Springer Series on Naval Architecture, Marine Engineering, Shipbuilding and Shipping 17

Luis Carral · Adán Vega · Jorge Carreño · José de Lara · María Isabel Lamas · Juan José Cartelle · Javier Tarrío · Rodrigo Carballo · Patrick Townsed *Editors*

Proceedings of the IV Iberoamerican Congress of Naval Engineering and 27th Pan-American Congress of Naval Engineering, Maritime Transportation and Port Engineering (COPINAVAL)

Springer

Springer Series on Naval Architecture, Marine Engineering, Shipbuilding and Shipping

Volume 17

Series Editor

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ISSN 2194-8445 ISSN 2194-8453 (electronic)
Springer Series on Naval Architecture, Marine Engineering, Shipbuilding and Shipping
ISBN 978-3-031-49798-8 ISBN 978-3-031-49799-5 (eBook)
https://doi.org/10.1007/978-3-031-49799-5

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Proposed Improvement in Vessel Design Requirements to Facilitate On-Board Additive Manufacturing

Ignacio Requena Rodríguez

Abstract Advances in additive manufacturing mean parts can be made from a wide range of materials, including metal alloys commonly used in the naval industry. The development of Industry 4.0 also enables the evolution of predictive logistics and the interconnection of digital files provided by system and component suppliers. Furthermore, incorporating additive manufacturing capabilities on board a vessel can provide benefits in terms of operational flexibility and space savings for parts storage. However, this capability is conditioned by the sensitivity of 3D printing systems to vessel motion. The need to carry out additive manufacturing in a wide range of sea conditions makes it advisable to incorporate a reserve space at the vessel's point of maximum stability, along with damping and movement compensation systems, including both horizontal (galleries) and vertical (elevators) access passages for efficient distribution of manufactured parts and components and their transfer to outer decks for easier transportation to other vessels.

Keywords On-board additive manufacturing · Vessel design · Shipbuilding · 3D printing · Predictive logistics · Industry 4.0 · Ship stability

1 Introduction

Techniques and specifications in the design and construction of vessels have been evolving with the development of new knowledge, technologies and needs.

Additive manufacturing is now a relevant part of Industry 4.0, combining advances in digitalisation with new 3D printing technologies that allow the production of complex parts with materials commonly found in the naval field, including metal alloys [1, 2].

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L. Carral et al. (eds.), *Proceedings of the IV Iberoamerican Congress of Naval Engineering and 27th Pan-American Congress of Naval Engineering, Maritime Transportation and Port Engineering (COPINAVAL)*, Springer Series on Naval Architecture, Marine Engineering, Shipbuilding and Shipping 17, https://doi.org/10.1007/978-3-031-49799-5_1

Incorporating this capability on board a vessel can provide significant logistical advantages by reducing storage space and increasing operational flexibility through the on-site manufacture of spare parts or bespoke tools [3].

2 Current Challenges

The experimental installation of polymer 3D printers in US Navy vessels started in 2014 aboard the *USS Essex*, followed by the *USS Bataan* in 2016 [4]. More recently, these two Wasp-class landing helicopter dock amphibious assault ships have received permanent metal alloy additive manufacturing equipment, along with scanning and machining tools [1, 2, 4]. Similar systems have also been installed on other ships of the same class, as well as on nuclear-powered vessels such as the aircraft carriers *USS John C. Stennis* and *Eisenhower*, the submarine *USS Virginia* [4], and the French aircraft carrier *Charles de Gaulle* [3]. In this regard, numerous companies and organisations are actively developing processes associated with certification of printed parts. Similarly, the new Defence Industrial Strategy 2023, published by the Spanish Ministry of Defence [5], includes this additive manufacturing capability in the naval field, and different evaluation tests have been carried out by the Spanish Navy (Armada).

The on-board use of these systems presents distinct challenges related to the movement of the ship, power requirements for the machinery (which are already available in the aforementioned large vessels), humidity and salinity conditions, and the distribution of large parts from the additive manufacturing points to the required locations.

It is therefore necessary to implement controlled environments in order to regulate salinity and humidity; to incorporate access galleries and spaces in the design of certain vessel types in order to ensure the smooth transportation of manufactured parts both inside and outside the vessel; and to provide sufficient storage capacity for the required materials.

At the same time, the sensitivity of 3D printing systems to vessel motion can significantly impact the quality and strength of the manufactured parts. Solutions are thus required in order to, as far as possible, dampen such movements and rotations during the additive manufacturing process, increasing the range of sea conditions in which effectiveness is maintained.

3 Stability Inside the Vessel

The centre of gravity (which, in a vessel, coincides with the centre of mass [6]), is initially calculated in the design phase, in order to ensure its stability by analysing the metacentric height [7] in conjunction with the centre of buoyancy, and in order to allow the hull's longitudinal trim.

While there may be slight changes in its position due to load distribution during vessel operation, the centre of gravity remains the point of least movement and maximum stability on board, with the displacement amplitudes caused by rotation (roll, pitch and yaw) being referenced according to the distances to this centre of mass [8].

4 Location and Access to Additive Manufacturing Systems

As mentioned above, in addition to the location of the additive manufacturing process at the vessel's point of maximum stability, it is necessary to incorporate access passages that allow adequate transport of the parts produced.

In this context, the centre of gravity's potential positions (depending on load distribution) constitute a volume located in the central part of the craft. This area often has limited access in many ships (such as corvettes, frigates, destroyers and civilian passenger vessels), making it impractical to transport large parts from this location to other areas within or outside the ship.

It should also be noted that the operational flexibility provided by on-board additive manufacturing is multiplied by the possibility of transporting the manufactured parts to other units of the same task group. As a result, it is foreseeable that the latest generation of vessels with this equipment will be able to play a joint role alongside previous generations (without such capability) in developing a mission. It is therefore considered advisable to ease transport to the outer decks and sides of the ship, in addition to facilitating access to those interior locations where temporary or permanent parts may be necessary (e.g., the engine room) (see Fig. 1) [9].

As shown in the diagram above, both horizontal (galleries) and vertical (elevators) access passages are incorporated for easier distribution of parts to the engine room, the aft deck, the flight deck (in this case located at the bow) and the side hatches for transfer to other ships, while also allowing the transport of materials in reverse direction to the storeroom and the additive manufacturing room. Compartmentalisation and security requirements must also be taken into account through the incorporation of bulkheads [10–12], which will depend on the civil or military nature of the vessel and its type of classification.

Longitudinal bulkheads can generally be used in the passageways, while transverse bulkheads can be employed in the vertical galleries, integrating watertight doors for personnel and larger doors for parts. These new access spaces can also replace other existing galleries in order to optimise interior distribution.

The feasibility of implementing such a design will vary depending on the type of vessel and on the typical use of the space around the centre of mass. Moreover, the larger the total volume of the hull, the less significant the relative impact of the location of these spaces in the central area in relation to overall ship design. Similarly, the system will be more effective in vessels with greater displacement, given their higher degree of stability.

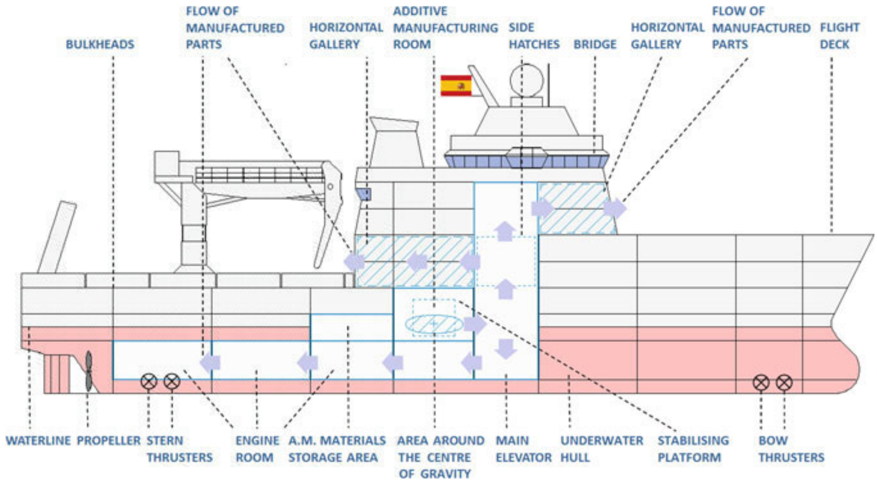

Fig. 1 Schematic diagram showing a possible design, by way of example, in an underwater intervention vessel, indicating the transport flow of the parts

At the same time, it is foreseeable that additive manufacturing equipment will need to be upgraded or replaced with newer systems or equipments with greater capabilities during the life cycle of a vessel. These access spaces can therefore allow the 3D printing machinery to be upgraded, or, if necessary, be replaced with other equipment that can benefit from installation in this area of greater stability of the ship, such as operating rooms, intensive care units, or certain scientific devices that are particularly sensitive to movement.

Similarly, the reserve space around the centre of mass enables the use of stabilisation platforms with pendular elements and shock absorbers, which can also be used for the medical or scientific applications mentioned above. It is also advisable to incorporate systems that allow a slight displacement of the stabiliser platforms along the longitudinal and vertical axes, in order to be able to relocate the systems in the event of a change in the centre of gravity due to the loads.

5 Conclusions

The ability to use additive manufacturing on board a vessel to produce robust, large parts in materials commonly used in the shipbuilding industry offers significant advantages in terms of utility, improving both logistics and operational flexibility, thus indicating the potential for this equipment to become standard.

The machinery used in 3D printing is extraordinarily sensitive to movement, and the quality and strength of the parts depends on achieving sufficient stability conditions during this process.

The reserve space around the vessel's point of greatest stability (centre of mass), combined with the incorporation of damping systems, can extend the range of sea conditions in which additive manufacturing is feasible.

The incorporation of interior access galleries (e.g., to the engine room), as well as access spaces to the outer decks and sides of the vessel, can allow the transport of large parts to where they may be needed, including to other vessels taking part in the mission.

In summary, these design proposals are aimed at facilitating the integration of additive manufacturing capabilities on board, which provide relevant logistical and operational advantages.

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An Introduction to Retro Bulb Concept

Sergio A. Benavides Kroff

Abstract The idea for the Retro Bulb concept presented on this paper it's originated from a linear approximation to obtain the roll motion damping coefficients from the decay test of high block coefficient vessels with bilge keels using Keulegan-Carpenter number (KC). Hence, from this analysis it is possible to understand that, the damping that's rules the roll motion of high block coefficient vessels with appendages its more effective at lower oscillations amplitudes (roll decay test latest cycles), its mean at lower KC numbers (KC<) were the laminar flow regime is predominant and the GM_T has a linear variation in the stability curve, which however didn't occur for larger oscillation amplitudes (roll decay test initial cycles) were highest KC numbers (KC>) are relevant and therefore the appendages effectiveness such as bilge keels are neglected as results of the turbulence derived from the back and forth oscillating flow, being the main source for the energy dissipation the hull geometry. Therefore, taking into account this factors, from the Submerge Trimaran (STR) hull concept which proposes a modification to the submerge hull geometry by considering the flow produced by the roll motion (oscillatory flux measure by KC numbers) like a free surface effect to be contained by making a draft variation at the same displacement, in order to generate a potential damping increment (energy dissipation) to reduce the angle of list (roll motion amplitudes) and from which the Retro Bulb concept arise by doing a geometrical projection from a conventional vessel bulbous bow to the STR hull extended draft to obtain an additional mass increment into the systrem to reduce the angle of list (roll motion amplitudes) within the stability curve in which GM_T varies linearly for a broad range of sea estate which allow navigate ocean routes more efficiently with energy savings and decarbonization.

Keywords Retro bulb (RTB) · Keulegan-Carpenter number (KC) · Roll motion control

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1 Introduction

The NTLS system concept (NTLS) as presented on the Introduction paper, it's a roll motion stabilizer mainly conceive for floating systems for offshore applications with not intent to sail like FPSO's, that act by increasing the hull resistance to oscillate by projecting a virtual draft from a light structure device with positive buoyancy acting like an additional mass modulator stabilizer, which also can be understood in comparison with the mechanical vibration principle of a dual mass spring system dynamic absorber used in tall buildings to absorb the vibrations of a large mass structure (hull), by adding on top a smallest mass that vibrates with the building (NTLS), being the effect of the energy transference back and forth process (additional fluid inertia that oppose to the oscillation motion) the reduction of the main structure (hull) vibration and therefore expanding a floating system margin of safely operation scenarios by reducing the angles of list (roll periodicity variation) contained within the envelope of the stability curve in which GM_TNTLS vary linearly for a broad range of sea estate as more external input energy its required to achieve the same angle of list (roll amplitude) that would be obtained with a bare hull. Therefore, taking into account this factors, from the Submerge Trimaran Hull concept (STR) which proposes a modification to the submerge hull geometry, by considering the flow produced by the roll motion (oscillatory flux measure by KC numbers) like a free surface effect to be contained by making a draft variation at the same displacement, in order to generate a potential damping increment (energy dissipation) the Retro Bulb (RTB) concept arise by doing a geometrical projection from a conventional vessel bulbous bow to the STR hull extended draft to obtain an additional mass increment to reduce the angle of list (roll motion amplitudes) within the stability curve in which GM_T varies linearly for a broad range of sea states which allow navigate ocean routes more efficiently with energy savings and decarbonization..

2 Retro Bulb and STR Hull Roll Motion

As previously explained, the NTLS additional mass effect with the STR hull it's substituting by a potential damping increment, hence from the STR hull development stages an additional variation that's could be obtained from the NTLS principia to insert an additional mass increment into the STR hull system,is by doing a modification from the VLCC [1], bulbous bow projected into the STR hull extended draft like an NTLS device at the bow from which its obtained an additional mass contribution into the STR hull system by adding a vertical projection at the bow to obtain an additional mass gain. Hence, from a STR hull obtained from a VLCC [1] (length 273 (m), length.pp 260 (m), breath 44.500 (m), depth 22.840, full load draught 16,180 (m) STR 17.68(m)), presented at the STR hull concept introduction paper, the bulbous bow modification is madr by extending the bulbous bow curvature (plane xz) with a vertical projected back ward interpolation to the STR hull draft, which form a convex vertical keel underneath the bow area named NTLS Retro Bulb (RTB) being this modification applied for the STR model with a vertical projection length of 2.5(m), inner length of 55 (m) and 19(m) width (Fig. 1).

Hence for comparison purposes the RTB modification is applied for both models STR and VLCC hull´s with a vertical projection length of 2.5 (m) STR (Fig. 2a) and 4 (m) VLCC (Fig. 2b), with an inner length both of 55 (m) and a max. width of 19 (m) as its desplayed on the following Fig. 2: Therefore, as a way to gain an understanding to the Retro Bulb concept let's start with VLCC STR hull modification and the relation with the VLCC vessel transversal stability parameters values and their influence on the roll amplitudes, and by considering that this modification didn´t cause a transversal stability variation, that for instance could be made by a symmetrical weight shifts to the ship's center of gravity or away from it without any appreciable variation in the gyration radius and whereas a very little variation can be made in the gyration radius without markedly varying the metacentric height, then let's consider the following assumptions having in mind the naval architectural formulations for transversal stability [4], hence as long the geometrical hull modification don't affect significantly the KB the Inclining arm GZ in the general expression of the restoring moment Mr = Δ GZ will not induce any significant variation and also as GZ = BM sin θ–GB sin θ (GZ = stability of form—stability of weight) expression modulated by the GB variation, as long ΔSTR ≅ ΔHull, BM it could be consider invariant as BM.STR = (Inertia.WL div ∇ STR) ≅ (Inertia.WL div ∇ Hull), therefore GZ.STR for small inclinations angle of list (sin θ ≅ θ) its assumed to be equal to GM_T.STRθ then Mr.STR = Δ.STR GM_T.STR. Hence, as the hull geometry vary with the draught increment, the bottom tanks compartment also will increase vertically and consequently the cargo area and by doing that, KG is expected to vary proportionally with KB at the same ratio as function of the expected structural re-arrangement, therefore also it could be assumed that GB.STR ≅ GB.Hull hence GZ.STR ≅ GZ.Hull which also is valid for GM_T = BM + (KB–KG) hence GM_T.STR ≅ GM_T.Hull, it's mean the STR restoring moment is Mr.STR ≅ Mr.Hull being the hydrodynamic roll potential damping increase by the hull draft shape variation B44.STR > B44.Hull although A44.Hull > A44.STR, which however, with the Retro Bulb modification (RTB) there is an additional mass contribution to the system

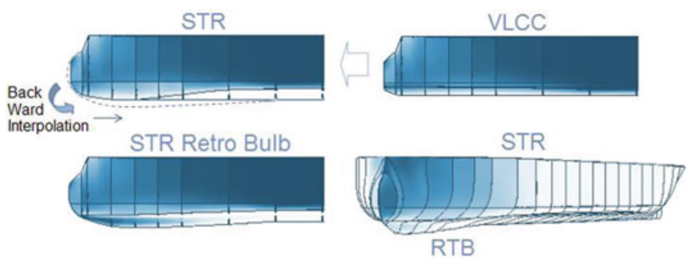


Fig. 1 STR hull modify with retro bulb

A44.STR.RTB > A44.Hull, and the same assumption it could be made, if it's considered a similar VLCC modification (RTB) A44.Hull.RTB > A44.Hull, therefore the STR hull modification with RTB could be consider in similarity with an implicit dynamical absorber that increase the vessel resistance to oscillate by varying the hull geometry by increasing the vessel energy dissipation plus an additional mass contribution from the Retro Bulb to induce an angle of list reduction as more external energy input its require to obtain the same original VLCC hull roll amplitude and therefore obtaining a gain on the transversal stability response within the stability curve in which GM_T.STR RTB varies linearly for a broad range of sea estate and consequently shifting the vessel roll natural period (e.g. pendulum with additional air resistance by varying the mass shape from a channel hull to a convex hull shape that generates additional vortex shedding or in this case potential damping plus an additional mass contribution from the Retro Bulb like an NTLS device, Fig. 3).

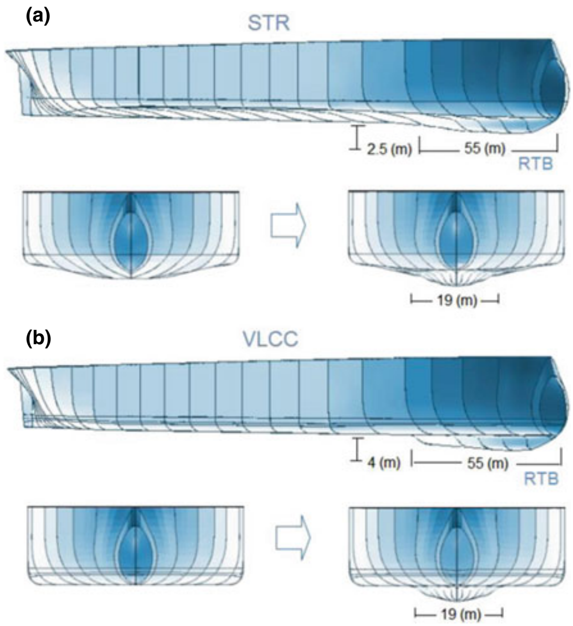


Fig. 2 STR hull (**a**) and VLCC hull (**b**) retro bulb modification

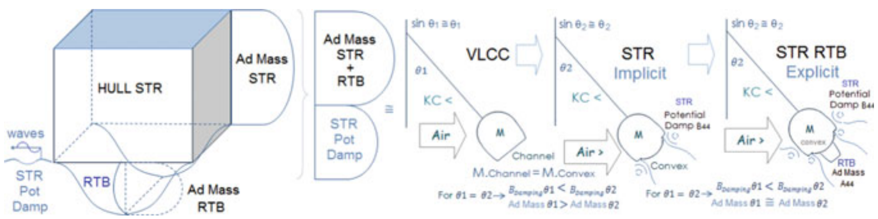


Fig. 3 STR Hull with RTB concept harmonic oscillator pendulum system comparison

Therefore, in order to quantify these effects in a simple mathematical modeling, from 1 degree of freedom uniform oscillating system under the linear assumption of uncoupled motions, the canonical equation that's represents the roll for a vessel floating in calm waters with stable equilibrium without resistance to the oscillation could be define as [1]:

$$I_{Total}(\omega)\frac{d\theta^2}{dt^2} + B_{Damping}\frac{d\theta}{dt} + C_{Restoring}\theta = 0 \tag{1}$$

Were θ, $\frac{d\theta}{dt}$, $\frac{d\theta^2}{dt^2}$ are roll angle, velocity, and acceleration associated with an external frequency of roll excitation were ω: is the oscillation responses in frequency and the index 44 indicate the transversal hull reaction (4) due to roll (4), being the total oscillation Inertia $I_{Total}(\omega)$ the sum of the free body vessel inertia I_{44} and $I_{44}(\omega) = A(\omega)_{44}$ hydrodynamic Inertia (additional mass)

$$I_{Total}(\omega) = I_{44} + A(\omega)_{44} \tag{2}$$

Interaction fluid hull damping coefficient (wave making)

$$\mathrm{B_{Damping}} = \mathrm{B_{44}}(\omega) \tag{3}$$

Restoring moment coefficient (hydrostatic restoring)

$$\mathrm{C_{Restoring}} = \rho\nabla \mathrm{g\ GM_T} = \mathrm{K} = \mathrm{C_{44}} \tag{4}$$

Re-arrangement the roll motion equation:

$$(I_{44} + A(\omega)_{44})\frac{d\theta^2}{dt^2} + B_{44}(\omega)\frac{d\theta}{dt} + \rho\nabla g GM_{T\theta} = 0 \tag{5}$$

For a linear oscillation motion GZ is assumed to be equal to $\mathrm{GM_T}\theta$ ($\sin\theta \cong \theta$) C44

$$C(\theta) = \Delta\mathrm{GZ} \tag{6}$$

$$\mathrm{GZ}(\theta) = \mathrm{GM_T}\theta \tag{7}$$

From [1, 2] the restoring moment coefficient on ballast condition (70%) could be considered linear until 20° and 30° for full load condition (100%), hence:

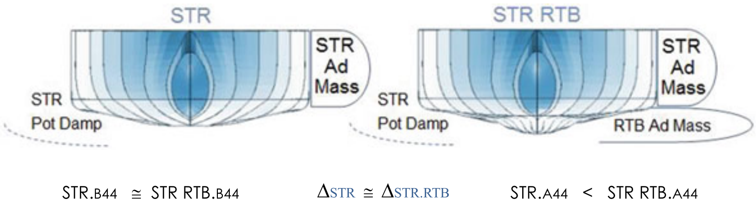
$$I_{44}(\omega) \cong I_{44} = Constant \tag{8}$$

Were the natural roll frequency:

$$Roll.\omega_{n_4} = \sqrt{\frac{\rho \nabla g \mathrm{GM_T}}{I_{44} + A_{44}}} \left(\sqrt{\frac{Static}{Inertia}} = Resonance \right) \tag{9}$$

Hence, the natural roll period:

$$Roll.T_{n_4} = \frac{2\pi}{\sqrt{\frac{\rho \nabla g \mathrm{GM_T}}{I_{44}+A_{44}}}} \tag{10}$$



STR

$$Roll.T_{n_{4STR\_RB}} = \frac{2\pi}{\sqrt{\frac{\rho \nabla g GM_{STRRTB}}{I_{44}+A_{44STR}+A_{44RTB}}}} > Roll.T_{n_{4STR}} = \frac{2\pi}{\sqrt{\frac{\rho \nabla g GM_{STR}}{I_{44}+A_{44STR}}}} \tag{11a}$$

VLCC

$$Roll.T_{n_{4Hull\_RB}} = \frac{2\pi}{\sqrt{\frac{\rho \nabla g GM_{HullRTB}}{I_{44}+A_{44Hull}+A_{44RTB}}}} > Roll.T_{n_{4Hull}} = \frac{2\pi}{\sqrt{\frac{\rho \nabla g GM_{Hull}}{I_{44}+A_{44Hull}}}} \tag{11b}$$

Therefore, the expression (11a) and (11b) represent the roll natural period variation for both STR and VLCC modify with the NTLS Retro Bulb (RTB) concept (Note: for edition simplification purpose $\mathrm{GM_T}$ it's considered to be GM).

3 Retro Bulb Application Examples

The Retro Bulb (RTB) concept natural roll period shift effect, can be appreciated from the RAO's roll plot obtained from the potential theory implemented on the program Scores [5], with the STR hull obtained from a VLCC modification [1–3] with a displacement 151,880.400 (m^3) (VLCC model 152,227 (m^3), STR model 155,242 (m^3) 2% variation) length 273 (m), length.pp 260 (m), breath 44.500 (m), depth 22.840 floating with a draught of 16,180 (m), Rxx_1 14.600 (m), $\mathrm{GM_T}$ 5.392

(m), CG 12.62 (m) and KB 8,347 (m) STR KB 8.147 (m), from the hull base, in comparison with the STR Retro Bulb (RTB) as presented on Fig. 2 a and the VLCC also modify with Retro Bulb (Fig. 2b) and with an additional set of hull's models with the NTLS FLIP SAIL (FPSL) presented on the NTLS introduction paper (Fig. 5), from which the roll RAO's are plot in the graph on the flowing Fig. 6 , being the results summarized on Table 1 as follow:

Therefore, from the roll motion RAO response for beam seas it's possible to determinate that, the roll natural period variation among the VLCC hull (13.7 (sec)) and the VLCC Retro Bulb (13.88(sec)) is 0.18 (sec) and the STR hull (13.9 (sec)) and the STR Retro Bulb (13.95 (sec)) is 0.05 (sec) which also is 0.25 (sec) shift from

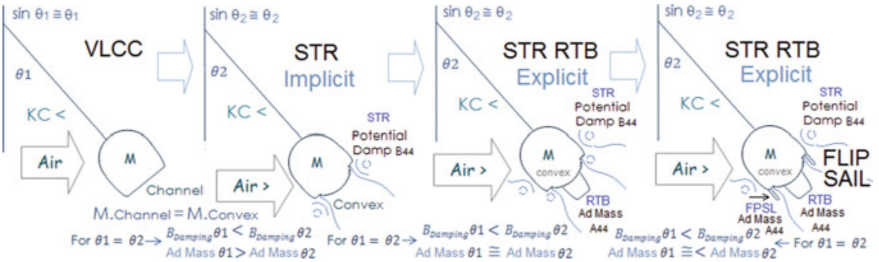


Fig. 4 VLCC, STR, STR RTB, STR RTB flip sail concepts harmonic oscillator pendulum system comparison

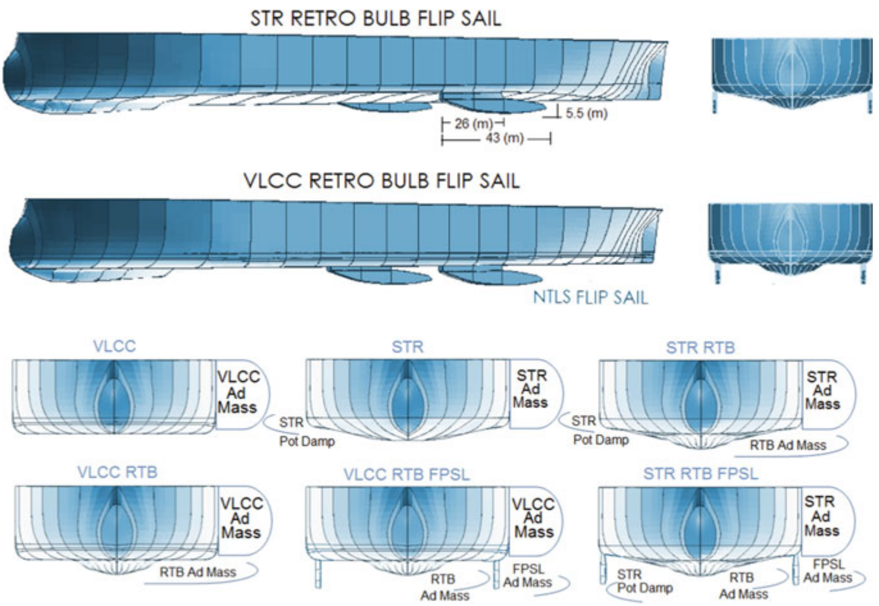


Fig. 5 VLCC and STR hull's with retro bulb and NTLS flip sail

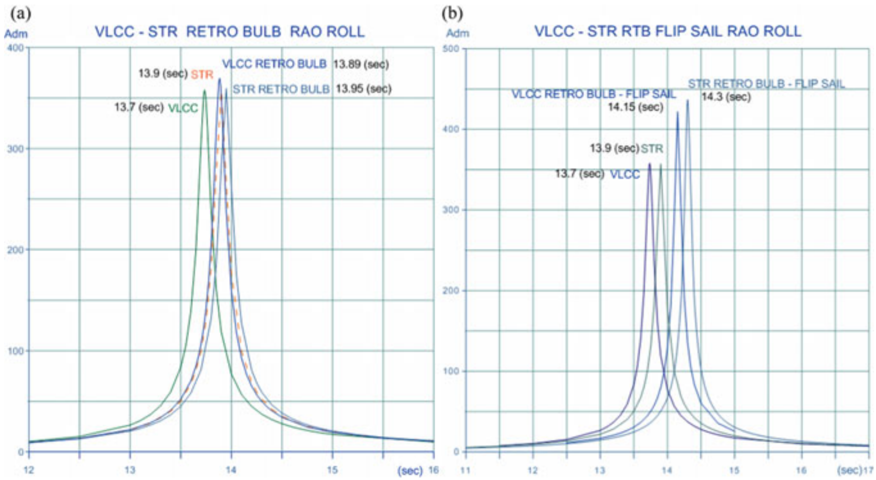


Fig. 6 **a** VLCC and STR hull's RTB RAO roll; **b** VLCC and STR hull's RTB Flip Sail RAO Roll

Table 1 .

Vessel model	GM_T(m)	KB (m)	Adm. A44 × ·10^7	T_P(sec)
VLCC	5.392	8.347	67.188	13.7
STR	5.034	8.152	49.19	13.9
VLCC RTB	5.256	8.29	66.548	13.88
STR RTB	4.998	8.133	49.42	13.95
VLCC RTB FPSL	5.211	8.26	80.571	14.15
STR RTB FPSL	4.956	8.11	67.166	14.3

the VLCC Tp. Furthermore, the STR hull modify with the Retro Bulb and NTLS Flip Sail have a natural roll period of 14.3 (sec) which mean produce a shift of 0.6 (sec) from the VLCC bare hull Tp and 0.4 (sec) shift, from the bare STR hull Tp. Also, is important comment that the VLCC hull with the same modifications (RTB and FLPS) have a natural roll period of 14.15 (sec) meaning a shift of 0.45 (sec) from the bare VLCC hull that match the STR hull model (13.9 (sec)) as the hull model VLCC Retro Bulb with a roll natural period of 13.88 (sec) (Table 1). Likewise, the motions that are directly affected with the NTLS implementation are those that have a restoring response from the hull displacement volume (roll, heave and pitch), hence, in order to obtain a broad perspective of the Retro Bulb concept potential application, an evaluation on heave and pitch motion were made for the models STR and VLCC modify with Retro Bulb and Flip Sail considering a RYY_1 approx. 65.75 (m), from which the heave and pitch RAO´s result are plot in the flowing plots Fig. 7(a) heave and Fig. 7(b) pitch: $_1$

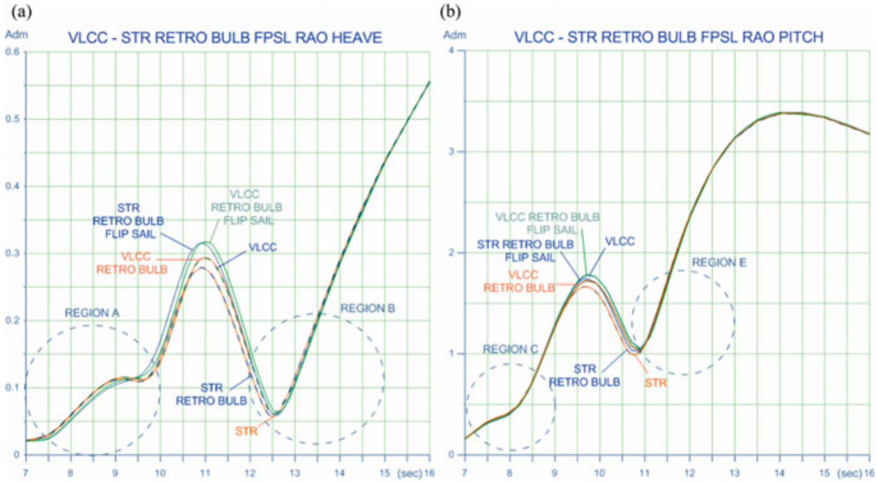


Fig. 7 VLCC and STR hull's with RTB and NTLS Flip Sail RAO's Heave (**a**) and Pitch (**b**) graphs

4 Summary

T The origin of the Retro Bulb (RTB) concept presented through these pages is an extension of the Nautilus System stabilizer concept (NTLS) which began to be developed early in 2020 from a Calm Buoy concept developed on 2010 base on [1] which is a proposal for a roll motion control and directional stabilizers with a structure design conceived with neutral or positive buoyancy that could easily be attached to the hull with a minimal maintenance and with the hydrodynamics geometry properties required to generate an additional mass with the aim to enhance floating systems such as FPSO transversal stability and directional stabilization, being the starting point to pursuit the RTB development to obtain a practical NTLS application with focus on conventional vessels to improve the sea keeping capability by doing a bulbous bow geometrical modification in order to contribuite from an additional mass increment to reduce the angle of list (roll motion amplitudes) within the stability curve in which GM_T varies linearly for a broad range of sea estate. Hence, the Retro Bulb concept presented on this publication is obtained from a STR hull derived from a VLCC hull from [1–3] with a displacement volume variation of 2% for a full load draught (Fig. 8), being this modification applied for both models VLCC and STR hull´s with a vertical projection length of 2.5 (m) STR and 4 (m) VLCC, with an inner length both of 55 (m) and a max. width of 19 (m) as its show on Figs. 2a and 2b, to be evaluated through the potential theory analysis using the program Scores [6] with the aim to obtain an understanding of the Retro Bulb effect considering a CG fix at 12.62 (m) from the VLCC hull base and with an additional set of hull´s models with FLIP SAIL (FPSL) state of the art presented on the NTLS introduction paper (Fig. 5) for a 90° beam seas and for heading seas (180°) heave and pitch motions. 1–3 6

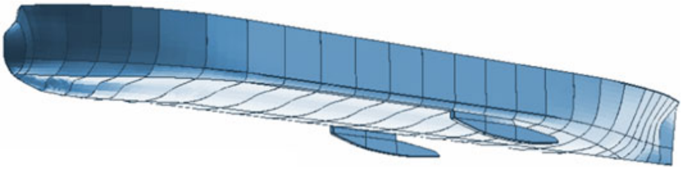


Fig. 8 STR retro bulb hull with NTLS flip sail concept

Therefore, from the roll motion RAO response analysis for beam seas it's possible to determinate that, the roll natural period variation (Fig. 6a) among the VLCC hull (13.7 (sec)) and the VLCC Retro Bulb (13.88(sec)) is 0.18 (sec) and among the STR hull (13.9 (sec)) and the STR Retro Bulb (13.95 (sec)) is 0.05 (sec) which also is 0.25 (sec) shift from the VLCC Tp (Table 1). Furthermore, the STR hull modify with the Retro Bulb and NTLS Flip Sail have a natural roll period of 14.3 (sec) (Fig. 6b) which mean a shift of 0.6 (sec) from the VLCC bare hull Tp and 0.4 (sec) shift from the bare STR hull Tp (Table 1). Also, is important to comment that the VLCC hull with the same modifications (RTB and FLPS) have a natural roll period of 14.15 (sec) meaning a shift of 0.45 (sec) from the bare VLCC hull that overcome the STR hull model (Table 1), as for instance the model VLCC Retro Bulb have a roll natural period of 13.88 (sec) that match the STR hull Tp (13.9 (sec)) as product mainly derived from the Retro Bulb vertical projection in a hull section (center line) with lower breath (bow) that increase the hull additional mass (Table 1) emulating the STR hull potential damping effect response, its mean a conventional vessel could be modify with a Retro Bulb to enhance the transversal stability, being the results of the combination VLCC RTB with the NTLS Flip Sail (additional mass modulator) (Table 1) a roll natural period of 14.15 (sec) which is 0.45 (sec) shift from the VLCC Tp (13.7 (sec)) and 0.6 (sec) shift from the STR RTB with the NTLS Flip Sail Tp (14.3 (sec)), (Table 1). Moreover, the VLCC models with Retro Bulb and Flip Sail have a significant roll motion shift response variation from the original VLCC hull as the STR hull with the same modifications, the results obtained for the response amplitudes operators (RAO) for heave and pitch motions (Fig. 7) the STR and STR RTB hull's models had the lowest amplitudes response on the interval of wave periods between 10.4 (sec) and 12.5 (sec) for heave (Fig. 7a) and the interval between 9.3 (sec) and 10.9 (sec) for pitch (Fig. 7b), mainly function of the wave irradiation capability of the STR hull and the STR hull with Retro Bulb, that have a closer roll natural period among them (13.9 (sec) to 13.95 (sec)) its mean, both generate more energy dissipation (potential damping) than the others models on these periods interval, being the response amplitude variation in heave (Fig. 7a) for the STR RTB Flip Sail with lowest amplitude response on the interval between 7 (sec) and 9.25 (sec) (Region A) and on the interval between 12.6 (sec) and 15.0 (sec) (Region B) in which also the hull model VLCC RTB Flip Sail had a lower amplitude response in similarity for the pitch response (Fig. 7b) (Region C) and on the interval between 11 (sec) and 12.5 (sec) (Region E), based on the oscillating flux equilibrium originated from the interaction among the RTB and the FPSL device that reduce the heave and pitch response on those intervals in comparison with the VLCC and STR hull's. Additionally, although the VLCC models Retro Bulb and the Retro Bulb Flip Sail had a considerable natural roll period shift response than the bare VLCC hull, the response amplitude variation in heave and pitch (Fig. 7) for the hull's models with NTLS Flip Sail is greater, base on the oscillating flux originated from the interaction among the hull and the NTLS device, being the response variation among all those hull's models mainly product of the hull form factor, its mean the bare STR hull and the STR Retro Bulb hull in terms of the response magnitude, has been improve the VLCC hull in heave (int. 9.4 (sec) and 12.5 (sec)), pitch (int. 8.25 and 11.0 (sec)) with a gain on the transversal stability from a natural roll period shift of 0.2 (sec) and 0.5 (sec) each, being all hull's models response for large wave periods (evanescent) becoming similar, product of the increasing relation among the potential damping and additional mass effects.

5 Conclusion

Furthermore, the Nautilus System (NTLS) concept (stabilizers for motions and currents) is based on the idea to use a passive and easily constructed device to reduce floating system roll motion amplitude and at the same time enhance the directional stabilization capability to align with the main environmental actions, which among others factors minimize mooring and risers tension, expanding the safety operation margin scenarios within a broader range of sea states that will allow the development of innovative, reliable and economic solutions for ultra-deep-water regions and environmentally sensitive areas and with the potential to be applied on conventional vessels as additional research studies could determinate the best STR hull to obtain an optimal combination of roll, heave and pitch motions to achieve a service velocity and maneuver capability in function of the vessel application as the structural and hydrodynamic impact of the NTLS Retro Bulb (RTB) and NTLS FLIP SAIL (FPSL) concepts (e.g. the relation among and the NTLS FPSL dimension with the roll motion reduction and the vessel dynamics for different load conditions)to be implemented on new or converted hull (Fig. 8) to cross ocean routes efficiently with energy savings and decarbonization (e.g. longitudinal structural strength improvements, reduction in the parametric roll and LNG vessels sloshing probabilities occurrences) and therefore, by considering all these factors that are part of the NTLS System potential applications like the STR hull, Retro Bulb (RTB) and FLIP SAIL (FPSL) , new fields of research and development it could open for classification societies, companies and academic institutions.