructure and were a part of the larger trade networks spread across the Mughal Empire in India, Safavid Empire in Persia and Ottoman Empire in Iraq, Syria and Egypt.[3] These networks were further deepened during the 16th century CE by the settling of the Portuguese amidst the already flourishing empires.[4] This is evident from the presence of one common currency scattered throughout the littorals stretching from the Persian Gulf to the Western coast of India till the far reaches of Ceylon (present day Sri Lanka)**, a silver currency of a quite curious and foreign pattern shaped like a fish-hook, the Larin.**

In antiquity and numismatic study, coins have rarely been of any other irregular shape than circular but Larin were coins of high finesse- a piece of slender silver wire or rod doubled in the middle- originally crafted in the mints of Laristan and Basra, of the Persian Gulf. [5] Around 1583 CE Gasparo Balbi, an Italian jeweller, was probably the first to mention the origin of Larin.[6] Noted travellers to India[7] like Pietro Della Valle (1614–1626 CE) and Sir John Chardin (1664–1674 CE), mention the fish-hook currency in their descriptions of the Indian subcontinent.[8]

Eventually Larin coins became the commercial currency of the Indian Ocean in exchanges tied to the Persian Gulf region[9] and was most popular amongst Arab marine traders.[10] In his travelogue, 'Chardin's Travel in Persia', it was mentioned that Larin was a currency being used in the Gulf of Cambay (present day Khambhat) and was also extensively used on the Malabar coast.[11] Upon their arrival in the Persian Gulf, the Portuguese found that Larin coins were a full-fledged trading currency and found them

Trade routes of the Indian Ocean
(Source: https://globalities.org/2024/01/the-red-sea-in-history-and-today/)

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already introduced along the Persian littorals, down the west coast of India, and were in extensive use up to Ceylon (present day Sri Lanka).[12]

(Pietro Della Valle travelled in India in 1623-24[13] and Jean Chardin from 1677-79[14])

Portraits of Pietro Della Valle and Jean Chardin

Larin was a 10 centimetres long silver wire or sheet usually folded in two equal parts and shaped like a C. Some Larin were also shaped like a J, an I or S. These were then stamped with an Arabic or Persian text, bearing the name of the local ruler.[15] Some old documents mention the *Dabholi Lari, Chauli Lari, Basri Lari* and *Hurmuji Lari*, obviously named after the towns where they were struck. Several old documents mention the *Lari* without any adjective; it seems therefore that the value of all Larin struck at different places was more or less the same.[16] The creator of Larin needed to ascertain the length of drawn wire of a specified thickness that would produce a particular weight. Subsequently, the wire would be cut to that length to ensure a consistent weight.

The only ruler to have issued Larin on the Indian subcontinent that we know of was Sultan Ali Adil Shah II of Bijapur.[17] The dates on these coins were rarely found to be clear, but what could be ascertained tells us that they were issued by the ruler of Bijapur. However, scholars are still studying if these coins were circulated over the extent of the Bijapuri kingdom or contained within the portions of the Konkan littoral only.[18] In 1846 CE, during the excavation for the foundation of a house in the village of Sangameshwara, in Ratnagiri, 397 pieces of Larin were found. The legends which are stamped upon these pieces on one side are *Sultan Ali Adil Shah* (سلطان علی عادل شاه) and on the other are *Zarb Lari Dangh Sikka* (ظرب لاری دانه سکاه).[19]

(Source: https://en.wikipedia.org/wiki/Pietro_Della_Valle and https://depts.washington.edu/silkroad/texts/chardin/chardin.htm)

Trade in the Indian Ocean was an interplay of multiple networks of economic exchanges conducted beyond localised zones

Eventually Larin coins became the commercial currency of the Indian Ocean in exchanges tied to the Persian Gulf region and was most popular amongst Arab marine traders

Captain Jourdain, a British captain in the service of the East India Company residing in India,[20] in his Journal (c. 1610–1619 CE) tells us that- *"the factour of the Portugualls pays the Governor of Dabul two thousand Larin per year for the monopoly of selling wine."* [21] The currency of Larin was used as late as 1711 CE where a grant of the land at the value of 200 Dabhol Larin was made for a place called Kharaputtun to the authorities of Satara.[22] This also indicates that the use of this money was not only adopted by the Bijapuri kings, but was also used by the Maratha principalities in the later times. [23]

During excavations in the year 1925 CE, in Gampola, Sri Lanka, an earthen pot containing a large number of Larin coins was unearthed in a garden.[24] Scholars suggest that it is likely that the Portuguese who first visited Ceylon to trade in the 16th century may have brought with them the Larin from the Persian Gulf.[25]

Why should a long piece of silver wire bent into two be used so substantially for about two centuries? A part of the answer to this lay far West in the New World. Silver had been a prominent means of currency, but between the 16th and 17th centuries CE, Spain imported 7,439 metric tons of silver from the Americas.[26] Silver was sold to Venetian and Portuguese merchants who in turn sold Eastern commodities in the West and ran a favourable balance of trade. Silver coming in was re-minted into Ottoman and Safavid coins, one of them being Larin and was put into the trade network moving towards the Indian Ocean.[27] Coastal kingdoms and markets were familiar with

Larin currency
(Source: https://www.spurlock.illinois.edu/collections/search-collection/details.php?a=1971.15.1383, https://www.f-in-d.com/stories/coins-and-currency-detective)

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Classification Society - A voice of influence or just an IMO ally?

The Bugle of Geo Politics - Sounds of the 21st Century for Shipping

Sustainable development - Is it only about climate change?

Powering Academic Research - Hulls, Propulsion Equipment, Vibration & Underwater Noise

The Connectivity Conundrum - Linking Rivers, Ports and Railways

Advancements in Product Technologies - Fuel Lubricants, Paints, Chemicals & others

Cost Leadership in Maintenance

Managing Learning - What can Shipping learn from other Industries?

foreign currencies and were tolerant of their circulation as legal tender for transactions.[28] With the high influx of silver currency the Mughal Empire became the biggest recipient of foreign silver outside Spain.[29]

In the beginning of the 17th century CE, the rush of Larin to the Indian Ocean littorals faded following the rivalry between Ottomans and Europeans over the control of the oceanic maritime trade.[30] During this time, there also began a monetary crisis in the Mughal Empire as these were contesting times between native indigenous and the Western colonial powers. Gradually, Larin ceased to be in demand and were melted down on account of their fine grade of silver. They were replaced by the currency of the colonial powers and Larin found its way into the crucible.[31]

Due to its large agrarian and industrial base, efficient monetary institutions and highly skilled mercantile groups, India remained the ultimate resting place of the Larin, the fish-hook currency of the Indian Ocean littoral

Due to its large agrarian and industrial base, efficient monetary institutions and highly skilled mercantile groups, India remained the ultimate resting place of the Larin, the fish-hook currency of the Indian Ocean littoral. The study of the Larin currency which was circulated across the massive spread of the seas is crucial for studying the global trade and cultural networks from the 15th to 17th centuries. The significance of the currency is that it was a common feature of this region. Its extensive circulation highlights the wide trade network that connected various regions around the Indian Ocean. They are a testament to the interconnectedness of economies, trade, cultures and societies facilitated by maritime commerce of that period. The abrupt disappearance of the Larin highlights the spread of European economies and commencement of Western influence over these regions that later changed the course of global history.

Portrait of Sultan Ali Adil Shah II
(Source: https://en.wikipedia.org/wiki/Ali_Adil_Shah_II#/media/File:Ali_Adil_Shah_II.jpg)

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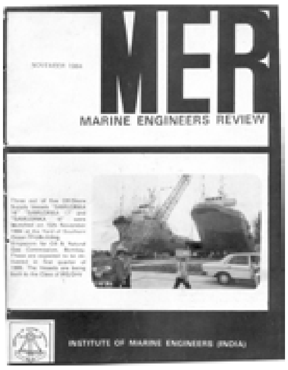
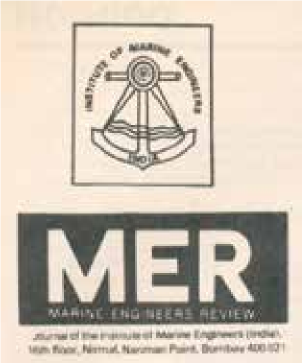
About the author

Soumya Pai is a Research Associate at the Maritime History Society (MHS). She holds a Master's degree in Ancient Indian History, Culture and Archaeology from St Xavier's College, Mumbai. Her research interests include the historical, social, cultural and architectural heritage of ancient times, with emphasis on India and its linkages with contemporary world civilisations. At MHS, she majorly researches the Indian maritime connections with contemporary world civilisations. Her academic interests also extend to studying languages of ancient India. She has presented papers pertaining to Pali language in national conferences as well. Besides her academic pursuits, she is also an avid reader, gardener and crocheter.

Email: researcher1@mhsindia.org

Going Astern into MER Archives...





The Editorial laments on the Bhopal Gas Tragedy and talks on the importance of safety and accountability ensured by way of audits etc. The OPINION highlights the over tonnage situation. The piece pitches for directing the subsidies and cheap finance towards demolition rather than new builds and purchase of tonnage.

The second piece of OPINION appreciates the move by the Swedish Club which has brought in a condition that the ship owners must authorise (on request) the Classification Society (CS) to submit all vessel related information (to the Club) pertaining to 'maintenance of class'. A case for credibility of the CS being weakened...

The short write-up says: *We hope that more underwriters follow suit in an effort to prevent* ***rust buckets*** *sailing the seas.* Agree? I see many hands going up. Comments are invited form the readers on this part.

The last tail piece talks on Pielstick introducing in-line medium speed diesels, in competition with the two stroke diesels. Any thought on these engines performed on HFO and maintenance?

The first of the articles is on Waste Heat Recovery (WHR) from medium speed auxiliary engines. Following this is an article on WHR turbo-generator systems. A few extracts are inserted for understanding the scope for recoveries and possible arrangements. Engineers with experience on such systems can give their inputs on the effectiveness of heat recoveries. The heat balance, graphs indicating the pinch points and layout can get one thinking on the systems and recall how they performed.

This is followed by an interesting article on Data Transmission via Satellite. This was the dawn of such protocols which have reaching another advancement in the current times. Then comes another interesting one on ship vibration. The requirement of compensators are discussed herein. This was an intriguing application in those times when B&W brought on these compensators. I would urge sailing engineers to discuss vibration and applications in present times. There are articles on: on Sulzer Z40 experience, HFO burning GMT high-speed engine, offshore submersibles.

Then comes the Transaction, **Some Considerations on Marine Residual Fuels. The discussion section of this is a must-read for the CoC Examination aspirants.**

The POSTBAG section has an interesting comparison of LNG containment systems viz., membrane and spherical tanks.

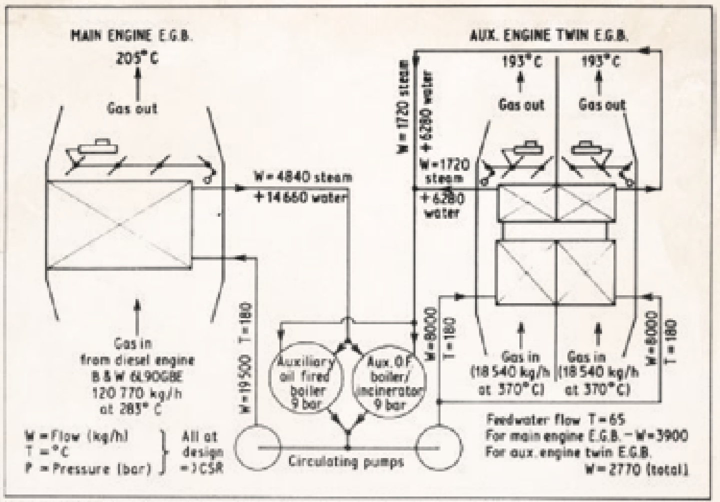
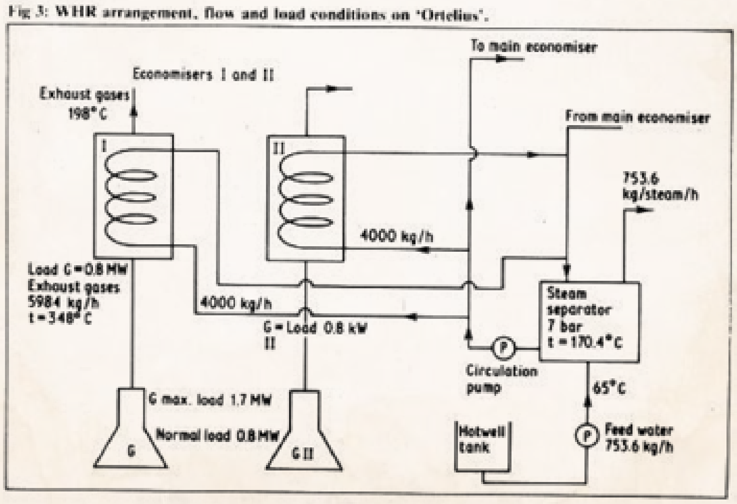


Fig 2: The waste heat recovery arrangement on 'Atlantic Conveyor'.

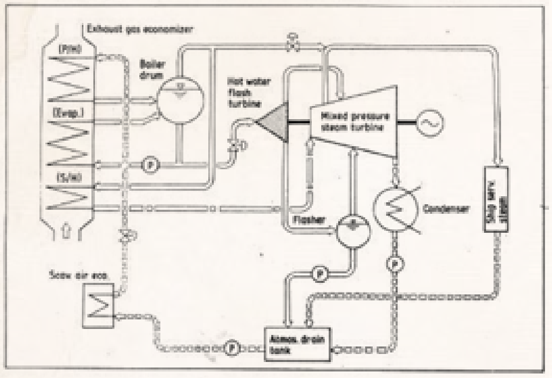
Fig 3: WHR arrangement, flow and load conditions on 'Ortelius'.

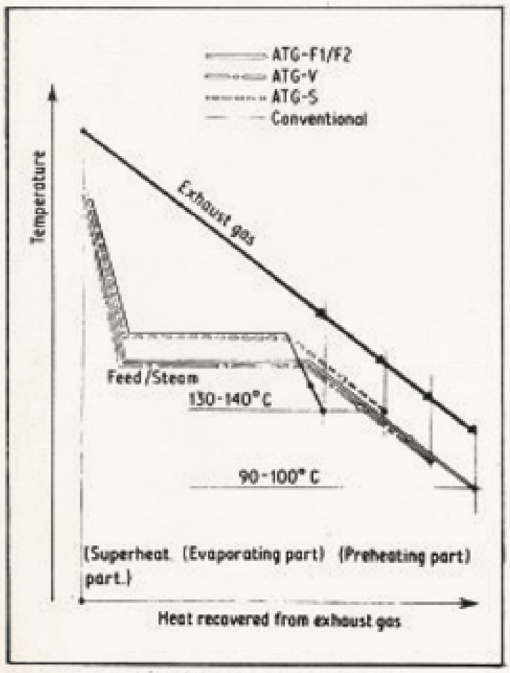


engine speed rev/min		1000/900		
engine output		100%	75%	50%
exhaust gas quantity	MDF	7.15 (5.3)	7.5 (5.5)	8.1 (6.0)
kg/kWh (kg/hph)	HFO	7.65 (5.6)	7.9 (5.8)	8.5 (6.2)
exhaust gas temperature after turbine °C	MDF	440	425	395
	HFO	420	405	385
Permissible exhaust gas back pressure after the turbocharger max. 25 mbar (250 mm WC) Air required for combustion at full load: MDF 6.95 kg/kWh HFO 7.45 kg/kWh				

Table 2: MAN-B&W L20/27 engines' exhaust gas data.

Fig 1: Flow diagram of Mitsui's ATG-F2 system incorporating a flash turbine.





▲ Fig 2: Temperature against heat recovery.

▼ Fig 3: Engine power against electric power.

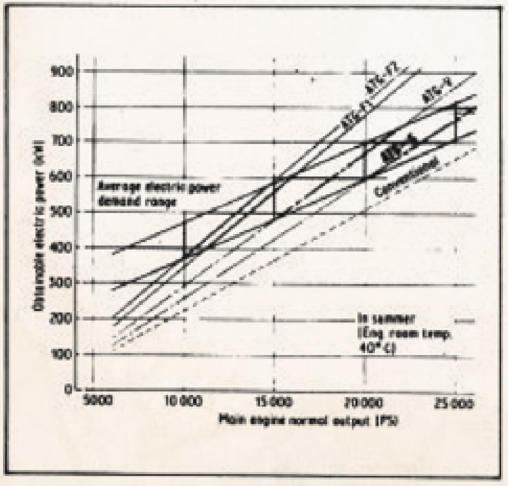
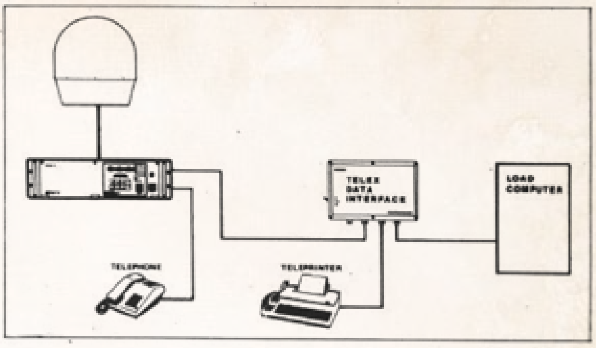


Fig 1: Satcom interface and load computer.



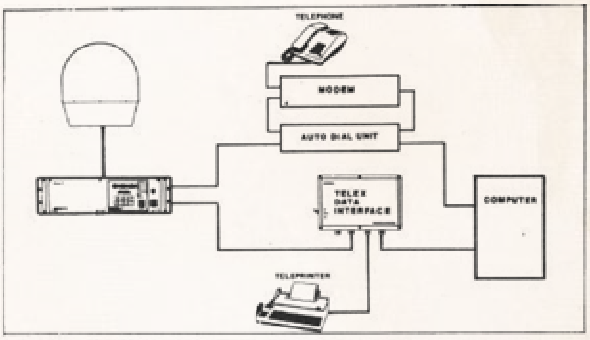


Fig 2: Satcom, modem, number transmitter, interface and ship's computer.

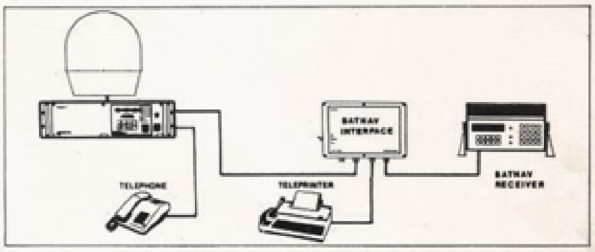
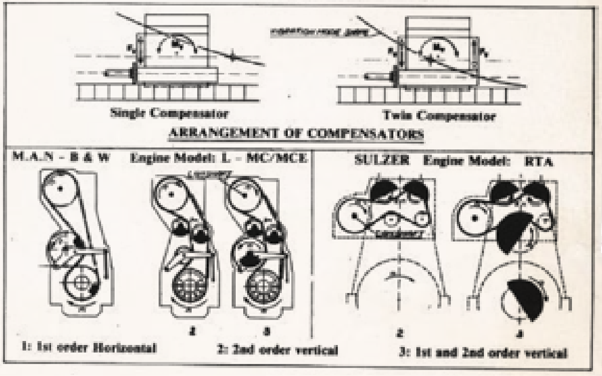


Fig 3: Satcom, Satnav interface and receiver.

Fig 3: When compensators are required on one or both ends of the engine.



POSTBAG

LNG tanks compared

Sir,
Our comments regarding Mr H Iversen's letter (Postbag Sept 84) are as follows:

The Technigaz Mk I is said to have a 20-year history of safe performance compared to the much shorter history of the spherical tank-type LNG carrier.

The TGZ Mk III has been based on the proven Mk I system but is more advanced and more economic in terms of construction cost. It has already been approved and authorised by the classification societies, as well as USCG and other authorities.

As a licensee of the membrane and spherical systems, respectively, from TGZ and SENER, and with more than 15 years of experience and development of an LNG containment system, we have completed a cost evaluation for both systems and also a detailed comparison. Mock-ups of the Mk I and Mk III membrane tanks and the spherical tank have been constructed for this and for establishing building practices.

We concluded that, when compared with tanks of the Sener spherical type to which the Moss type is very similar, the Mk I and Mk III construcion costs can be reduced by up to 8% and 15%, respectively.

According to our investigation of both systems, in the case of a 130 000m^3 LNG carrier, the ship's dimensions and materials required for the tanks and insulation panels are as follows:

	Mk III
LPP × B × D × d =	260 × 42 × 25.4 × 11
Gross tonnage	84 000 t
Tanks	(SUS 304L) abt 400 t
Insulation panel	abt 1200 t
	Spherical
LPP × B × D × d =	275 × 45 × 25 × 11
Gross tonnage	106 000 t
Tanks	(Al) abt 3200 t
Insulation panel	abt 300 t

Compared with the spherical system, a ship with relatively smaller principal dimensions adopting the Mk III system can accommodate the same volume of cargo. Furthermore, the number of man-hours required in the construction of the spherical tank, including insulation, is about twice as much as for the membrane tank.

Lastly I wish to add that the Mk I cargo containment cost, including membrane, is much greater than 8% and within this figure the insulation cost forms a significant part. Therefore, Mk III can save a further 7% to 8% of the ship's cost, compared with Mk I.

T Watanabe

Technical Director
Shipbuilding Division, NKK

Scorching day

Sir,
I wish to draw your attention to the editorial 'The boss leads from the front' under Opinion (MER July).

You have claimed that Mr Graham Day manned the British Shipbuilders' stand for the best part of a week in temperatures of well over 80 °C! I am very keen to know what heat-protective clothing Mr Day used to stand that scorching heat and, by the way, what happened to other people who were in Athens that week? Surely it is °F and not °C.

M M Siddiqui

Benghazi,
Libya

● *It is indeed!—Ed*

Hubble bubble

Sir

As part of your icebreaking feature, you described the friction reducing air bubbler system fitted aboard the supply vessel *Terry Fox*. Whilst we would like to have been the originators of this very successful system, in fact the Finnish company Wärtsilä must be given due credit for the original idea and its early development.

Ampower Canada (1982) Ltd are nevertheless the Canadian licencees for the patented system, and the installation aboard *Terry Fox* is the sixth to be fitted to Canadian owned vessels.

Taran Hewitt

Ampower Canada (1982) Ltd

We invite observations, discussion threads from readers, taking cues from these sepia-soaked MER pages. – Hon.Ed.

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