ПРОЕКТИРОВАНИЕ И КОНСТРУКЦИЯ СУДОВ

DOI: 10.24937/2542-2324-2022-2-400-67-78
УДК 629.5.017:623.8

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COMPARATIVE RESISTANCE & SEAKEEPING ANALYSES OF WARSHIP DISPLACEMENT MONOHULLS, WHEN MODIFIED TO INVERTED BOW FORMS FROM CONVENTIONAL BOW

The paper primarily includes comparative performance analyses (i.e. changes/improvements in Resistance & Seakeeping characteristics) of a warship monohull (with a conventional bow), operating in displacement mode, when modified to various inverted bow forms. The work presented in the paper has been inspired by various research works already published worldwide and available literature regarding the same.

For the research problem, a naval warship hull with conventional bow was taken as the benchmark and was suitably modified to a number of different hull form variants with inverted bow forms (i.e. Axe bow, Uistein X-bow, Sword bow and typical Inverted Bow forms), preserving sufficient characteristics for a meaningful comparison, yet making enough changes in various hull form parameters to obtain sufficient variations in hydrodynamic characteristics. Based on the analyses, it was possible to undertake multistage screening of the hull variants, as well as to obtain a considerable overview which enabled to make definitive comments regarding the research questions formulated.

The author declares no conflicts of interest.

SHIP DESIGN AND STRUCTURE

DOI: 10.24937/2542-2324-2022-2-400-67-78
UDC 629.5.017:623.8

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ СОПРОТИВЛЕНИЯ И МОРЕХОДНЫХ КАЧЕСТВ ВОДОИЗМЕЩАЮЩИХ ОДНОКОРПУСНЫХ КОРАБЛЕЙ ПРИ ИЗМЕНЕНИИ НОСОВОЙ ОКОНЕЧНОСТИ С ТРАДИЦИОННОЙ НА ИНВЕРТИРОВАННУЮ

Статья содержит сопоставительный анализ изменения/улучшения характеристик сопротивления и мореходности однокорпусного водоизмещающего военного корабля при вариации формы носовой оконечности от традиционных обводов до различной конфигурации обводов с обратным наклоном форштевня. Представленная работа инспирирована различными исследовательскими работами, уже опубликованными во всем мире, а также имеющейся литературой по данной тематике. При решении исследовательских проблем корабль с традиционными носовыми обводами был принят в качестве базового варианта, и было разработано несколько его модификаций с формированием вариантов носовых обво-

For citations: Biplabananda Talukdar. Comparative resistance & seakeeping analyses of warship displacement monohulls, when modified to inverted bow forms from conventional bow. Transactions of the Krylov State Research Centre. 2022; 2(400): 67–78 (in Russian).

Для цитирования: Биплабананда Талукдар. Сравнительный анализ сопротивления и мореходных качеств водоизмещающих однокорпусных кораблей при изменении носовой оконечности с традиционной на инвертированную. Труды Крыловского государственного научного центра. 2022; 2(400): 67–78.

дов, предусматривающих обратный наклон форштевня (в частности, топорообразный нос (Axebow), X-форма носа (Ulstain X-bow), мечевидная форма (Sword bow) и типичная форма носа с обратным наклоном форштевня). При этом сохранялись основные характеристики для корректного сравнения, хотя изменения при формировании различных обводов корпуса были достаточны для получения заметных изменений гидродинамических характеристик. Проведенный анализ позволил получить многоплановую картину для вариантов корпуса, а также сделать обобщения, которые позволяют формулировать определяющие комментарии в отношении решения исследованной проблемы.
Автор заявляет об отсутствии возможных конфликтов интересов.

Introduction

Введение

1. Several advanced Navies of the world are promoting R&D of next-generation hull forms to achieve superior operational capabilities and improved fuel efficiency, especially in higher sea-states. This is spurring interest in research and developmental works in non-traditional hull forms. The *Enlarged Ship Concept* (*ESC*) and Inverted Bow form hulls are being designed/researched upon towards achieving the same goal. The research work included in this paper was conceptualized based on available information/ published research works in open source for various non-traditional hull forms. The work presented in this paper attempted to investigate the effects of bow modification to various types of inverted bow forms by comparing their resistance and seakeeping performance vis-à-vis the baseline hull of a naval combatant ship with conventional bow by using commercial CAD and CFD tools.

Concept studies

Концептуальное исследование

2. In recent years, several studies have been published, where various types of inverted bow forms were tested and their merits/ performance characteristics are documented, which include overall effect on ship performance, safety and fuel economy. The salient bow forms which were studied for undertaking the subject research works are *Ulstein X-Bow* of Ulstein Group, Norway [9, 22, 23, 25] (characterized by a backward sloping bow that starts at the extreme front of the vessel, a sharper bow entrance, and a smoother volume distribution in the fore-ship), *Enlarged Ship Concept* (*ESC*) jointly developed by Delft University and Damen Shipyard since 1995 [1–3] (hull form of 'fast patrol crafts' lengthened by 25 % and 50 %), *Axe Bow* Concept [5, 7] developed by a collaboration between Royal Netherlands Navy, U.S. Coast Guard and the Marine Research Institute, Netherlands (MARIN) for application in fast patrol vessel (36 m) as well as in frigates (L_{OA} = 134.46 m, extended to 147.62 m in 'Axe bow' form) [6], *THALES Programme for Frigate Designs* [4] (an interdisciplinary research and innovation program co-funded by the European Union and Greece that ran from 2000–2004 based on ESC/Axe bow concepts) which published papers including results of resistance and seakeeping experiments on seven design alternatives including an *Axe-Bow* hull and a *Wave Piercing Bow* having the same deadweight and internal volume as well as meeting the Navy's intact stability requirements, the experimental investigation study conducted in the US Naval Academy Hydromechanics Laboratory (NAHL) of two ship models (one of the baseline frigate, i.e. US Navy's the Oliver Hazard Perry class frigate (FFG-7) and other is the inverted bow frigate model keeping displacement, waterline length & draft constant) [8, 9] and NSWCCD Studies regarding Flared v/s Tumblehome Hull Forms [9].

3. Additionally, information/ characteristics of several Naval ships, already designed with inverted bow forms, were also studied, which include US Navy destroyer Zumwalt (DDG-1000) [23, 24], new frigate program (FTI) [27, 28] and C-Sword 90 corvette program [29, 30] unveiled for French Navy, Axe bow form Offshore Petrol Vessels (OPV) designs of Damen Shipyard, Netherlands [31], Offshore Patrol Cutter design with Ulstein X-Bow [33]. Further, several yachts design with inverted bow [22, 32] were also studied.

Problem statement

Постановка задачи

4. The ideas regarding application of ESC and various types of Inverted Bow forms were infused in the research works presented in this paper based on the aforementioned concept studies. It could be inferred from the concept studies that changing the bow shape has the potential to influence the dynamics of wave-body interaction, thereby changing the properties of the modified hull forms in terms of resistance as well as motions in a real-time ocean environment. Accordingly, in this subject study, it was attempted to evaluate the effect of various inverted bow forms by comparing the computational results of resistance and motion characteristics of a conventional 'frigate type' hull form with modified variants of the same hull with various forms of inverted bows.

Design of inverted bow forms

Проектирование формы носа с обратным наклоном форштевня

5. The bare hull of a generic ‘Frigate Type Naval Ship’ (L_{WL} = 151.5 m, T = 4.9 m, mass displacement ≈ 6,200 tonnes) was taken as the baseline hull for this study. Based on ideas obtained from concepts studies (as elaborated above), it was decided at the preliminary stage of the project that different bow forms (i.e. typical inverted bow forms as well as other variants, viz, Sword, Axe and Ulstein X-bow forms) would be modelled and preliminary comparative analyses of their calm water-resistance as well as seakeeping performances, would be attempted. The main challenge in converting the baseline hull to the inverted bow hull variants was to preserve enough characteristics for a meaningful comparison, but also to make sufficient changes in various hull form parameters to obtain noticeable variations in hull form characteristics as well as in hydrodynamic performances. Based on the comparative analyses, the hull variants with ‘improved performances’ would be selected progressively, i.e. multi-stage screening process.

6. **CAD Software Used.** The hull modelling/ modifications were carried out using advanced CAD (i.e. Rhinoceros) as well as ‘*parametric design software*’ (*i.e. CAESES*). Baseline hull was modelled in CAD software Rhinoceros-5 and 45 m length (approx $1/3^{rd}$ length of L_{WL}) in forward region (L_{fwd}_body) was decided to be modified to facilitate smooth connection between the modified bow and the existing hull. To create hull variants parametrically, CAESES software was used. The aft portion of the baseline hull (unchanged) modelled was imported and suitably merged with the bow-form surfaces to complete the hull variants for computational analyses.

7. **Parametric Modelling in CAESES.** Separate ‘parametric designs’ were created in CAESES software for all four types of bow forms (i.e. *Axe bow, Uistein X-bow, Sword bow and typical Inverted Bow forms*) and several variants of each were created within the realms of feasible ‘*parameter variations*’ *and* ‘*constraints*’ imposed as elaborated hereafter. CAESES, a product made by Friendship Systems was found to be very suitable for variable geometry, CFD process automation and optimization of flow-exposed products. The system is already in use worldwide by many shipyards and universities for applications ranging from optimization of ship fore-bodies for wave resistance, automatic optimization of ship aft bodies for delivered power to design of energy-saving devices in self-propelled full-scale condition etc. In CAESES, the numbers characterising the variables governing the shape/ form of the model i.e. ‘*parameters feature relationships*’ can be changed to obtain new model variants (for example, changing the values defining the ‘radius’ and ‘length’ of a cylinder). Additionally, to maintain the fairness of the hull, practical limits are established

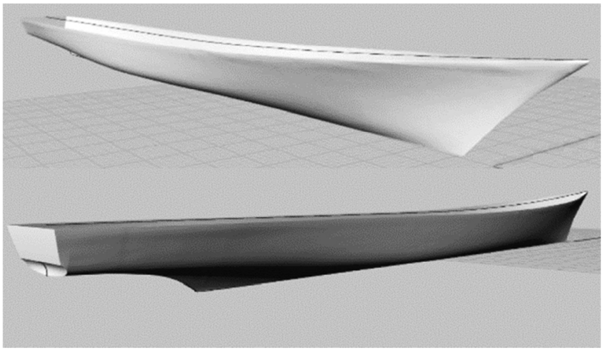

Fig. 1. Rhinoceros-5 Model of the Baseline Hull

Рис. 1. Модель базового корпуса

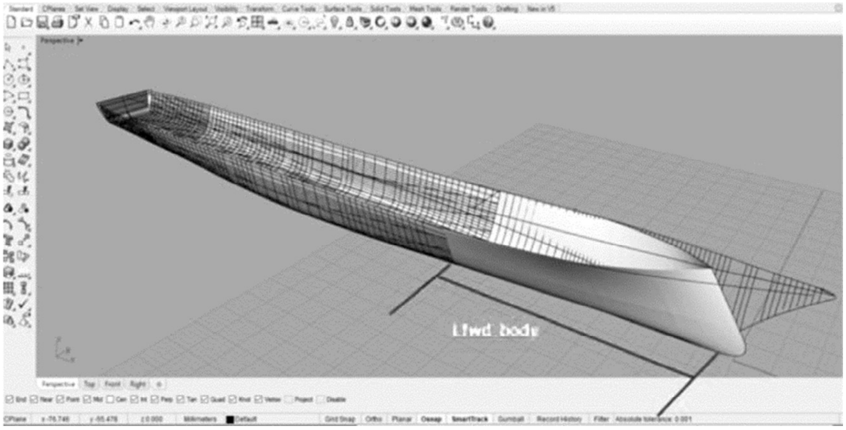

Fig. 2. Rhinoceros-5 Model showing *Lfwd_body* of Modified Hull

Рис. 2. Модель, показывающая длину носовой оконечности *Lfwd_body* модифицированного корпуса for each parameter (for example, acceptable limits for 'surface area' and 'volume' of the various cylinder models obtained). A fully parametric model developed in CAESES allows the designer to rapidly make changes to the geometry of the hull.

8. **Hull Form Parameter Varied and Constraints Imposed.** For all four types of bow forms, several variants were created in CAESES. The details of parameters varied and their range are presented in the following tables:

(*a*) **Inverted Bow Variants.** For Inverted Bow Variants, i.e. with underwater inversion of bow profile, a total of 09 parameters are varied, as indicated below. Therefore, to limit the number of variants feasible to be analysed, but to capture the whole range of the spectrum of variables, the CAESES Design Engine based on '*Sobol Algorithm*' (a quasi-random low-discrepancy sequence) was used to generate 100 nos hull variants, out of which 32 hulls were found to be in the acceptable range and form (table 1).

(*b*) **Axe Bow, X-Bow and Sword Bow Forms.** The parameters varied were the *length of the forward region and the area of the water plane in the modified region.* In total, 16 nos hull variants of each type were generated using 'Exhaustive Search Method' in CAESES where the two parameters were varied in four steps as following (table 2).

Table 1. Parameter variation ranges (09 nos) for Inverted Bow Form
Таблица 1. Диапазон изменения девяти параметров для модифицированной формы носа

Ser	Variables	Variation Range	
		Max	Min
(i)	Overall length of the bow section up to Forward Perpendicular (FP) from the junction of Aft Hull (retained from baseline hull) named as *Lfwd_body*	45 m	52 m
(ii)	Distance of the forward most point of the bow, ahead of FP, as a percentage (%) of *Lfwd_body*	2	8
(iii)	z-position of the forward most point of the bow from the baseline as a percentage (%) of *Draft* ($T = 4.9$ m)	25	70
(iv)	Tangent angle of a waterplane, defined at a z-position of the tip of the bulb, which influences the shape of the underwater hull and also affects the sectional area of the bulb at FP as well as its form/size	7.5°	15°
(v)	Distance of the forward most point of the main deck from FP, towards aft direction, as a percentage (%) of *Lfwd_body*	4	20
(vi)	Tangent angle from vertical the bow form curve makes at the intersection of point of the design waterline with FP which controls the shape of the bow profile between the main deck and design waterline	5°	90°
(vii)	Tangent angle with x-axis at the end of design waterline curve at FP which influences the shape of the waterline	10°	20°
(viii)	Area of the waterplane (defined at the z-position of the tip of the bulb) for the *Lfwd_body* region which influences the shape of the U/W hull and also affects the sectional area of the underwater bulb form at FP	100 m^2	200 m^2
(ix)	Area of design waterline curve for the *Lfwd_body* region which influences the shape of the design waterline	140 m^2	190 m^2

Table 2. Parameter variation ranges for Axe Bow, X-Bow and Sword Bow Forms
Таблица 2. Диапазон изменения параметров для вариантов Axe Bow, X-Bow and Sword Bow Forms

Ser	Variable	Variation Range	
		Min	Max
(i)	Area of design waterline curve for the *Lfwd_body* region (the portion of the WL affected by bow modification) which influences the shape of the design waterline	160 m^2	190 m^2
(ii)	Length of the forward region of the hull modified *(Lfwd_body)*	45 m	53 m

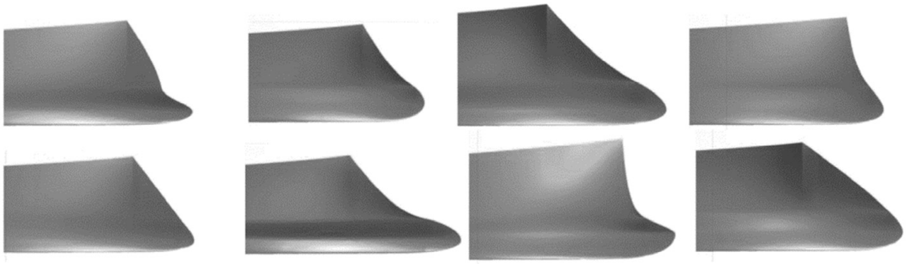

Fig. 3. Some of the salient Bow Shapes Obtained for Inverted Bow hull forms

Рис. 3. Некоторые из характерных носовых форм, полученных для вариантов обводов с обратным наклоном форштевня

(c) **Constraints.** It was important to preserve the limited computational resources and meaningfully engage them towards the finite research goals. Therefore, at the very beginning stage of the project, it was important to discard the hull variants being created by the CAESES *Design Engines* which were unlikely to meet the realistic design standards for a Naval combatants (or show significant deterioration in comparison to the parent ship) with available knowledge of basic naval architecture/ Naval ship requirements/ design constraints. Further, the hull variants, which may fall out of the '*equivalent ship definition*' (i.e. significant variations in displacement etc.) would also be discarded. *Constraints*/*limits* those were imposed on various hull form parameters are as follows:

(i) *Mass displacement range* – 6,200 ± 150 tonnes (< 2.5 %) considering comparative ship class/ equivalence. This also would affect the internal volume of the ship.
(ii) Increase of *block coefficient (forward)* of the hull ($C_{B\,fwd}$) – 0.03.
(iii) Increase of *prismatic coefficient (forward)* of the hull ($C_{P\,fwd}$) – 0.04.
(iv) Reduction of *weather deck area* – Up to 10 % of the area of that of the parent ship.
(v) Reduction of transverse metacentric height – Up to 1 m of that of the parent ship.
(vi) Due to the increase of *U*/*W* volume forward due to bow modification, there would be a tendency of LCB to shift forward. Hulls with LCB *locations* up to 1 metre aft of midship were accepted.
(vii) Increase in length of the *fore body* – 9 meter (modified hull forms should not exceed LOA of the baseline hull)

Computational methods

Расчетные методы

9. The CFD software tool used for computational analysis was FLOWTECH-SHIPFLOW DESIGN 6.4.0, which is most compatible with the parametric design

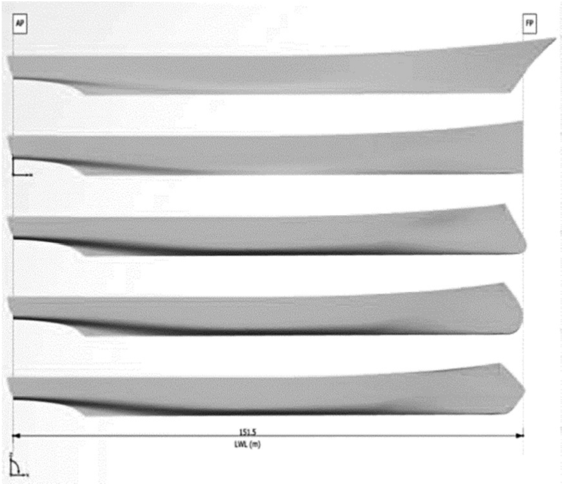

Fig. 4. Various types of hull forms modelled in CAESES with L_{WL} = 151.5 m (From top): Parent Ship Hull, Axe Bow form, Inverted Bow form, X-Bow and Sword Bow form

Рис. 4. Различные формы обводов корпуса, смоделированные с помощью программы CAESES с длиной ватерлинии L_{WL} = 151.5 м (от конечной точки): базовые обводы, формы с топорообразным носом Axe Bow, с обратным наклоном форштевня, X-образная форма (X-Bow) и мечевидная форма (Sword Bow)

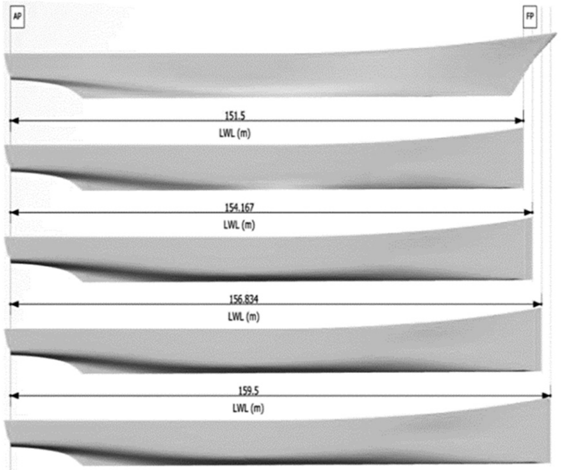

Fig. 5. 04 nos Axe Bow hull variants of different L_{WL}

Рис. 5. 4 варианта корпуса с топорообразным носом (Axe Bow) с различной длиной ватерлинии L_{WL}

software used, i.e. CAESES. The various computational modules of the SHIPFLOW which were used for undertaking computational analyses are as follows:

(a) **Preliminary Calm Water Resistance Evaluation.** The *calm water resistance* analyses of the variant hulls vis-à-vis the baseline hull were undertaken using *potential flow modules*. XPAN and XBOUD modules were used to evaluate resistance, i.e. Wave Resistance (R_W) and Frictional Resistance by thin boundary layer method (R_F) respectively, for 56 nos hull variants for the speeds 12 kn, 18 kn, 21 kn, 25 kn and 31 kn.

(b) **Seakeeping Analyses.** Total 39 nos selected hull variants were examined for the wave resistance and motion properties in higher sea states (*in head waves only*). XPDT module was used to analyse these hulls at 21 kn in SS-4 and SS-6 and at 31 kn in SS-4 for irregular sea conditions (ITTC Wave Spectrum).

(c) **Resistance Evaluation of Selected hulls by RANS method.** For further accurate estimation of the resistance performance, Viscous Resistance (R_V) component is also required to be estimated, which was not possible by potential *flow methods*. Hence, *Reynolds-Averaged Navier-Stokes* (*RANS*) method was used (by using the XCHAP module) to find the resistance values of 08 nos selected hull variants vis-à-vis the baseline hull for the speed range 10–31 kn. SHIPFLOW RANS, when run with 'double body method' can compute '*Viscous Pressure Resistance*' (R_{VP}) in addition *to Frictional Resistance* (R_F) which enabled estimation of *the Form Factor* $(1 + k)$ and thus, the '*bare hull resistance values*' could be computed more accurately.

Computational results

Результаты расчета

10. The results obtained from the computational analyses, i.e. Calm Water Resistance as well as Seakeeping (head waves), of the various hull models in SHIPFLOW software (as elaborated above) are summarized in this part of the paper.

11. **Resistance Analyses by Potential Flow Panel Method.** This use of SHIPFLOW modules XPAN and XBOUD enabled to make optimum use of computational capability/ time to undertake first stage of comparative analysis for variant hull forms, i.e. comparison of *Calm Water* Resistance performance (i.e. the sum of $R_W + R_F = R_t$), and to screen-in suitable hull forms for Motion Studies. It was observed that Wave Resistance (R_W) is the dominating component influencing the total resistance (R_t) of the hull variants. During the screening of the hull variants, more preferences were given to the performance of hulls for 21–31 kn, i.e. likely to have more effect on '*installed power onboard*' as well as '*fuel consumption*' (will effect endurance and operational cost). Additionally, the following observations were made from the computational results obtained for various hull form variants:

(*a*) **Sword and X-Bow Forms.** An increase in Frictional Resistance (R_F) has been observed for all hull forms and a direct relation between *increase in Frictional resistance and the length* of the hull, as expected, could be observed. However, the increase in RF was limited to a very small extent, i.e. for the longest hull ($L_{WL} = 159.5$ m) for max speed (31 kn), the increase in R_F was found to be < 3 %. Further, the increase in *Wave Resistance* (R_W) was observed for lower speed (12 kn), i.e. up to about 20 % for X-Bow and up to about 11 % for Sword Bow in comparison to the baseline hull. However, reduction of R_W, in general, was observed above 21 kn for both the hull forms, i.e. up to approx –18 % for both 21 & 31 kn for different hulls of X-bow form and up to approx –21.5 % for 21 kn and –16 % for 31 kn for Sword-bow form hulls. The gain on a cumulative basis, i.e. maximum reduction of Rt $(= R_W + R_F)$ was found to be up to –8 % at 31 knots.

(*b*) **Inverted Bow Form.** Wide variations in the trend of resistance components were observed for different *Inverted Bow Form hulls*, due to the *random combination of multiple hull form parameters* (*Sobol Algorithm*) and *the presence of the* '*bulb*' feature in the bow. Max reduction of total resistance (Rt) was found to be up to –6.8 % at 31 kn and –5.13 % at 21 kn. However, Frictional Resistance (R_F) was observed to be increasing for all speeds (i.e. 3.3 % at 31 kn, 3.8 % at 21 kn and 4.33 % at 12 kn). An increase in *Wave Resistance* (R_W) was observed for lower speed i.e. 12 kn; however, reduction in Wave Resistance (R_W) in general observed above 21 kn. The maximum increase in Wave resistance observed for 12 kn was up to approx 41.8 %, where for the same hull, at 31 kn, R_W reduction observed was –8.1 %. The maximum decrease in R_W observed was up to approx –15 %, for 31 kn, where for the same hull, at 12 kn, the increase in R_W observed was 35.4 % in comparison to the baseline hull.

(*c*) **Axe Bow Form.** A direct relation, as expected, between increases in *Frictional Resistance* (R_F) and *increase in hull length* (i.e. corresponding increase in Wetted Surface Area) could be observed for this type of hull variants. However, the increase in Frictional Resistance (R_F) even for the longest hull ($L_{WL} = 159.5$ m) for max speed (31 kn) has been found to be 3.05 % in comparison to the baseline hull. Additionally, the maximum reduction of *total resistance* (R_t) was found to be up to –6.024 %. Increase in Wave Resistance (R_W) observed for lower speed (12 kn) was up to 12.3 %. However, reduction of Wave Resistance (R_W) in general was observed above 21 kn, i.e. up to approx –22.7 % for both 21 kn and up to approx –13.75 % for 31 kn.

12. **Seakeeping Analyses.** Analyses were carried out for selected variants for each hull forms with different bow types for min three different lengths ($L_{WL} = 151.5$ m to 159.5 m) and creating further hull variants with a variation of the *degree of bow inversion* (above deign waterline) from 5–15 % (i.e. the ratio of the distance of the forward point *of the weather deck from FP to* L_{fwd}_body), as shown in Fig. 6. *Wave Resistance* values were averaged over the time domain and motion response values were obtained in ‘time domain’. Following interpretations could be derived out of the computational results:

(*a*) **Wave Resistance.** It has been observed that it was possible to obtain a significant reduction in *Wave Resistance* values for hull variants in higher sea states by increasing the length of hull variants, as indicated below for variants with $L_{WL} = 159.5$ m:

- Up to –15.187% at 21 kn/SS-4, –11.84 % at 31 kn/SS-4 and –6.56 % at 21 kn/SS-6 for Axe Bows
- Up to –8.31% at 21 kn/SS-4, –13.41 % at 31 kn/SS-4 and –2.413 % at 21 kn/SS-6 for Sword Bows
- Up to –5.874% at 21 kn/SS-4, –10.78 % at 31 kn/SS-4 and –2.903 % at 21 kn/SS-6 for X-Bows

However, for different *Inverted Bow hull* variants, it was observed that there is a tendency for an increase in Wave Resistance at a lower speed, i.e. at 21 kn, in both SS-4 and SS-6. However, a reduction in the wave resistance was observed for 31 kn/SS-4, i.e. up to –13.15 %. Further, it was also observed that the hull variants with *lower calm water wave resistance*, in general, continue to hold the edge of having comparatively lower wave resistance even at higher sea states.

(*b*) **Added Resistance.** Although, the inverted bow forms (all types) have shown an advantage in terms of Wave Resistance (RW) in higher sea states when their lengths were increased, as mentioned above, however, the ‘*Added Wave Resistance*’ values computed for different sea states (vis-à-vis respective calm water wave resistance values of the hulls for corresponding speeds) for these hull variants of Axe bow, X-bow and Sword bow forms were seen to be higher than that of the parent ship with the conventional bow form. But, *for Inverted Bow* forms analysed, the *added wave resistance was found* to be lower than that of the parent ship for 31 kn/SS-4.

(*c*) **Effect of Bow Inversion.** The effect of *bow inversion* (studied for a range of 5–15 %, as elaborated

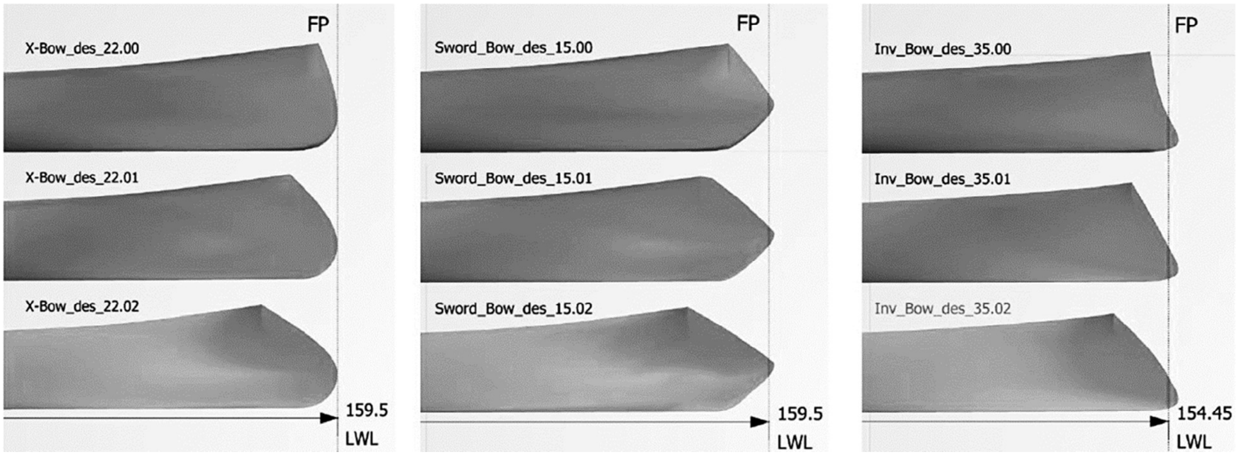

Fig. 6. Hull Form Variants with Different Degree of Bow Inversions, i.e. 5, 10 and 15 % from top to bottom for X-Bow, Sword Bow and an Inverted Bow Hull form variant (from left to right)

Рис. 6. Формы корпуса с различной степенью обратного наклона форштевня, включая 5, 10 и 15 % от верха до днища для вариантов X-Bow, Sword Bow и варианта с обратным наклоном форштевня (слева направо) above) was found to be not very prominent on wave resistance, i.e. difference up to 2 % only observed. Nevertheless, it was observed that higher bow inversion has a positive effect (to a small degree, as mentioned above) at 21 kn and at the lower sea state, i.e, SS-4. For 21 kn/SS-6 and for 31 kn/SS-4 different forms/ variant hulls showed different trends.

(*d*) **Motion Analyses.** For each hull variant, time-domain results for motions, i.e. displacement, velocity and acceleration in all six degrees of freedom, were studied for various hull variants from the results pool that the SHIPFLOW software generated. Some of the salient observations of *Motion Analysis Results* obtained for the selected hull variants are elaborated below:

(*i*) **Heave Motion.** It was observed that, at SS-4, all types of hull variants with higher lengths has shown a reduction in RMS values of *heave displacement* ($R3$), and acceleration ($A3$) in both speeds i.e. 21 kn and 31 kn, wherein RMS *heave displacement* ($R3$) at 21 kn/SS-6 for *Inverted Bow* and *Axe bow* types of modified hulls were found to be higher than the parent ship, but within individual types, there were comparative reduction in *Heave displacement* ($R3$) for longer variants. The longer Sword Bow and X-bow forms variants have shown lesser RMS values of heave displacement even at 21 kn/SS-6.

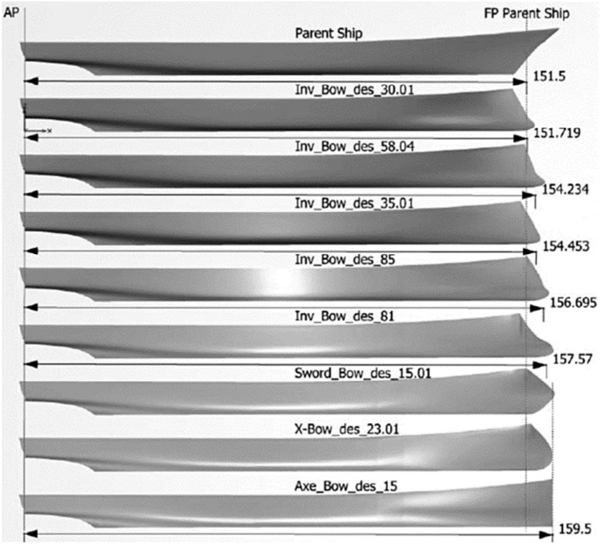

Fig. 7. Selected Hull Form Variants (08 nos) for RANS Analysis

Рис. 7. 8 вариантов формы корпуса, выбранные для RANS анализа

(*ii*) **Pitch Motion.** The longer modified hulls had shown higher pitch motion in all speed-sea state combinations. However, variations in pitch motions were observed for different '*degrees of bow inversion*' (however to a small extent up to 2 %). At 31 kn/SS-4, all the pitch motion parameters, i.e. *pitch displacement* ($R5$), pitch velocity ($V5$) and pitch acceleration ($A5$) decreased with an increase in the degree of above water bow inversion. Where the reverse was observed for 21 kn/SS-6. However, for 21 kn/SS-4, it was observed that RMS pitch displacement ($R5$) had reduced for all types of modified hulls with an increase in the degree of above water bow inversion. However, for the same, the patterns of RMS velocity and acceleration had shown either an increase or a curve with a point of inflection.

(*iii*) **Bow Motion.** For all sea states, there was an increase in the amplitude of *Bow Emersion* ($+R_B3$ max) and reduction of *Bow Immersion* ($-R_B3$ max) for longer modified hulls. There was also a corresponding increase in RMS *Bow velocity* (V_B5) and Bow Acceleration (A_B5) for longer modified hulls in all speed-sea state combinations. For Sword bow and X Bow hull variants, reduction of the amplitude of bow immersion has been observed for SS-4 for both 21 kn and 31 kn speed with an increase in the degree of bow inversion. However, the reverse was observed for all modified hulls at 21 kn/SS-6.

(*iv*) **Stern Motion.** For all sea states, there is an increase in the amplitude *of Stern Immersion* ($-R_S3$ max) and reduction of Stern Emersion ($+R_S3$ max) for longer modified hulls. For, Sword bow and X-bow form hull variants of higher lengths, RMS values of *stern velocity* (V_S3) was observed to decrease at 21 kn/SS4, where the *Sword Bow* hull had shown improvement in stern *acceleration* (A_S3) also. One Inverted Bow hull variant (i.e. Inv_Bow_des_35, see Fig. 7) was also observed to have improved the result in this respect.

13. **Calm Water Resistance Analysis by RANS Method.** Total 08 (eight) nos of hulls (five nos Inverted *Bow Hulls* and one each of *Axe bow*, *X-bow* and *Sword bow* hull forms) were selected for this comparative analyses based on preliminary calm water performance analyses carried out with XPAN/ XBOUND modules (Fig. 7). To do a comparison for the *form factor* $(1 + k)$,

the RANS analysis was undertaken using XCHAP module with double body method at very low speed, (i.e. 03 kn/Froude's no (Fn) in the order of 0.04), considering the theoretical definition that '*wave resistance at this Fn is negligible*'. It was observed that reduction in (1 + *k*) value could be obtained for these modified hulls in comparison to parent ship hull (Fig. 8). A comparative resistance analyses were also carried out for these selected hulls for the speed range of 10 kn to 31 kn. Following were observed from the computational results:

(*a*) Some *Inverted Bow* forms and the variants of other bow forms (i.e. *Axe bow, X-bow and Sword bow*) which were of increased length had shown better calm water resistance performance for higher speed ranges, i.e. above 21 kn.

(*b*) Due to the increase in length, i.e. corresponding surface area, there was an increase of *Frictional Resistance* up to around 2 %. However, the modified hulls were observed to have reduction in Wave Resistance (R_W), and also importantly, the modified hulls fared in terms of *Viscous Pressure Resistance* (RVP) offsetting the increase in *frictional resistance*.

(*c*) Summing up the differences in resistances components for different speed through RANS analysis, a reduction in values of the *Total Resistance* (R_T) up to approx 8.5 % could be observed for 31 kn. The improvement in R_T in Fig. 8. Form Factor (*k*) for various selected hull variants was observed to be lower for lesser speeds i.e. up to approx 7 % for 21 kn, as shown in Fig. 9. At a speed of 12 kn, all hull variants had shown higher resistance up to around 9 % for the worst case.

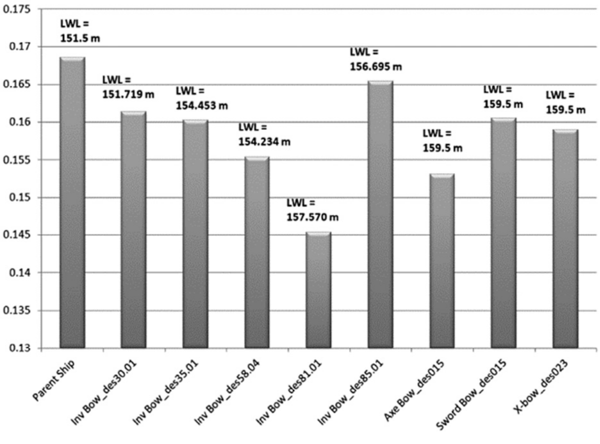

Fig. 8. Form Factor (*k*) for various selected hull variants

Рис. 8. Формфактор (*k*) для различных выбранных вариантов корпуса

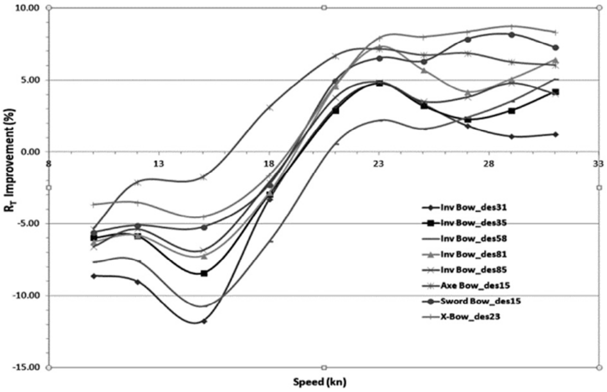

Fig. 9. Comparison for Total Resistance (R_T) values for various selected hull variant

Рис. 9. Сопоставление полного сопротивления (R_T) для выбранных вариантов корпуса

Scope for future work

Цели дальнейшей работы

14. The work undertaken during this project tenure is considered just the preliminary step towards conceptualization, modelling and analyses for development of a new alternate hull form to an existing frigate type hull based on concepts of *bow inversion* as well as *Enlarged Ship Concept* (*ESC*) meeting/ improving upon all the operational and economic requirements. This research work has also the scope to provide necessary baseline data, to an extent, to develop a new ESC/ Inverted bow hull form for a future naval frigate type mono-hull design. Some of the important scope of work envisaged in future are elaborated below:

(*a*) **Physical Model Testing**. An extensive hydrodynamic model testing program will be required to validate and extend the computational results, i.e. to subject the hull form variants to identical testing programs in calm water as well as for regular/ irregular waves.

(*b*) **Further Parametric Variation of the Selected Hulls and Analysis**. Further model variants can be created with additional variables and can be analysed for more speeds/ sea states, in smaller incremental steps, for arriving at optimization point as well as to generate more data series.

(*c*) **Effect on Propulsor & Control Devices.** Although the stern forms for all variants were kept unaltered from the parent ship, the change of bow dimensions/ forms would affect the wake properties in aft as well as hydrodynamic properties pertaining to propulsive efficiencies, roll motion, straight-line stability, manoeuvring etc. Hence, there is a scope for undertaking further studies in this regard to quantify the effects as well as to identify necessary modifications that would be required to be undertaken to the aft region of the hull, propulsors, manoeuvring and other motion control devices.

(*d*) **Effect on General Arrangement.** The effect of lengthening the hull and modification of the bow form on spatial layout and volumetric efficiency of the ship also needs to be concurrently studied in detail, both qualitatively and quantitatively to establish the acceptability of a 'hydrodynamically superior hull form variant' obtained in the process for the ship's envisaged mission specific roles.

Summary and conclusion

Выводы и заключение

15. The emphasis of work presented in the paper was based on, as well as is considered applicable to medium and large frigate type hull forms. It can be commented that the hull form of such naval ships can be improved to a certain degree with respect to resistance and seakeeping if it undergoes design optimization. The idea of 'bow inversion', in this context, provides the allowance to increase the underwater hull length unhindered, to the navigational restriction limit (often equal to L_{OA} of the base hull form), thereby enabling to play with additional volume in the forward region of the hull for optimisation of the bow as well as various other hull-form parameters.

16. The results discussed in this paper have shown that considerable reduction in Wave Resistance (R_W) could be achieved for several hull forms variants when analysed for calm water resistance performance, especially at higher speed ranges, i.e. 20–31 kn. These hulls too held an edge over the others in terms of wave resistance in higher sea states; however, in general, these modified hull forms have shown an increase in added resistance in wave (in % term) with respect to their corresponding wave resistance values in comparison to the parent ship hull with conventional bow. Further, the form factor of the hulls $(1 + k)$ could also be reduced by increasing the underwater hull length, keeping the volume constant (or minimum change), which could offset the increase in Frictional Resistance (R_F) to an extent. Thus, implementing the idea of Bow Inversion along with the *Enlarged Ship Concept* (*ESC*), it is possible to obtain hull forms with better resistance performances in calm water as well as in higher sea states.

17. However, at the same time, motion results have indicated that increasing the length and modifying the bow to the inverted form from conventional bow form (with forward overhang and flare) has resulted in to higher sensitivity in higher sea states resulting in degradation in some critical motion parameters for some hull variants (e.g. higher pitch motion, higher motion values at bow etc., however to a limited extent). Notwithstanding the same, some hull variants, e.g. Sword Bow hulls of $L_{WL} = 159.5$ m, has shown a reduction in the values of stern velocity and acceleration which would be favourable for 'halo operations' from the helo-deck located astern.

18. Further, it is also important to consider that, the modification of the forward region of the hull/ bow shape and overall configuration of a naval ship would give rises to several critical issues pertaining to the general arrangement, viz, deck space/ spatial layout of ship's components, access by crew, operational constraints, difficulties in mooring arrangement/ anchor handling etc. Hence, the 'side effects' envisaged need careful studies, and appropriate mitigation measures/ design refinement, to the extent feasible, would be required to be implemented in the modified hulls. Hence, it can be stated *that quantification of the* '*perceived gain*' *by the modifying the bow form calls for a very* '*careful*' *and* '*complex*' *definition*.

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Поступила / Received: 29.03.22
Принята в печать / Accepted: 11.05.22