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SCHOOL OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

SHIP DESIGN LABORATORY

DIPLOMA THESIS:

''On the Reduction of Fuel Consumption Of Bulk Carriers''

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Abstract

The fact that humanity has achieved to transfer 90% of all international transport of goods through the oceans undoubtedly underlines the importance of shipping in the world trade and the broader lives of people. Over the past decade though, the regulatory framework surrounding shipping has increased pressure in the shipping environment in two main ways; firstly, new designs must comply with the rules and regulations, and secondly existing vessels must be improved in order to become more eco friendly and reduce the environmental footprint of the shipping industry. These new regulatory constraints in addition to the very fragile economic environment nowadays, have led to fluctuations that affect both the freight rates and the heavy fuel oil prices, challenging ship owners to attempt to optimize their vessel's performance, by reducing operational costs. In order to do so, they attempt to lower fuel oil consumption, which represents by far the greater percentage of cost when breaking down the operational costs of a vessel.

This diploma thesis is concerned with the evaluation of the real time consumption information gathered from three similar cape size bulk carriers in different voyages and loading conditions. After gathering information on the consumption of the three similar bulk carriers, one of them was taken as a template and analyzed in order to try to reduce its fuel oil consumption by minimizing the total resistance it produces. Through experimenting and altering operational aspects of the ship, such as optimizing trim and even hull form designs (different bulb types), an attempt was made to lower its total resistance by minimizing the wave resistance it produces. In such types of ships, and in Froude numbers as low as the ones these ships are operating on, we have come to understand that little can be made with the aforementioned changes, because the wave resistance of these types of ships plays a minor role when calculating their total resistance. Thus, in the effort of minimizing fuel oil consumption of a cape size bulk carrier, it was concluded that lower consumption levels may be obtained by optimization, based on the attempt to reduce the vessels wetted surface, and therefore their frictional resistance, which is beyond doubt, the prime factor affecting these kinds of vessels' total resistance. Adding to the above, positive outcomes are also achieved by the installation of different components, which aim to increase the propeller efficiency and generally utilize better the main engine power.

It is underlined though, that probably the most immediate and efficient way for the precedent is to reduce the speed the ship operates on. Nevertheless this course of action would result in longer voyages, and consequently a very thin economical line that has to be taken seriously under consideration.

Introduction

If one considers today's continuously changing environment, they will understand the impact that shipping has in the economy, the global warming and the everyday lives of millions of people. Fuel consumption is a topic that rarely concerned businesses before the millennium, but now, it is a vital matter for many reasons and must be taken into serious consideration in naval architecture.

When breaking down the ship operation costs, it is found that more than 60% of these are comprised of fuel oil consumption costs, making it clear that any deduction of the ships fuel oil consumption may play a great role into giving additional profits to ship owners. In addition, nowadays with the existing high oil prices, the low freight rates for similar ships and the general downturn of the economy, the topic of ships fuel oil consumption has turned into one of the most contemporary issues to be solved.

In addition to the above, ever since the 2011 Energy Efficient Design Index (EEDI) regulation of MARPOL, ship companies must reduce Co_2 emissions, an objective that can be achieved by controlling fuel consumption. As previous generation ships were not designed with the specifications that the EEDI imposes, the companies that own high emission – previous generation ships will pay economic damages to the government in order to compensate for the externalities they cause. Therefore, it is very costly for ship owners to not comply with the EEDI regulations, and this causes a shift towards new technologies and new ship designs that will lower Co_2 emissions and consequently fuel oil consumption.

I drew the inspiration of my thesis topic on the "optimization of fuel consumption of bulk carriers", from a concern I had ever since I remember myself as a child: how can I make this world better? My ambition to contribute into improving the economic and environmental situation of shipping, in addition to several stimuli I received from my university studies and my association and intercourse with my professors, led me to challenge myself into finding out how fuel oil consumption of bulk carriers can be optimized. Taking into account the Greenhouse effect and the global warming, I came to believe that fuel oil consumption is a

matter that is the duty of my generation to solve, as we are those who will mostly experience the severe results that are to come.

More analytically, in chapter One the background of the Bulk carriers industry is described, regarding the general aspects of their fuel oil consumption in combination with the strict impact imposed by the EEDI regulations. In addition the general information and particulars of the three study ships examined is presented.

The second chapter contains the operational costs breakdown for a Cape size Bulk carrier, the parameters to be taken into account when examining ship operation and fuel consumption and different knowledge systems and software tools that are useful in ship operation and voyage optimization.

In chapter three the employed methods (HOLTROP & Computational Fluid Dynamics CFD packet SHIPFLOW) for the estimation of resistance powering and fuel consumption are presented.

The forth chapter presents the on board information regarding fuel consumption gathered in addition to the sources of uncertainty that surrounds them.

The fifth and final chapter includes the calculation of ships resistance and powering derived from the methods used in this diploma thesis. In addition the effect of trim, loading and seaway conditions is investigated providing comments for the results for both full load and ballast condition.

Chapter one:

Thesis Framework

i. *General Aspects of Fuel Oil Consumption of Bulk Carriers*

In order to gain insight in shipping as a business and as a method of transportation of goods, one must investigate the economic environment behind all the operations. The ship owner is the person who provides the ship as a transportation vehicle, while the charterer is the person who wants to transfer the cargo through the sea. The profitability of operating bulk carriers for the owners of the ship depends upon the current level of the freight market. Similarly, the charterer will gain from lower levels of the freight market, as the transportation will render cheaper, and will suffer from higher freight rates when the market is high. Therefore, before every transaction deal, both parties must investigate the freight market or the daily time charter value and evaluate their transaction.

The reason why shipping has been so important to humanity throughout history is because people always had the urge to conquer the world. Ships would be the vehicles for the mankind to reach out to places that no one had ever been before, and then expand their kingdoms through colonialism. Later, ships became the means by which culture, ideas and goods would travel across the world and spread among all civilizations. And today, with globalization and radical technological improvements, humanity has achieved to transfer through the oceans 90% of all international transport of goods. This enables the shipping industry to expand, innovate and buy new cargo vehicles in order to serve better customers and make profits.

Transferring cargo through the sea is not a random choice, as commercial shipping is the most fuel-efficient way of transporting bulk carriage. The economic importance of fuel consumption is mainly twofold: firstly, the owners and charterers will have to face and incur the cost of embarking a ship that consumes high priced fuel. Secondly, the more fuel being consumed, the higher the negative externalities to the society due to pollution, which again results to the two parties paying Pigovian taxes.

Ever since the economic crisis of 2008, the heavy fuel oil prices have risen significantly, reaching a cost per tone higher than $700, translating at a cost of $50,000 per day for a Cape size bulk carrier. When breaking even the ship's operating costs, it is found that steaming would cost about $25,000 per day. Therefore, it is clear that the parties interested in embarking a commercial ship have experienced additional fuel costs for the past 5 years,

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and this led to a reduction of profits. In addition, ship owners have experienced significant reduction of income and profits, as the freight rates, which are defined as "the charges for transporting a cargo by common carrier", have declined dramatically.

In order for the aforementioned commercial parties to check the freight rates at any given time of any day of the year, an institution has arisen. This is called the Baltic Exchange, and it is a membership organization that publishes indices with information withdrawn from the real world fixtures. The Baltic Exchange publishes the Baltic Dry Index (BDI), which comprises of twenty six physical routes that are then subcategorized into six groups of ships that range from 28,000 DWT, called handy size, to 80,000 DWT and over, called cape size bulk carriers. Through this system, the market has managed to serve both the owner and the charterer, in order to accomplish the maximum level of transparency between the two parties, and to minimize asymmetric information, which would lead to higher transportation costs, and thus higher prices that the rest of the world would have to incur. Additionally, the BDI is given in USD and presents the daily average hire for ships from each of the aforementioned groups. This can also translate as the daily value of the ship for the owner, as it is the money they would earn from the charterer. The BDI comprises of four components[1]:

– BCI (Baltic Exchange Capesize Index) based on ships over 150,000 DWT,
– BPI (Baltic Exchange Panamax Index) based on ships 74,000 DWT,
– BSI (Baltic Exchange Supramax Index) based on ships 54,000 DWT,
– BHSI (Baltic Handy Size Index) based on ships 28,000 DWT.

The economic environment nowadays is very fragile, and this has led to fluctuations that affect both the freight rates and the heavy fuel oil prices. The main index of the freight market (BDI) has dropped from $12,000 to $700 per day during the years that followed the 2008 crisis, which indicates a major decline in the economic profits of the owners and a fall in the daily ship value. A panama size ship in 2008 could earn about $100,000 per day, a freight rate that after the crisis, in 2012 fell to 12,000 USD, with reported drops that even reached $6,000. In every economic fluctuation, the resulting inflation or deflation has a six-month delay before the average consumer can acknowledge it. This means that when the

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[1] Doskocz, Dariusz. *PROFITABILITY OF REDUCTION OF SPEED AND FUEL CONSUMPTION FOR SEA GOING BULK CARRIERS*. Diss. Folia Oeconomica Stetinensia, 2012. Print.

crisis began, heavy fuel oil prices seemed to remain unaffected, thus fuel appeared to be relatively cheaper, and this resulted in lower freight rates. But in 2009, when the effects of inflation started to appear into the economy, heavy fuel oil prices rose significantly, and continue to rise ever since. It appears, that in the future fuel oil prices will continue to rise due to the continuous and rising world demand for energy. In addition, there is strong regulatory and public pressure on environmental emissions, and higher prices on fuel oil will lower the world consumption and thus the pollution. In the following figures, BDI indices (Figure 1) are compared with oil prices (Figure 2).
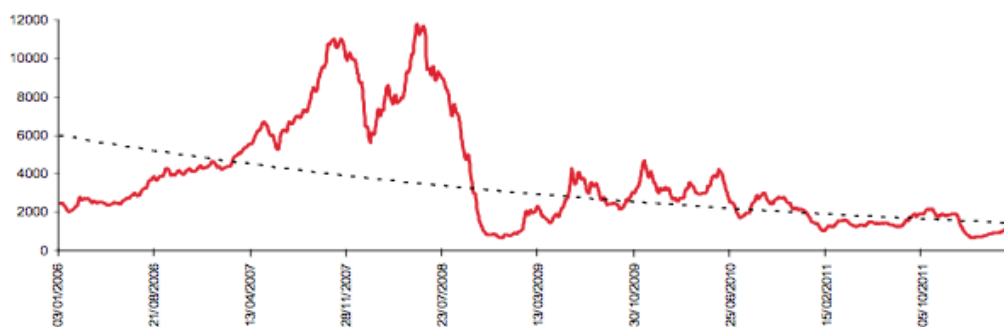
Figure 1: Baltic Dry Index (from Baltic Exchange)
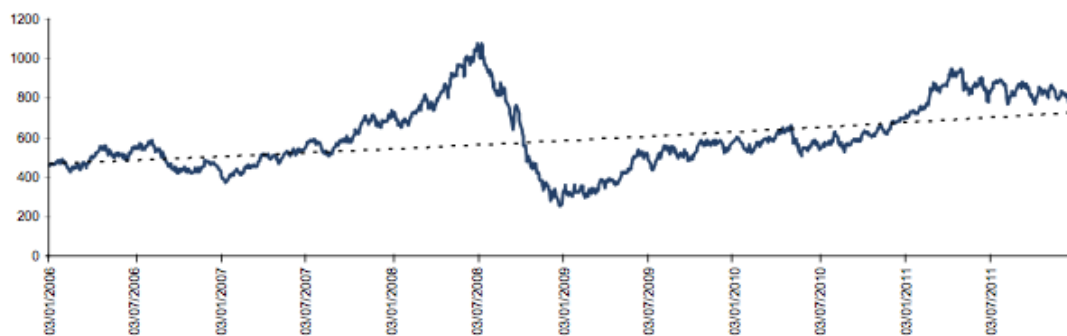
Figure 2: Brent oil price, USD per mt (from London Stock Exchange)

The above figures depict the diverging trends of the freight rates and the brent oil price for the years between 2006 and 2011. As seen in the diagrams, in both cases in 2008 there were extreme fluctuations, which then later cooled down. In Figure 1, the tremendous decline in ship hiring can be depicted, and after 2009, a gradual and continuous fall in freight rates can be acknowledged. On the other hand, in Figure 2, one can depict an extreme increase in 2008 which continued as a gradual and slow increase after 2009, creating an up sloping trend. If the two diagrams were to be put together, then the two diverging trends would indicate an ineffective operation with ship owners experiencing loss of profits. For this reason ship owners are forced to cost minimize, and the main cost in shipping is fuel consumption. Therefore, by reducing the heavy fuel oil consumed in each voyage, ship owners try to get the two trend lines of cost and profit, shown in the above figures, closer.

The International Maritime Organization (IMO) studied, in 2000, a variety of methods that would reduce fuel consumption and Greenhouse gas (GHG) emissions. These methods were mainly categorized as technical measures[2], that included new ship designs, fuel improvements and maintenance of the hull as well as the propellers, and operational measures, that included weather routing, fleet planning, optimization of trim, ballast, rudder pitch, reducing time in port and speed management. These studies concluded to the fact that the most effective and immediate measure that could be taken in order to reduce fuel consumption was to reduce the speed of the ship. The results of this study suggested that with a speed reduction of 10%, the CO2 emissions would reduce by 23%. This indicates that a relatively small reduction of speed results in the reduction of more than double the pollution. Similarly, the research indicated that when speed is reduced by 20%, the reduction of CO2 emissions is close to 50%, a number that is significant for environmentalists, but for ship owners too, who would pay less Pigovian taxes[3]. But a mandate to reduce speed by 20% is not in the interest of commercial ship owners, as there is a clash of interests: in one hand they would pay less Pigovian taxes, but on the other hand, shipping is an industry whose profits result from trustworthiness and on time transit times. For example a ship carrying perishable cargo cannot reduce its speed, as the cargo will get destroyed. In addition, modern ports have tight logistics and if a ship arrives late, it can

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[2] Ballou, Phil, PhD, Henry Chen, PhD, and John Horner, Capt. "Advanced Methods of Optimizing Ship Operations to Reduce Emissions Detrimental to Climate Change." Jeppesen Commercial Marine Operations, 2008. Web. <http://www.jeppesenmarine.com/files/whitepapers/VVOSandClimateChange.pdf>.

[3] A tax applied to a market activity that is generating negative externalities to the society

result in significant additional costs that would be negating the aforementioned savings of fuel consumption cost reduction.

When naval architects and engineers approach high block coefficient bulk carriers and tankers, there are two core sectors they must investigate; the bow area and minimizing the wave formation. In ships that their hulls have up to 13 meters difference in draft between ballast condition and laden, bulbous bows are not suitable, but they still remain suitable for fine-lined container and passenger vessels. The other sector the experts must look at is the flow around the propeller. There have been studies showing that by taking advantage of the forward motion of the ship and connecting it with the propeller, flow would be improved in the latter. This, according to the study, could reduce the power requirements of the ship from 5% up to 9%. In order to understand what these percentage numbers mean, one can understand that a 5% reduction of fuel consumption translates to 3.5 tonnes or $2,500 per day less than the initial operating costs. In addition, another way to improve the propeller efficiency could be by fitting a wake-equalizing duct in front of a propeller that would normalize the flow and increase the propeller efficiency

Measure No.	Description	Existing ships gain %	Newbuildings gain %
1	Main Engine efficiency rating	2	
2	Main Engine optimization		2
3	Waste Heat Recovery		5-10
4	Optimize hull shape, incl. re-duced Cb		3-10
5	Optimized propeller	2	3-6
6	Maintenance of wetted hull surface	2-5	2-5
7	Improved anti fouling paints	2-8	1-2
8	Twin skeg + twin propeller		5-8
9a	Trim optimization – large Cb ships	1-2	1-2
9b	Trim optimization – small Cb ships	Max 10	Max 10
10	Misc. Fuel saving devices	2-6	2-6

Table 1: Methods of fuel reduction that can be utilized by new or existing ships[4]

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[4] Bjørn Mortensen, Niels. "Ship Fuel Efficiency in a Historical Perspective" Print.

In the above table, some methods of reducing fuel oil consumption in new and existing ships are presented. The percentage of gain is expressed for each method on the new or existing vehicle. Measures 1 and 2 are in-engine improvements that are achieved through continuously changing technology. Measure 3 is pertinent to ships with large power plants and it is not likely to be retrofitted on existing ships, while measure 4 can be subcategorized to optimized bulb, stern and reduced Block Coefficient (Cb). Measures 6 and 7 can result in double counting if they are calculated as two independent measures, while it they are more effective if they are put into use on existing ships. Measure 8 is used to improve the ships maneuverability instead of optimizing the fuel consumption, but measure 9, which is trim optimization and has small effect for slow steaming ships with high Cb (eg. Tankers and bulk carriers), has, large effects as much as 10% fuel saving on fast ships with low Cb (eg. containerships, reefers). Finally, measure 10 is comprised of many devices, such as ducts, fins etc, in order to improve water flow to the propeller[5].

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[5] Bjørn Mortensen, Niels. "Ship Fuel Efficiency in a Historical Perspective" Print.

ii. *The impact of EEDI - Different Systems used on vessels in that direction*

Although ships are considered the most fuel-efficient method of transportation of bulk cargo in the world, the Second IMO GHG Study that took place in 2009, acknowledged more means in which emissions could be reduced. These were mainly comprised of already existing technologies, such as improved hull designs, more efficient propulsion systems and engines, and larger ships. The study concluded that with further design-based and technical measures, the CO2 emissions of vessels and their fuel consumption could be reduced significantly on a capacity basis (tonne-mile). Other operational measures that would further reduce the Greenhouse Gas emissions are lower speed and voyage optimization. Therefore, in the future it is anticipated that the harmful substances emitted from vessels will be minimized due to the strict regulations that are to come from the IMO and other organizations considering the environment and the green house effect.

The following figures illustrate the international rules concerning the emissions of NOx and Sox from the vessels.
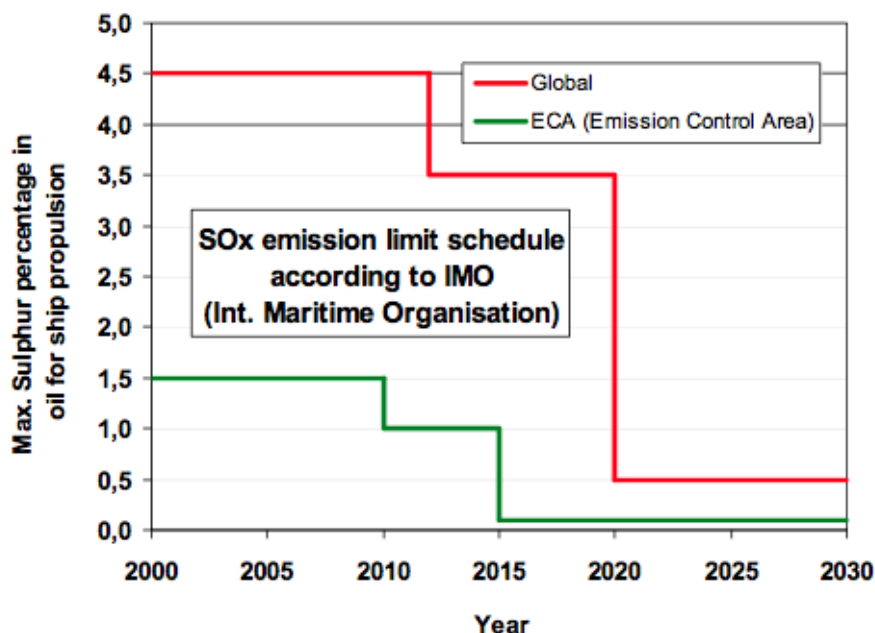
Figure 3: Max Sulphur percentage
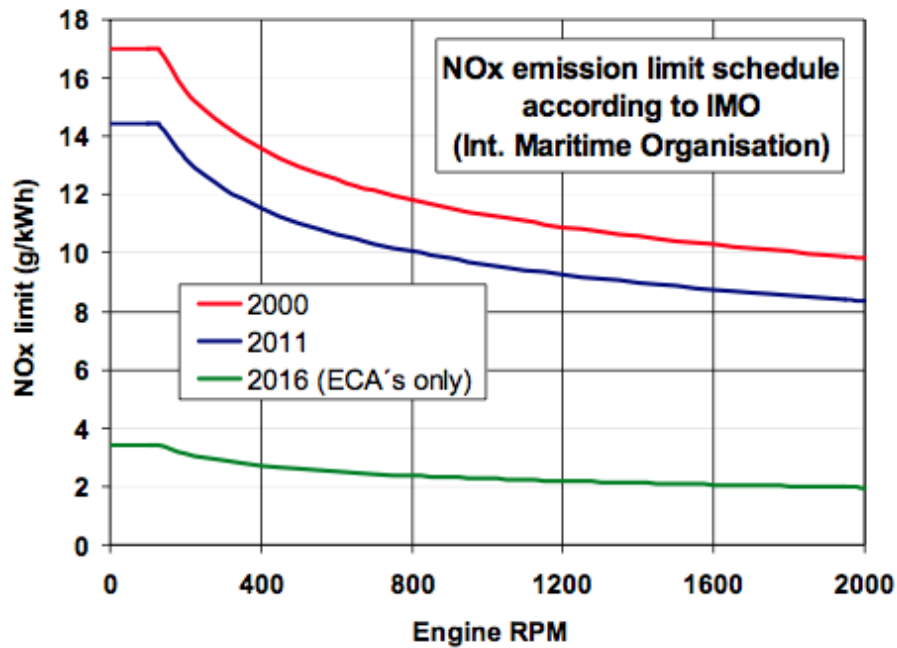
Figure 4: NOx limit

As we can see there is a demand of fuels containing less than 0,1% sulphur (SOx) from 2015 as well as an 80% NOx reduction from 2016. In order to produce such low amounts of sulphur exhaust gas cleaning devices, so called scrubbers, come into play.

Regarding CO_2 emissions of vessels, that constitute 3 % of the worlds CO_2 emission, new vessels should meet the regulations of the EEDI which enforces CO_2 indexing of new ships and provides an upper limit for new designs.

It would be useful to mention different measures and patents used from ship owners in that scope and of course in order to minimize the fuel consumption of their vessels.

✓ **Installation of a speed nozzle at the propeller and a Costa-bulb at the rudder of the vessel**

To obtain the most thrust, a propeller must move as much water as possible in a given time, especially when a high thrust is needed at a low ship speed. Due to propeller immersion requirements at ballast drafts, the propeller diameter on a bulk carrier is normally restricted leading to a relatively high propeller loading. In connection with the low speed, typical of a bulk carrier, this leads to a relatively low propeller efficiency. Therefore a velocity increase of the flow, which would lead to a relatively higher level of kinetic energy in the propeller wash is necessary and would improve the relatively low propeller efficiency. The propeller nozzle creates a utilized circulation around the nozzle's wing section and the contraction of the flow forward of the propeller is increased diverting the flow aft of the propeller and creating a flow pattern equivalent to the flow generated by a larger propeller.

The following figure depicts a propeller with a speed nozzle

Figure 5: Propeller with speed nozzle

In order to have a more homogeneous flow distribution behind the hub area a Costa bulb can be installed. The Costa bulb is a streamlined body fitted on the rudder, behind the propeller hub, as we can see at the following figure. By creating a more homogeneous flow behind the hub area it minimizes the hub vortex and its related loss and therefore the energy of the propeller induced vortices can be partially converted into thrust.
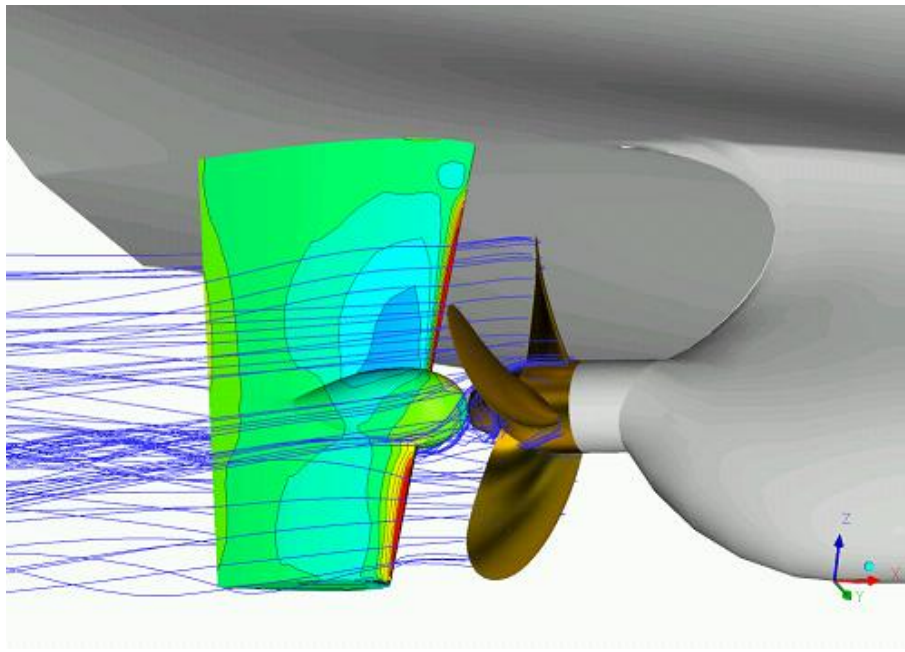
Figure 6: Costa bulb on rudder

The total reduction in propulsive power at service speed (85 % MCR) with an unchanged speed, from the application of the above mentioned devices, has been estimated by FORCE Technology (the Danish ship model basin in Lyngby) to 4 %.

✓ **Installation of wake equalizing duct system**

Despite the fact that the installation of a wake equalizing duct system is not mentioned on the above table it is believed to have a great impact on the reduction of fuel oil consumption and the resulting hazardous substances. The duct system consists of two rings fitted at the aft of the ship before the propeller that direct to the propeller a flow with a higher velocity. Consequently the duct system results in an improvement of the propeller efficiency from more axial flow and more equal velocity distribution over the disc area. Furthermore, the asymmetrical arrangement of half ducts gives a rotational direction to the water entering the propeller, which is opposite to that which the propeller will pass on, and consequently minimizes the loss from rotation energy in propeller wash. Except from the reduction of flow separation at the after body, uniform flow not only reduces propeller excited vibrations, but also helps in the improvement of steering qualities from more straightened flow to the rudder. Studies have shown that with an installation of a duct system not only the fuel oil consumption is reduced from 3 to 5%, but also the vibrations are reduced 50%. Considering the low cost and the simple installation of such a system many ship owners have chosen to use the wake equalizing system on their vessels.

At the following figure we can see the W.E.D. (Wake Equalizing Duct) installed on a vessel
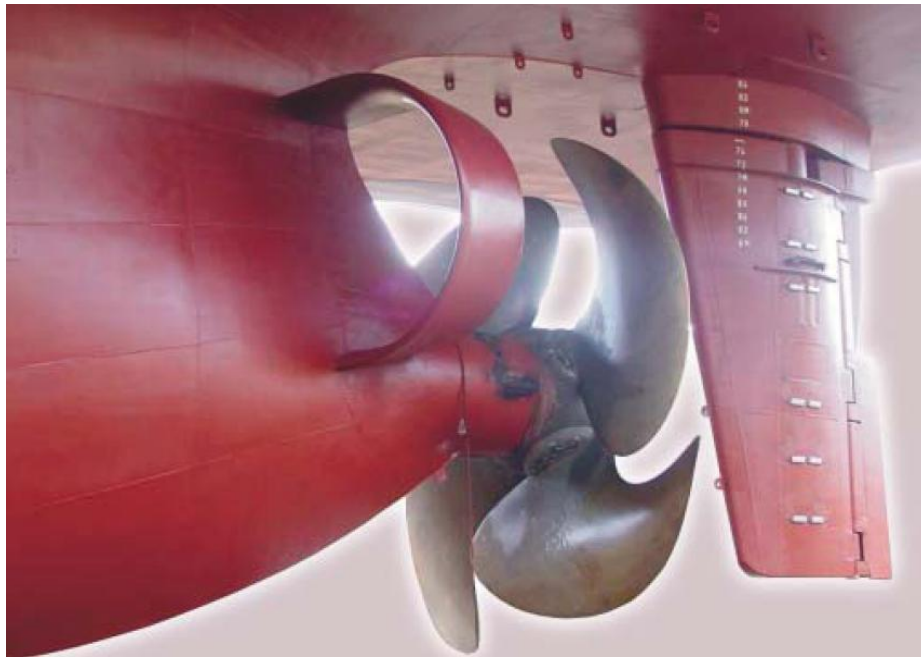
Figure 7: Wake Equalizing Duct system

✓ **Exhaust gas scrubber**

The exhaust gas scrubber is a large component installed in the exhaust system after the engine or boiler that treats the exhaust gas with a variety of substances including sea water, chemically treated fresh water or dry substances. It removes most of the SOx from the exhaust and reduces particles (PM) to some extent, about 98 % and 80 % respectively. This is achieved by the reaction of strong acids with the natural alkalinity of the seawater, or the alkalinity derived from the added substances and mostly sodium hydroxide, forming soluble sodium sulfate salt, which is a natural salt in the seas.

The sea water pump for the exhaust scrubber is one of the major consumers of electrical power and therefore the scrubber unit is usually located as low as possible in order to minimize the lifting height of the water. After scrubbing, the cleaned exhaust is emitted into the atmosphere and a waste stream is created containing the substance used for the cleaning process plus the SOx and PM removed from the exhaust.

A typical scrubber unit using sea water is shown on the following figure.
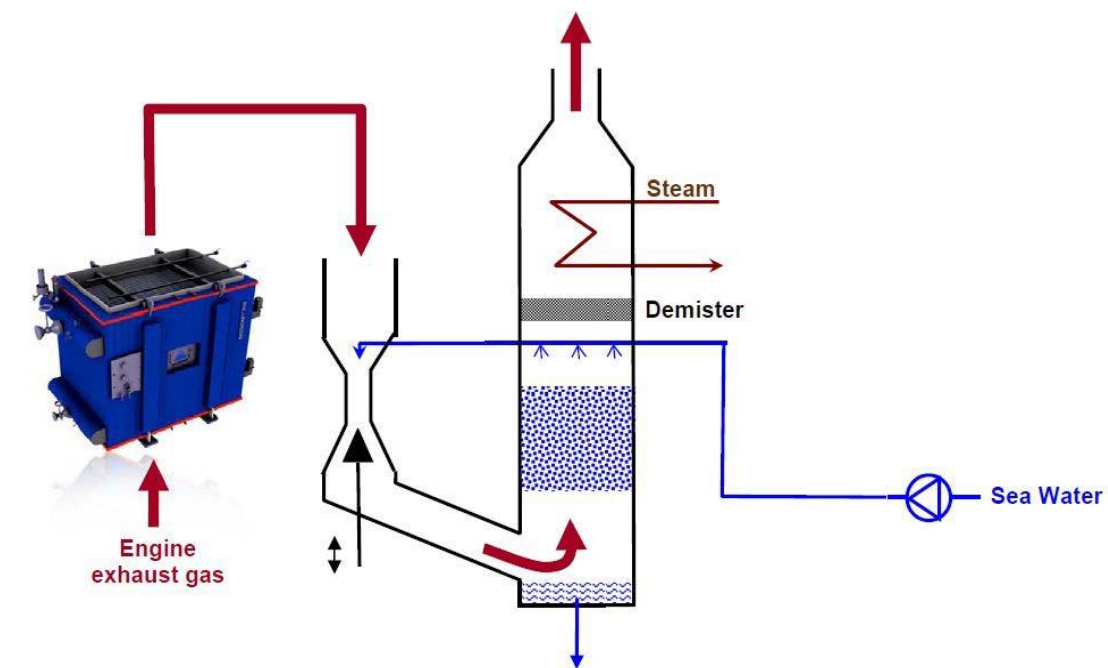
Figure 8: Exhaust gas Scrubber unit

✓ **Exhaust Gas Recirculation (EGR)**

This is a well known method of reducing NOx emissions from internal combustion engines. The basic concept of the EGR technology is to reduce the peak combustion temperature, which suppresses the thermal formation of NOx . EGR obtains this, partly because the heat capacity of the re-circulated exhaust gas is higher than that of normal combustion air (ambient air). Furthermore, the lower oxygen content (compared to the ambient air) in the re-circulated exhaust gas lowers the chemical reaction rate for the combustion of the fuel, thereby also reducing the peak combustion temperature. The three parts consisting an EGR unit are the following:

- A **scrubber** unit which removes SOx and particle matters from the recalculated gas, to prevent this from damaging the engine. The scrubber uses re-circulated fresh water, which is being cleaned continuously and neutralized with NaHO, in a special water cleaning unit.

- A **cooler** ensuring that the re-circulated gas does not raise the scavenge air temperature significantly above the temperature of the air from the charge air coolers.

- A frequency controlled **blower**, which overcomes the pressure differential between exhaust gas receiver and scavenge air receiver, and controls the flow. The electrical power consumption of the blower is about 85 kW when the engine runs at 85 % SMCR, corresponding to service speed.

The following figure depicts an EGR unit indicated in the recirculation loop.
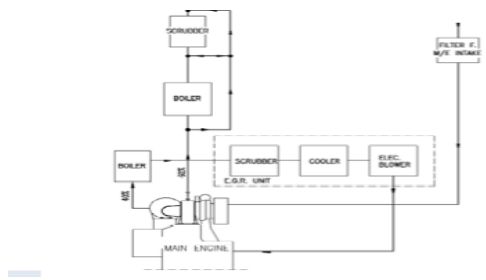
Figure 9: Exhaust Gas Re-circulation unit

✓ **Waste Heat Recovery System (WHRS)**

Waste heat recovery systems is probably the most common method used in the reduction of the exhaust gas emissions and has been used on ships for decades. Based on existing installations WHRS gives by far the largest emission reduction and shows a potential for recovery of 10-15 % of the main engine power. In many cases, WHRS will be able to supply the total electricity need of the ship as a standalone power source.

The primary source of waste heat of a main engine is the exhaust gas heat dissipation, which accounts for about half of the total waste heat, i.e. about 25% of the total fuel energy. On the WHRS part of the exhaust gas flow is bypassed the main engine turbocharger(s) through an exhaust gas bypass resulting on a reduced amount of intake air and exhaust gas. The reduction of the intake air amount and the exhaust gas amount results in an increased exhaust gas temperature after the main engine turbocharger(s) and exhaust gas bypass, which increases the maximum obtainable steam production power for the exhaust gas fired boiler – steam and can be used in a steam turbine for electricity production. Moreover, the revised pressure drop in the exhaust gas bypass, part of the WHRS, by applying a power turbine can be utilized to produce electricity.

On the following figure we can see the principles of the Waste Heat Recovery system
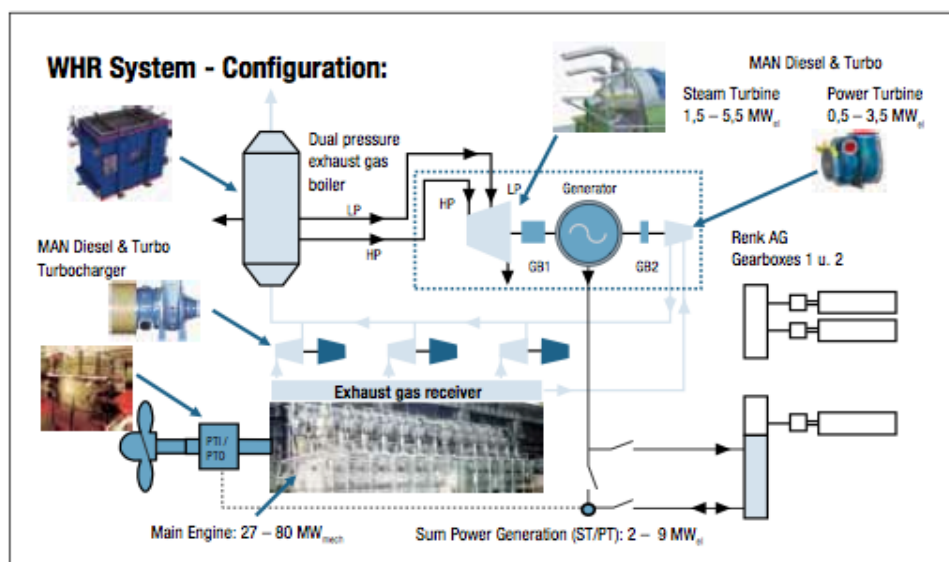
Figure 10: Waste Heat Recovery System

The methods used in the reduction of the exhaust gas emissions not only are very important in order to minimize the costs of operating a vessel, but also nowadays may even be the only way for the ships to meet the very strict regulations that are to come considering the environment and the substances emitted from ships. On the other hand, we should outline the fact that many of these systems are contain large components, which use space that could be used for other reasons. Furthermore, due to such modifications the total lightweight is increased, which must be deducted from the deadweight of the ship. Lastly, many of these modifications are quite expensive in order to be installed on the vessel.

On the following table one can see the cost estimation for some of these modifications.

Additional weight (estimate)
160 t

Additional cost (estimate)

	USD
Speed nozzle/optimized propeller	700.000
Twisted spade rudder with Costa bulb	160.000
Water in fuel (WIF)	200.000
Exhaust gas recirculation (EGR)	600.000
Waste Heat Recovery system (WHR)	1.250.000
Exhaust Gas Scrubber	1.200.000
Ducted/direct air intake for main engine	20.000
Optimised coolers and cooling pumps	150.000
Auxiliary engine operation on marine gas oil (MGO)	-
High capacity fresh water generator	50.000
Installation of Ballast Water Treatment System (BWT)	810.000
	5.140.000

Table 2: Cost estimation of modifications

It would be worthy to mention that the International Maritime Organization (IMO) has been trying to give incentives to naval architects to design ships with reduced marine-based Greenhouse Gas emissions (GHG). These incentives include The Energy Efficient Design Index (EEDI), which aims at simplifying the machinery provisions in ships, and makes use of a reasonably simple equation to calculate the tones of CO2 emitted per ton of nautical miles travelled. This formula equation (MEPC 62) uses the payload, 75% of the Maximum Continuous Revolution (MCR) of the engines and some correction factors for fuels.

The CO2 emissions factor signifies the total CO2 emission from the ignition and combustion of fuel, which also includes the propulsion and auxiliary engines and boilers. When calculating the above, one must bare in mind the carbon content of the fuels in question. In addition, mechanical and electrical technologies installed on board a ship, such as the use of solar or wind energy, save energy that is deducted from the overall CO2 emissions of the vessel, based on genuine effectiveness of the systems. The transport work is calculated by "multiplying the ship's capacity (dwt), as designed, with the ship's design speed measured at the maximum design load condition and at 75 per cent of the rated installed shaft power (MCR)[6]". Finally, naval architects and ship designers were free to select the technologies to fulfill the EEDI regulations of the given ship type, thus allowing diversity in the specific field.

The calculated as above EEDI index (Attained EEDI) must be less than a required price (Required EEDI) that comes from a baseline, created from different existing ships build from 1998 to 2007 (Reference Line). This restriction on the EEDI index applies in new ships bigger than 400 gross tons (GT) and differs regarding the ships type, size and operation. The required EEDI index for Bulk Carriers follows.

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[6] "Emissions from Fuel Used for International Aviation and Maritime Transport." *IMO.org*. Web.
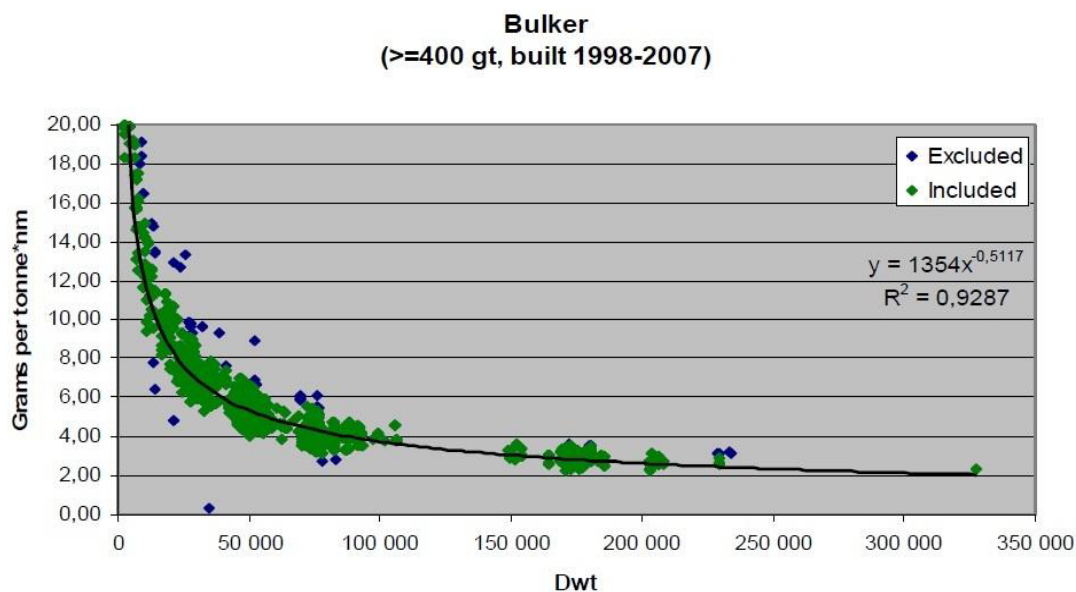
Figure 11: The EEDI reference line for Bulk Carriers, GHG-WG 2/2/7

The Energy Efficient Design Index (EEDI) is a measure that makes ship owners reduce CO2 emissions, an imposition that got into effect in 2011. In order to achieve its objectives, the EEDI addresses operational measures by obliging owners of new vessels to consume a minimum energy efficiency level. This will be achieved through the stimulation of technical development of all the parts of the ship that affect its fuel efficiency and through the separation of operational and commercial measures from the design-based and the technical. The EEDI makes comparisons of the energy efficiency between similar individual ships, of the same size, that could carry the same cargo, are taking place.

As people increase their awareness and their concern on the effect of human activities to the environment and the emergence of the GHG emissions, there has been increasing pressure to reduce shipping's negative input to this occurrence. In order to achieve this, a new set of regulations has been introduced into the shipping market, in addition to the creation of Special Emission Control Areas (SECAs) and of Key Performance Indicators (KPIs). All these regulations are in the context of the efficiency performance of ships, that are the EEDI, the EEOI (Energy Efficient Operating Index) and the SEEMP (Ship Efficiency Management Plan), and that will be explained later.

Ever since these measures were introduced, naval architects must design ships that ensure that the baseline of the ship's type is met (seen in figure 3). When the actual sea trial takes place, the shipyard in which the ship was built must certify that the EEDI baseline is, in fact, met. The concept is to lower the baseline in each subsequent year, in order for all the ships that will be designed and built in the future, to be getting more and more efficient.

The main disadvantage the EEDI displays is the involuntary mandate to limit speed to operation and slow steaming. This can sometimes improve the operational sector of the vessel and reduce the CO_2 emissions, but it can also diminish the safety and the security on the ship. In addition, with limited speed and slow steaming, the vessels arrive delayed at their destination, causing a significant loss of income to the ship owners. Furthermore, if the cargo of the ship includes perishable products, these may go bad, an event that would not only significantly diminish the profits of the ship company, but also the reputation of the company as a whole.

The Energy Efficient Operating Index (EEOI), makes use of actual data acquired from ship operations, in order to detect the identical metric. This index is considered accurate, due to the new ships that could take advantage of retro-fitting opportunities, and due to their large production in the past decade. When comparing the EEOI with the EEDI, it is found that the latter results in an uncertain index for ship designers and naval architects, as it is argued that the EEDI is unable to form the basis of a legally binging design objective. This is because it does not take into account commercial aspects of ship operations.

The Ship Energy Efficient Management Plan (SEEMP) forms a mechanism for operators to develop the energy efficiency of vessels. From 1 January 2013, there is a regulation that states that SEEMP applies for all vessels of 400 gross tonnage and above. There is though a period of six and a half years since the introduction of this regulation, where the IMO may renounce the requirement to comply with the EEDI for some new vessels, e.g. those who are currently under construction.

Another important remark is the universal impression that there is a positive influence to the EEDI when larger ship sizes are in operation. This is explained by the perception that an increase in deadweight is followed by a relatively smaller increase of the installed power.

Although the EEDI was created for the purpose of improving the heavy fuel oil consumption of new ships, the SEEMP is aimed to trigger better practices of fuel-efficient operations, in addition to installing the latest technology to already existing ships. Improving trim is part of the strategic plan of the SEEMP, which improve cost effectiveness and create useful measures to expand the ship's efficiency. The SEEMP is considered one of the most easily tangible heavy fuel oil saving measures that are currently accessible.

The DNV has created a simulation model that uses international shipping information and technology data to foresee the positioning of emission cutback and energy efficient technologies up to 2020. The results of this research show that high costs of fuel will lead to an effort towards more energy efficient ships, more than the EEDI indicates in its regulatory timeframe.

iii. General Information and Particulars of the Three Study Ships

The three ships in question are three cape size bulk carries designed to transport unpackaged bulk cargo and mostly iron ore and coal. Today, bulkers make up 15% - 17% of the world's merchant fleet. At the following figures we can see the major bulk carrier sizes (the percentages of each in the market - the prices for a new or used one), and the composition of bulk carriers in the shipping fleet of different type of vessels.

. Major bulk carrier size categories					
Name	**Size in DWT**	**Ships**	**Traffic**	**New price**	**Used price**
Handysize	10,000 to 35,000	34%	18%	$25M	$20M
Handymax	35,000 to 59,000	37%			
Panamax	60,000 to 80,000	19%	20%	$35M	$25M
Capesize	80,000 and over	10%	62%	$58M	$54M

Table 3: Major bulk carrier categories
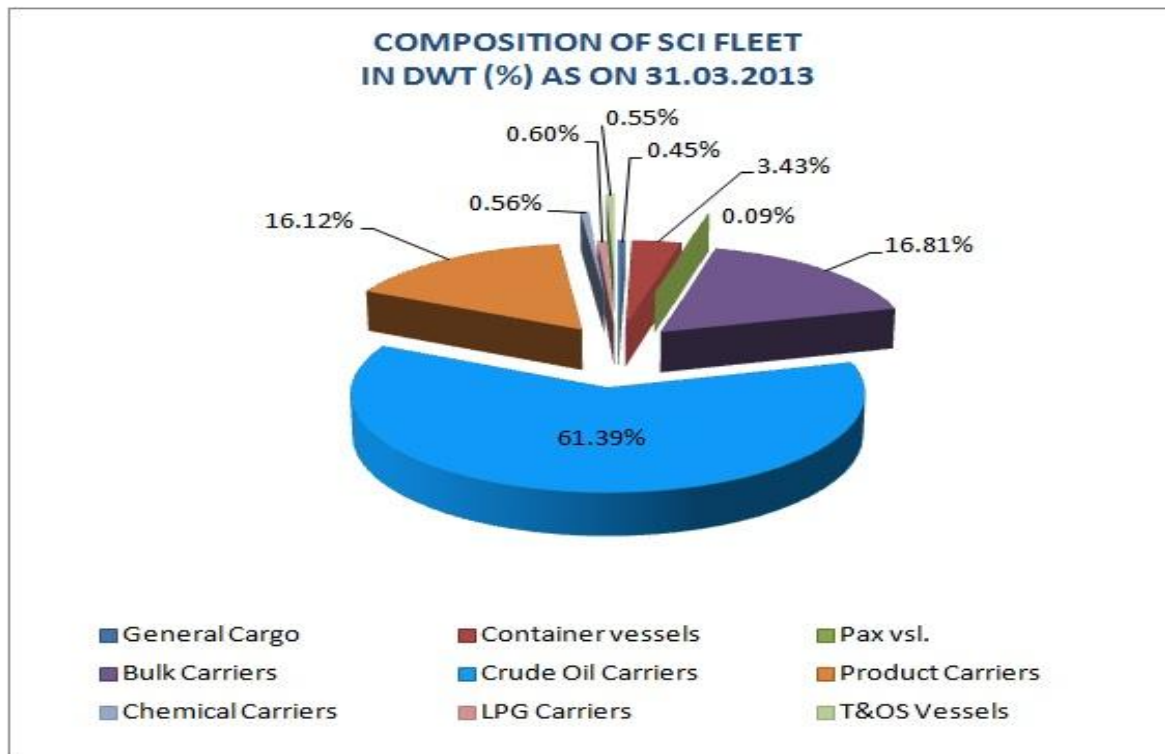
Figure 12: Composition of shipping fleet

The general characteristics and main data of the three ships under investigation in this thesis appear in the following table. All three of them are from the company of Mr. John Angelicoussis, 'Anangel Maritime'.

NAME	ANANGEL DYNASTY	ANANGEL HARMONY	ANANGEL VOYAGER
YEAR OF BUILT	03/02/1999	07/06/2010	26/05/2010
BY **HULL NO**	HYUNDAI 1115	STX 1284	DSME 1177
GRT/NRT	86.600/54.718	91.656/58.431	94.510/58.114
DWT(MT)	171.101	180.391,3	179.718,6

DRAFT(M)	17,66	18,200	18,225
LOA/LBP(M)	288,8	283	292/283
B(MLD)/D(MLD) (M)	45/24	45/24,80	45/24,70
LIGHT WEIGHT (TN)	21.625	26.991,6	26.035,6
HOLDS/HATCHES	9/9	9/9	9/9
MAIN ENGINE	HYNDAI B&W	STX MAN B&W	B&W
TYPE	6S70MC	670MC-C(MARK VII)	6S70MC-C
BHP/MCR	22.920/91	25.320/91	25.320/91
BHP/NCR	19.480/86,2	22.790/87,9	22.790/87,9
PROP/BLADES	FIXED/ 4 BLADES	FIXED/ 4 BLADES	FIXED/ 4 BLADES
DIAM/PITCH MM	8.100/5497,8	8.200/5658	8.300/5610,8
WEIGHT	36.432 KG	39.647 KG	39.817 KG
MATERIAL	Ni Al Bronze	Ni Al Bronze	Ni Al Bronze

Table 4: General characteristics of the three vessels under investigation

Chapter two:

Design and Operational Parameters Affecting Fuel Oil Consumption

i. Operational Costs Breakdown for a Cape size Bulk Carrier

It is a fact that the best way in order to minimize the hazardous emissions of vessels and to meet the strict regulations that are already in use and are to come regarding gas emissions and the environment is to try and minimize the fuel the vessels consume in their voyage. Moreover, it should be outlined that fuel consumption is the major cost of the vessels operation and with bunker costs at their highest, ship owners are desperate to cut down this cost. A breakdown of one of the similar vessels in question, the vessel 'VOYAGER', operational costs that follows is important in order to understand the significance of fuel consumption on the vessels operational costs.

Operating scenario - Trips per year:

We assume that the ship travels continuously, on the same path, in a circular manner and that the voyage duration remains constant. The timing of entry and exit from the port is 2h. So for a circular voyage the time wasted in a port is 4h. The total time for loading and unloading is 24h. So the total time into the port will be 28h. We also assume that the vessel travels 335 days a year (the remaining 30 are spent in port or for repairs or are excluded taking into account the days traveling at ballast condition leading to a reduced fuel consumption). We also assume that the vessel performs 5 circular trips / year.

Conclusively the time at sea for the vessel is:

$365 - 30 - 2 \times N = 365 - 30 - 2 \times 5 = 325$ days

The cost of consumables is:

Cost of Fuel Oil   : $c_{F.O.}$ = 600 $/t

Cost of Diesel Oil   : $c_{D.O.}$ = 850 $/t

Cost of Lube Oil   : $c_{L.O.}$ = 1800 $/t

Cost of Fresh Water   : $c_{F.W.}$ = 8 $/t

Cost of Crew payroll   : $c_{M.\pi.}$ = 3000 $/person-monthly

Cost of Provisions   : $c_{T.}$ = 12 $/person-daily

The consumption of consumables per round trip are:

- $W_{F.O.}$ = 2 · ($W_{F.O.}$ (Departure) − $W_{F.O.}$ (Arrival)) = 2 · (4264,6–426,46) = 7676,28 tn
- $W_{D.O.}$ = 2 · ($W_{D.O.}$ (Departure) − $W_{D.O.}$ (Arrival)) = 2 · (608,2–60,82) = 1094,76 tn
- $W_{L.O.}$ = 2 · ($W_{L.O.}$ (Departure) − $W_{L.O.}$ (Arrival)) = 2 · (197,6–19,76) = 355,68 tn
- $W_{F.W.}$ = 2 · ($W_{F.W.}$ (Departure) − $W_{F.W.}$ (Arrival)) = 2 · (571,2–57,12) = 1028,16 tn

➢ Fuel Oil

The consumption of Fuel Oil per round trip is 7676,28 tn.

For cost of fuel oil of c_{FO} =600$/tn and for 5 trips per year, the total cost per year is:

$$C_{FO} = 7676,28 \times 600 \times 5 = 23028840 \text{ \$/year}$$

➢ Diesel Oil

The total quantity of Diesel Oil (for main and auxiliary engines) required per round trip is 1094,76 ton. For a cost of 850 $ / ton and 5 trips / year, the total cost per year is:

$$C_{DO} = 1094,76 \times 850 \times 5 = 4652730 \text{ \$/year}$$

➢ Lub.Oil

The total amount of Lube Oil (for main and auxiliary engines) required per round trip is 355,68 tn. For a cost of 1800 $ / ton and 5 trips per year, the total cost per year is:

$$C_{LO} = 355,68 \times 1800 \times 5 = 3201120 \text{ \$/year}$$

➢ Fresh Water

The total quantity of Fresh Water required per round trip is 1028,16 tn. For a cost of 8 $ / ton and 5 trips per year, the total cost per year is:

$$C_{FW} = 1028,16 \times 8 \times 5 = 41126,4 \text{ \$/year}$$

➢ Provisions

The crew constitutes of 27 members. Therefore, if the cost of supplies is $ 12 / person / day and the ship travels 365 days per year (it is assumed that during the repairs remains on board) the total cost for provisions per year is:

$$C_{Prov} = 12 \times 27 \times 365 = 118260 \text{ \$/year}$$

Other costs:

➢ Payroll costs

For a crew of 27 members, a payroll cost of $ 3,000 / person / month and the ship travels for 12 months / year + 2 monthly wages as benefits, the total payroll cost per year is:

$$C_{PM} = 3000 \times 27 \times 14 = 1134000 \text{ \$/year}$$

➢ Maintenance and repair costs

✓ The expenditure on maintenance and repairs of the metal structure given by the following empirical formula (measurements in feets):

$$C_{rep,st} = 25000*(L_{BP}*B*D/10^5)^{2/3}$$

$$C_{rep,st} = 577429,88 \text{ \$/year}$$

L_{BP} =283 m = 928,24 ft

B = 45 m = 147,6 ft

D = 24,7 m = 81,02 ft

✓ The expenditure on maintenance and repairs of the mechanical installation are given by the following empirical formula:

$$C_{rep,MA} = 13,6 * BHP = 13,6 * 25023,47 = 340319,19 \text{ \$/year}$$

Hence the total expenditure on maintenance & repairs is:

$$C_{Rep} = C_{RepSt} + C_{RepMe} =$$

$$C_{Rep} = 917749,07 \ \$/year$$

➢ Insurance cost

The cost of insurance for 27 crew members and for a GRT of 94510,89 gross tons is given by the empirical formula following:

$$C_{INS} = 1925 * (N_{CREW} + GRT/1000)$$

$$C_{INS} = 233908,46 \ \$/year$$

➢ Port expenses

The cost of each approach to a port is given as following:

$C_{PORT} = 600 + 50 * (L_{BP}BD/10^5)$

$C_{PORT} = 6150,2 \ \$ / year$

    $L_{BP} = 283 \ m = 928,24 \ ft$

    $B = 45 \ m = 147,6 \ ft$

    $D = 24,7 \ m = 81,02 \ ft$

Since the ship makes 5 trips per year, the total cost for docking per year will be:

$$C_{Port,Total} = 2 \times 5 \times 6150,2 = 61502 \ \$/year$$

➢ General expenses

The empirical formula for the calculation of general expenses is the following:

$C_{GEN} = 6500 + 70(L_{BP}BD/100)$

(Measurements in metres)

    $L_{BP} = 283 \ m$

B = 45 m

D = 24,7 m

Resulting in general expenses of:

$$C_{Gen} = 226688,15 \ \$/year.$$

Overall operating costs for the vessel

Consequently, the total operating costs of the vessel per year will be the sum of the expenses calculated above and are depicted at the following table.

Vessels Operational Costs			
General Category	Costs	$/year	Percentage (%)
Cost of Consumables	Fuel Oil (CFO)	23.028.840	68,51%
	Diesel Oil (CDO)	4.652.730	13,84%
	Lub Oil (CLO)	3.201.120	9,52%
	Fresh Water (CFW)	41.126	0,12%
	Provisions (CProv)	118.260	0,35%
Other Costs	Payroll (CPM)	1.134.000	3,37%
	Maintenance and Repair (CRep)	917.749	2,73%
	Insurance (CINS)	233.908	0,70%
	Port (CPortTotal)	61.502	0,18%
	General Expenses (CGen)	226.688	0,67%
Total Vessels Operational Costs		$33.615.924,08	100,00%

Table 5: Total vessels operational costs

The following figure depicts a pie diagram of the percentages of the above expenses. We can see, as outlined above, the key role fuel consumption has on the vessels operational costs.
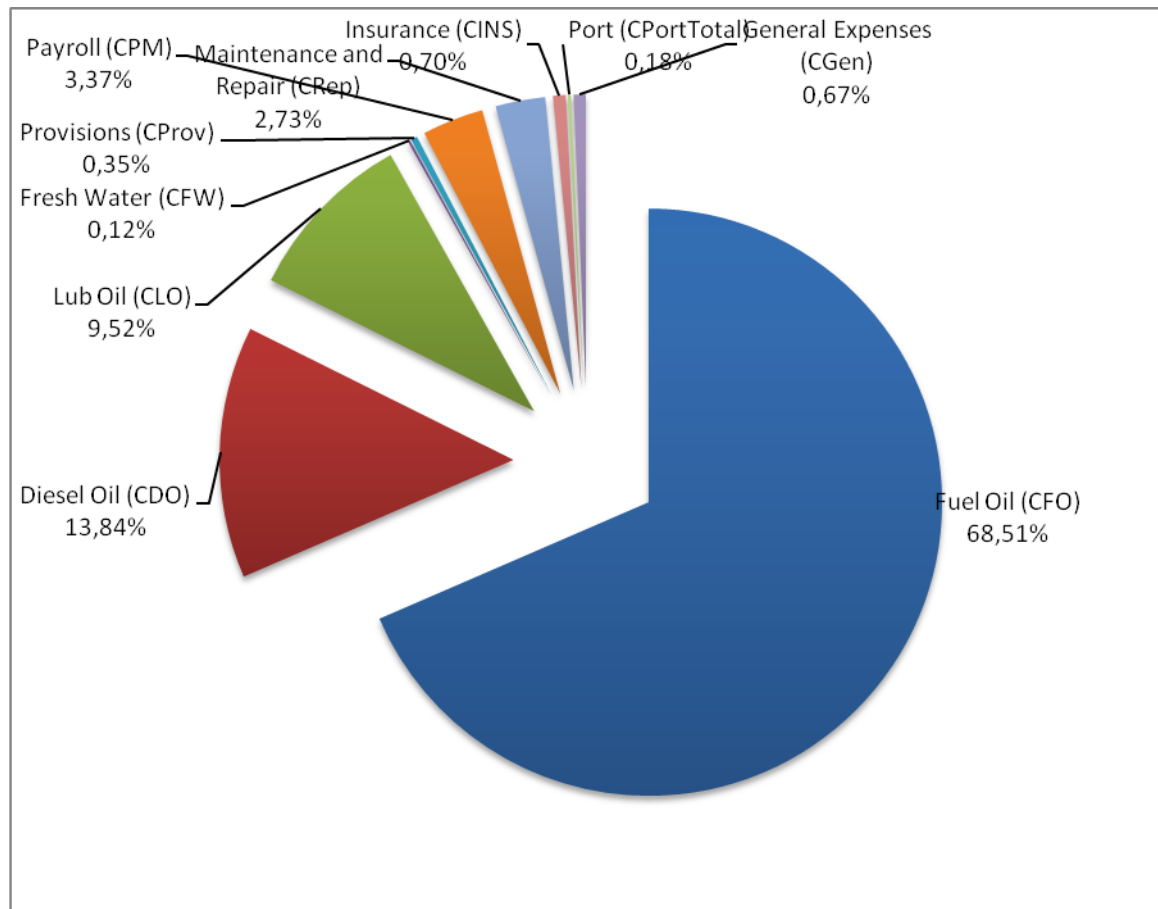
Figure 13: Percentages of vessels operational costs

ii. *Ship Operation and fuel Consumption - Parameters to be taken into account*

In order to minimize fuel oil consumption and operate the ship the best way on different voyages and loading conditions many factors should be taken seriously under consideration. For instance the optimum speed, in order the vessel to be on time on the next port or destination, or the optimum trim for the vessel to have the most cost efficient voyage are aspects of great importance for the shipping company. In order to be able to calculate these parameters accurately many variables must be taken under consideration, with the most important being the weather forecast and the specifics of each voyage. This procedure is not in any way an 'easy job' for the reason that in general, in order to calculate the resistance a ship produces, there are numerous factors to be taken under consideration. When the influence for most of the factors in the total resistance of the ship is minimized, we can say that the ship operates well in order to minimize fuel consumption, provide time reliability and safety for the crew and the cargo that is transported. Some of the factors that play a great role in the total resistance of a ship, which should be taken under consideration in order to plan an optimum voyage, are the following:

➢ The actual sea state and the additional resistance in waves and rough sea. It is important to have information for the encounter angle, meaning the angle of the ships true course and the direction of the sea, the wave height and the wave period.

➢ Currents; It is important to know the direction of the currents the vessel will encounter in its voyage. In some cases the currents a ship will encounter may even 'work' in favor of the ships route and are called optimal currents.

➢ Added resistance due to course keeping efforts especially when encountering winds from lateral directions

➢ Additional resistance due to shallow water, a phenomenon called squatting, that leads in an increase of the both the frictional and the wave resistance. An optimized voyage may include to slow down when reaching shallow waters and increasing the speed for the rest of the voyage.

➢ Added resistance due to wind also plays a significant role, however little can be done to optimize the vessels voyage in that scope.

Some examples of factors affecting optimal trim and performance are shown in the following figure
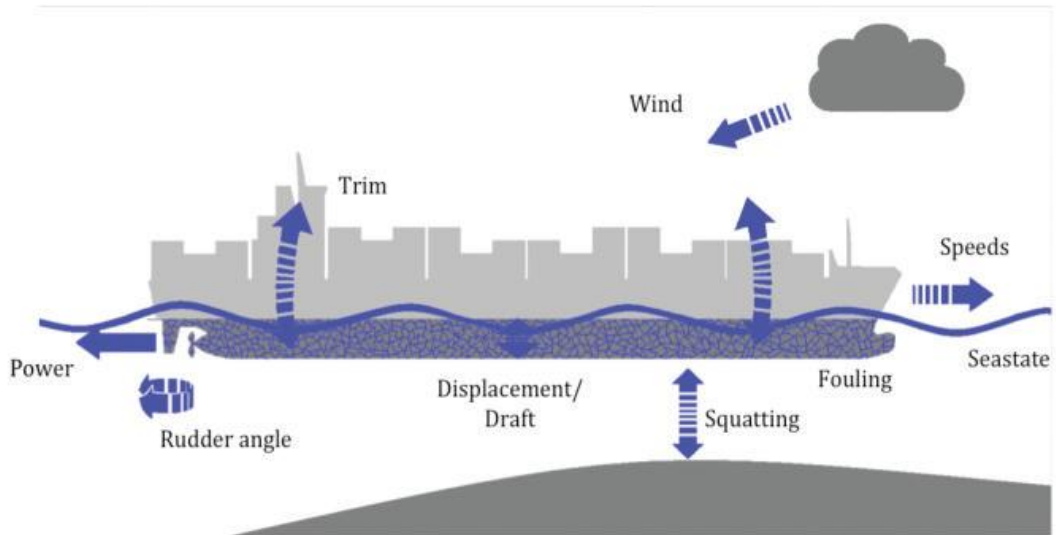
Figure 14: Factors affecting vessels resistance

The two following figures depict the weather forecast for the actual sea state (wave height – wind speed – wind direction) and the Gulf Stream south currents
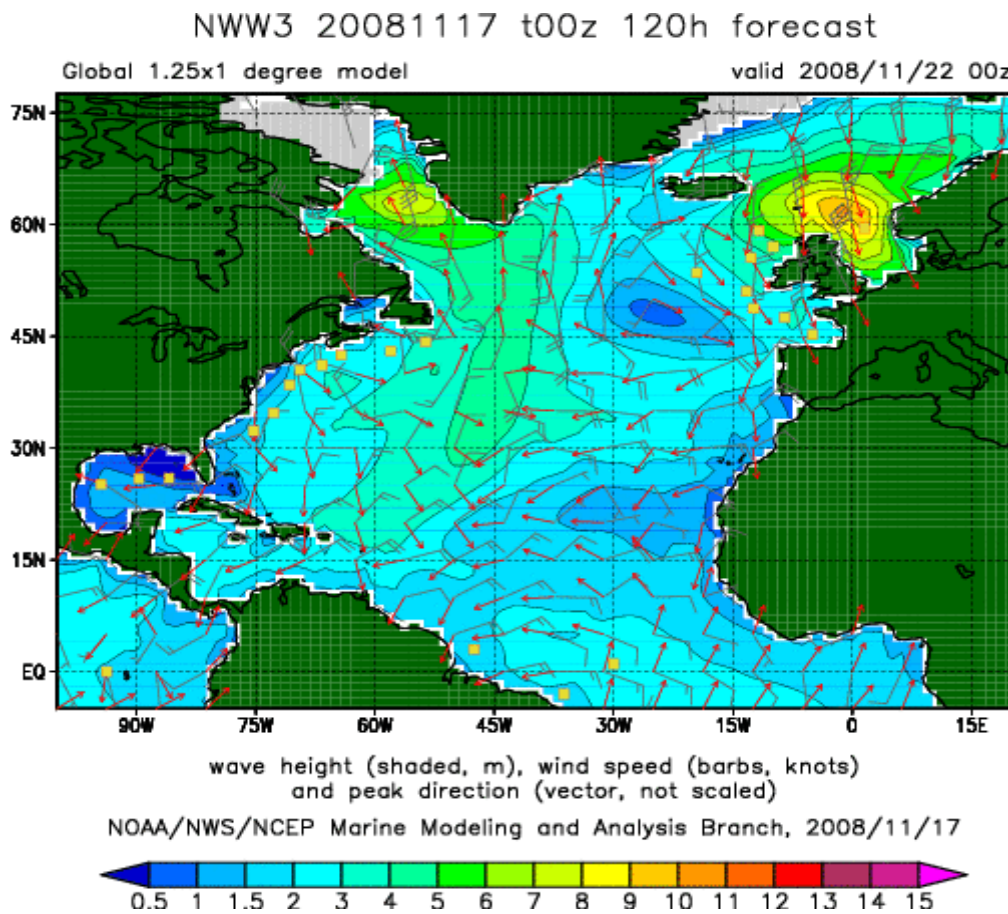
Figure 15: Weather forecast for actual sea state
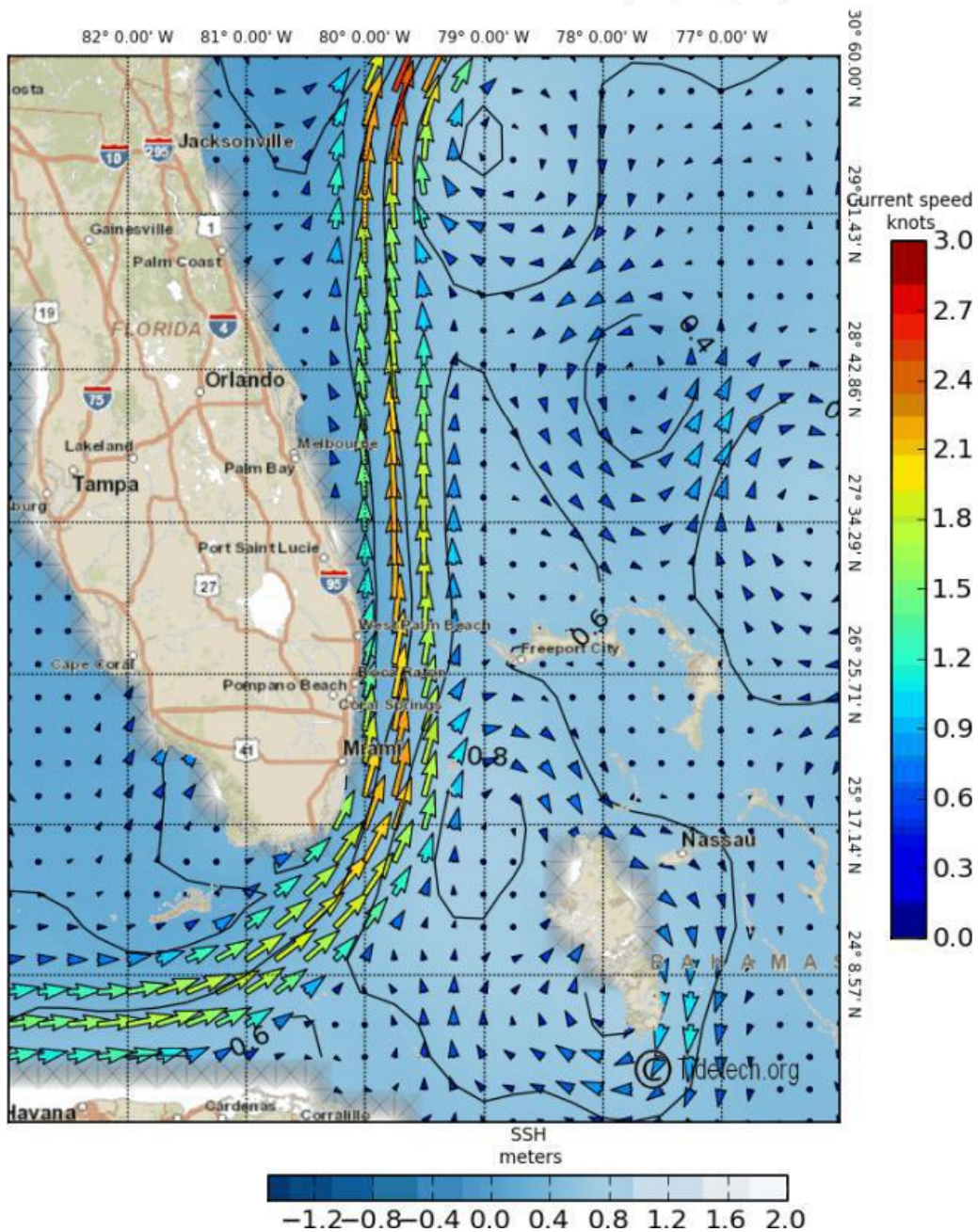
Figure 16: Gulf stream south currents

One of the most effective ways to 'run' a ship optimized is by selecting the suitable trim that can result in minimizing the ships fuel consumption by reducing its total resistance or achieving better speeds by its improved sail. If the vessel is not sailing at or near the optimum trim then it produces more resistance and particularly more wave making energy which again requires more power and fuel.

There are two types of measuring the trim of the vessel:

- The static trim

The static trim is measured when a vessel is not moving and is really easy to calculate. Traditionally, optimal trim has been explored using tank testing – the results of which are compiled into a static trim chart or table, which displays values for the optimum trim for a reasonable number of speeds and drafts and pre-defined parameters. To date many ship owners/operators are still using static trim tables as the predominant method of obtaining values for optimal trim. These static trim tables are prepared for the vessel in simulated conditions and are usually calculated based on 2 or 3 variables for example draft, speed. Thus they are not able to reflect on the dynamic external factors that affect a vessel at sea, such as weather, currents and wave-making. . Recently methods combining Computational Fluid Dynamics (CFD) and model test results with dynamic measurements have been tested out onboard different vessel types in order to produce more accurate trim tables.

- The dynamic trim

On the other hand the dynamic trim is the actual trim the vessel has when travelling in the sea and may differ significantly from the (static) trim calculated. Knowing the optimum dynamic trim, means knowing what angle to the waterline the vessel should operate at in order to consume the least amount of fuel, which lowers the costs of operating the ship and the CO_2 emissions. As we can understand calculating the dynamic trim of a vessel accurately is quite a difficult task due to multiple changing factors, but is of crucial importance in order to monitor the vessels performance. It is of significant importance that data in real-time are taken into account including the effect of dynamic conditions such as wind, and sea state. This delivers a greater accuracy and insight into how the vessel is performing and how this affects propulsion power and related fuel consumption.

These two different types of trim evaluation invariably produce different results due to a complex set of factors including vessel design, loading conditions, speed, weather, and water depth. While using static trim tables can help vessel trimming at sea, dynamic trimming is the certain way to pinpoint optimum efficiencies, while building up a data repository for longer term efficiency benefits. Given the difficulty to accurate calculate the dynamic trim of the vessel experienced seafarers, through trial and error, have been able to identify a suitable trim at which their vessel is believed to perform at optimum level.

However, the growth in vessel size over recent years has resulted in various developments in structure and hull form and in more modernized designs especially for the bow and stern of the vessel. Therefore the performance of the vessel has increasingly become sensitive to trim, with the optimum trim range becoming narrower, resulting to a direct relation between the trim of the vessel and the way the vessel performs. It is therefore now important to identify the trim (or optimum dynamic trim) at which the vessel performs at its best and reap the benefits of enhanced performance.

The Optimum dynamic trim can be defined as the trim angle at any particular displacement and speed where the propulsion power used is lower than the propulsion power used for any other trim angle at the same displacement and speed. Operating the vessel at its optimum dynamic trim can result in the vessel sailing at a higher speed and/or lower propelling power. This translates to savings in fuel as well as other economical and environmental benefits.

At the following figure we can see the decomposition of the propulsion of a ship and the factors except from the trimming of the vessel that affect it.

Propulsion decomposition of the period
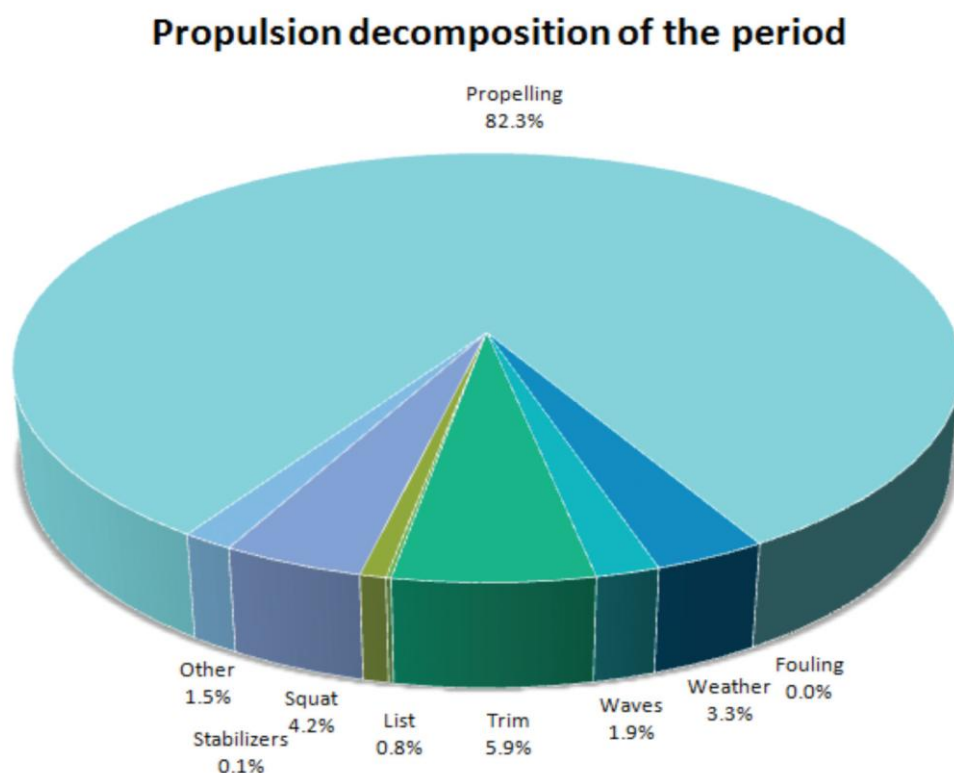
Figure 17: Propulsion decomposition

Whilst the majority of the power is used for propelling the vessel, non-optimum trim accounts for a significant amount of power that is wasted. For example it has been calculated that a Panamax size cruise vessel that was sailing 30-40cm off the optimum trim would have been able to save 700 tons of fuel annually if the vessel had been sailing at optimum trim. On average, 25 cm off trim equates to 2% in propulsion power on the vessel type in question. Based on HFO at $600 per ton this equates to $420,000 savings per annum, a notable impact for just a few centimeters. Moreover, deviations have been observed measuring static and dynamic trim. Particularly, these deviations are up to 200cm due to squatting effects and 40cm for a slight tail wind to a head wind. Therefore, one must be very careful when measuring and applying the suitable trim for a certain vessel at a certain voyage.

The other factors affecting propulsion power are not only the current weather conditions of the voyage, but also the fouling of the vessel and more significantly geographical affects such as shallow waters causing squatting.

The **squat effect** is the hydrodynamic phenomenon by which a vessel moving quickly through shallow water creates an area of lowered pressure that causes the ship to be closer to the seabed than would otherwise be expected. This phenomenon is caused when water that should normally flow under the hull encounters resistance due to the close proximity of the hull to the seabed. This causes the water to move faster, creating a low-pressure area with lowered water level surface. This squat effect results from a combination of (vertical) sinkage and a change of trim that may cause the vessel to dip towards the stern or towards the bow. The squat effect increases the resistance of the vessel and can lead to unexpected groundings and handling difficulties. It is believed to have been one of the causes of the 7 August 1992 grounding of the *Queen Elizabeth 2* (QE2) off Cuttyhunk Island, near Martha's Vineyard. At the time of the QE2's grounding she was reportedly traveling at 24 knots and her draft was 9,8m. The rock upon which she grounded was an uncharted shoal later determined to be at 10,5m beyond the sea level, which should have given her room to spare, if not for the "squat effect."U.S. National Transportation Safety Board investigators found that the QE2's officers significantly underestimated the amount the increase in speed would increase the ship's squat. The officers allowed for 0,61m of squat in their calculations, but the NTSB concluded that her squat at that speed and depth would have been between 1,4 and 2,4m. The squat effect has also been held responsible as a important factor in the collision of the bulk carriers *Tecam Sea* and *Federal Fuji* in the port of Sorel, Quebec, in April 2000.

The squatting effect is presented in the second illustration of the following figure
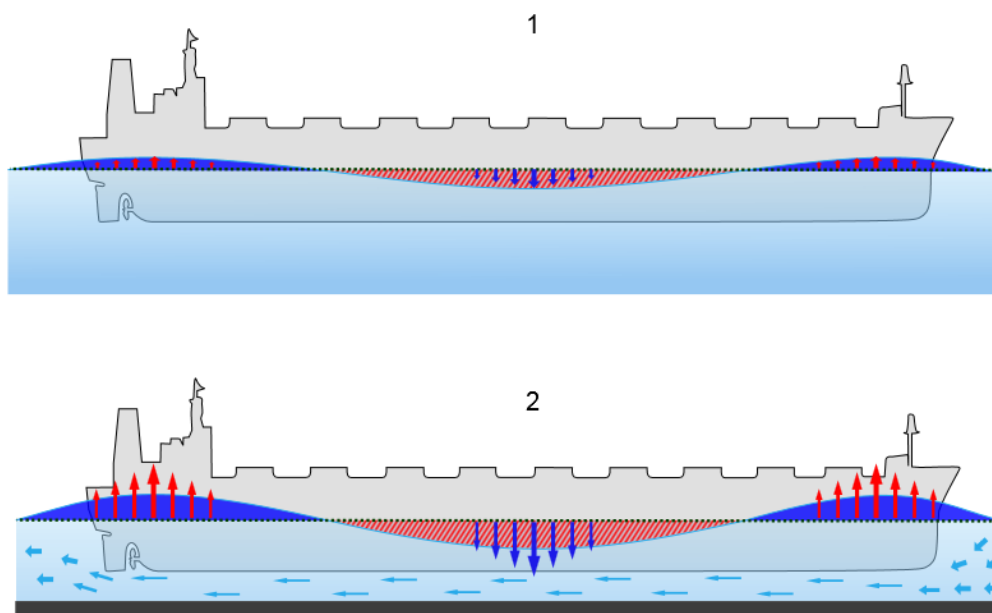
Figure 18: Squat effect

On a design basis an effective bulbous bow can prove to be very useful in order to minimize the fuel oil consumption and the wave making pattern. A bulbous bow modifies the way the water flows around the hull, reducing drag and thus increasing speed, fuel efficiency and stability. Large ships with bulbous bows generally have better fuel efficiency about 10% than similar vessels without them. Bulbous bows have been found to be most effective when used in vessels that meet the following criteria:

- Vessels that operate most of the time at or near its designed cruising speed.

- The bulbous bow is at the precise depth below the water line.

- The waterline length is longer than about 15 metres

Large vessels that sail most of the time near their design speed will benefit from a bulbous bow. This would include cargo vessels, passenger vessels, container vessels, tankers and bulkers. All of these ships tend to be large and usually operate within a small range of speeds close to their top speed.

In a conventionally shaped bow, a bow wave forms immediately before the bow. When a bulb is placed below the water ahead of this wave, water is forced to flow up over the bulb. If the channel formed by water flowing off the bulb coincides with the bow wave, the two partially cancel out and reduce the vessel's wake. While inducing another wave stream saps energy from the ship, canceling out the second wave stream at the bow changes the pressure distribution along the hull, thereby reducing wave resistance. The effect that pressure distribution has on a surface is known as the form effect.

A graphic demonstrating of how the bulbous bow influences water flow is following
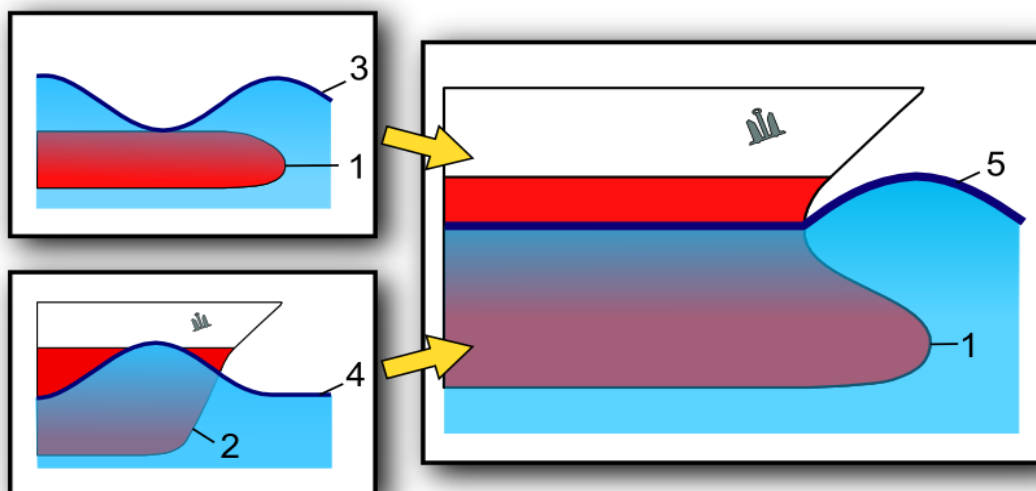
Figure 19: Bulbous bow influence on water flow

The water flowing over the bulb depresses the ship's bow and keeps it trimmed better. Since many of the bulbous bows are symmetrical or even angled upwards which would tend to raise the bow further, the improved trim is likely a result of the reduced wave action as the vessel approaches its service speed, rather than direct action of water flow over the bulb.

Depending on the type of the vessel and its use there are different types of bows. Generally speaking ships that are due to sail in an increased speed such as warships or even containerships tend to have a more sharp and long bow producing lower waves in the area around the bow and consequently lower resistance. On the other hand waves coming from the side would strike it harder and, in heavy seas, water flowing around the bulb would cause pitching movements. Vessels that are due to sail on lower speeds, such as bulkers and tankers, have a more short and wide bulb. Furthermore, the addition of a bulb to a ship's hull increases its overall wetted area. As wetted area increases, so does drag. At greater speeds and in larger vessels it is the bow wave that is the greatest force impeding the vessel's forward motion through the water. On the other hand for small vessels or for vessels that spend a great deal of its time at a slow speed, the increase in drag will not be offset by the benefit in damping bow wave generation. Therefore as the wave counter effects are only significant at the vessel's higher range of speed, bulbous bows are not energy efficient when the vessel cruises outside of these ranges, specifically at lower speeds. A good example would be a warship which has two speeds, the patrol speed and the war speech which is much higher. A bulbous bow would be effective only on the war speed and would cause the vessel to have a worse sail and consume larger amounts of fuel at its patrol speed. Taking into consideration that the vessel mostly operates at its patrol speed and rarely at higher speeds second thoughts arise whether a bulbous bow, especially designed for its war speed would be worth it.

Different bulbous bow designs are shown on the following figures.
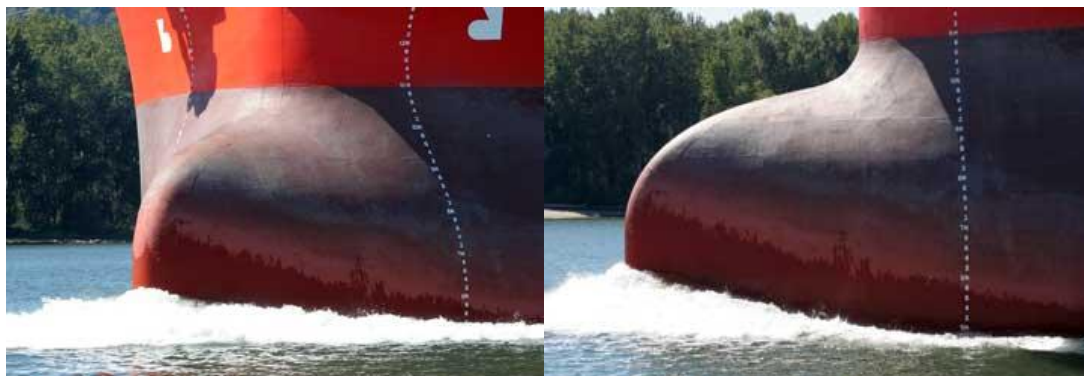
Figure 20: Bulbous bow for a bulk carrier
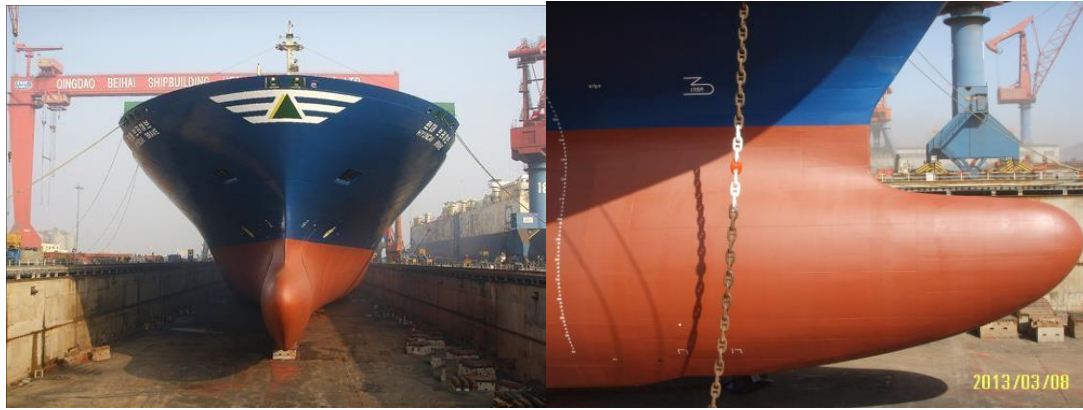
Figure 21: Bulbous bow for a containership

The design of the bulb is a complicated procedure, for the reason that a bulb is designed depending on the vessels characteristics and is effective when the bulb is properly immersed in the sea. Otherwise, for example when the vessel is travelling at light ballast condition where the bulb may not be completely immersed, the bulb produces a larger bow wave and consequently more draft leading to a not effective function of the bulb. Furthermore, quite often there is a perception in the shipping industry that the lighter the ship, the lesser the power required to propel the vessel efficiently that is not always true. A vessel sailing with normal ballast at optimum trim and perhaps a completely immersed bulb can perform better than the vessel sailing just on minimum ballast. This is because the water ballast can be used to obtain the proper immersion of the bow and stern of the vessel which allows the propeller and bulbous bow to be more effective.

The following figure depicts the effectiveness of the function of a bulbous bow.
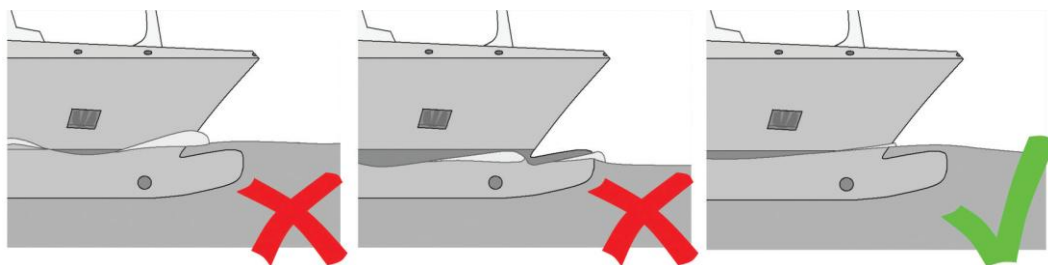
Figure 22: Effectiveness of bulbous bow

iii. Knowledge Systems and Software tools supporting Ships Operation and Voyage Optimization

Nowadays ships are equipped with numerous sensors and advanced systems which help the crew operate the vessels more efficiently. However, most of the times the data produced onboard are not utilized to their full extent, resulting in not optimized voyages from an economical and sometimes safety scope. Furthermore, it has been observed that the measurements gathered from the crew regarding the data produced onboard, and most importantly the fuel consumption, are not accurately transferred back to the shipping company. The reason for this may simply be the negligence of the crew for accurate measurements. Unfortunately, something that should be reported is the fact that during the years, seldom illegal fuel trade has occurred, from crew members in ports the vessel visits. In that case the non accurate measurements are done on purpose from the crew.

Due to the economical crisis and the very low in general freight rates ship owners try to operate their fleet in the most economical way. Thus, in order to take advantage of an optimized voyage and to accurately monitor the fuel consumptions, during the last years even more ship owners seek professional help from companies that specialize in this field. One of the major companies in this field is 'Eniram'.

'Eniram' gathers all type of data coming from a vessel with their advanced technology and transfers them through satellite immediately in the office of the shipping company without the need of human intervention from the crew. Thus, not only the data collected are far more accurate, but also this company specializes in the elaboration of these data to accomplice the perfect voyage of the vessel cutting down the cost in different circumstances. With bunker prices on an upward trend, and proven fuel savings of $3 - 5\%$ per vessel, this company offers a return on investment within a matter of months on most vessels. The way this company operates presents significant interest.

'Eniram' collects a billion measurements every day from different vessels being monitored, specifically over 10,000 measurements per second, forming a very rich database of operational vessel sensor data for the past years including 100,000 sea days of high accuracy real-time data. Combining naval architectural knowledge the approach this company has is based on real measured data and algorithms that can result in optimizing the vessels voyage for different type of ships and weather conditions. Their philosophy is the optimization should be based on utilizing this real data collected and not to utilizing any artificial counterparts such as performance curves from simulations or laboratory tests including CFD simulations, wind tunnel tests and towing tank tests and for the reason that at sea most of the times the reality never matches the laboratory. After gathering the information needed and with the help of the large database they have built through the years a mathematical model of the vessel arises that surpasses the accuracy of other existing modeling methods. Thus, the connection between crew operations and fuel consumption is clearly seen and the

impact of influencing factors such as current, wind, waves and trim is able to be precisely pinpointed and quantified, something not possible previously due to the small changes in performance were buried under the constantly changing external factors. Apparently, a method with extreme precision in order to to remove these fluctuations and uncover the subtle changes enabling the savings is needed.

Eniram's solution system contains onboard applications as well as onshore performance management tools and a range of data intelligence services designed to help improve vessel efficiencies and cut down cost. The solution suite includes Onboard Assistants, Performance Management Solutions and Data Analytics Services. 'Eniram' uses a broad database of actual vessel performance data for a variety of different operating conditions. With over 130 vessels and a billion real-time signals collected every day the optimal performance model for every single vessel in every condition easily built up.

Most importantly, the data is gathered in real-time and become very easily accessible to the office of the shipping company. The data is gathered by two or more sensors on the vessel and processed by the Eniram Vessel Platform (EVP), which contains all the important data collected from multiple sources through the years and is integrated with bridge and automation systems. This information is complemented with additional measurement of vessel propulsion data, fuel flow and consumption as well as vessel draft and movement.

The following figure shows roughly where the high accuracy attitude sensors are installed on a vessel

Figure 23: High accuracy attitude sensors

The data collected are analyzed from onboard assistances, which deliver clear insights into vessel performance in real-time enabling the crew to monitor and easily maintain optimum operations for best fuel efficiency while taking account of all dynamic conditions including weather and sea state.

Two of the most common used onboard assistances are the following:

➢ Dynamic Trimming Assistant (DTA)

A decision support tool for monitoring and optimizing the dynamic trim of a vessel in real-time, delivered via an intuitive graphic user interface, guiding the crew to make appropriate adjustments. Dynamic trim optimization involves collecting and performing multidimensional analysis on real-time data on a vessel. It takes into account most of the changing variables to calculate the effect of trim on performance - including hydrodynamic forces, such as squat, propeller thrust and maneuvering rudder angles. It also factors in the dynamic impact of weather conditions such as wind, sea state, rolling and surging. Even a small dynamic trim adjustment can lead to significant fuel savings.

➢ Optimum Speed Assistant (OSA)

A comprehensive and easy-to-use solution to help the crew maintain the most efficient speed on a given vessel taking into account external conditions and schedule, maximizing fuel efficiency and enabling just-in-time arrivals in port and minimize costs.

Both of these technologies are really simple to operate and do not require specialized crew knowledge. Furthermore, from these systems arise different analysis and reports for the shore based managers to evaluate with the scope of improving and monitoring the vessels performance. After the data collected are analyzed and the factors affecting performance are identified, strategic decision making in a wide range of areas can be improved including the following:

✓ Trim potential - Trim savings

✓ Hull Fouling/Aging

✓ Speed - Route profile

✓ Engine Efficiency

✓ Dry Dock Impact

The following figure shows a Dynamic Trimming Assistant (DTA). It is very simple to use and allows vessel trimming to be a self-guided process.

Figure 24: Dynamic Trimming Assistant (DTA)

Due to the ever increasing demand for assistance in voyage optimization from shipping companies in their desperate need to cut down costs, even more companies have developed systems that provide important insight in voyage optimization like 'Eniram'. 'Jeppesen Marine' is one of the many companies nowadays that have also developed a similar system of advanced computerized optimization of ship operations called Voyage and Vessel Optimization System (VVOS). The operating principle of VVOS is to reduce fuel consumption and associated emissions while maintaining the same overall transit time. Moreover, a ship's speed and route can be optimized based on the wind, waves, and currents, taking into account the ship's performance criteria such as hull shape, horsepower, load, trim, ballast, pitch and roll limits, and other factors. As the previous program from 'Eniram' the VVOS program incorporates advanced voyage optimization algorithms that include the ship's hull design, propulsion systems, and sea keeping models, as well as user-defined safe operating limits in combination with a analytical weather forecast of the condition the vessel will encounter in its voyage including wind, waves, currents, and special weather warnings. 'ABB' has also developed a similar system and generally speaking a ship owner nowadays can find a variety of systems to choose between, all being easy to install and offering a very fast return to their investment, due to the very high fuel prices and the strict regulations regarding hazardous emissions.

Chapter three:

Employed Methods for the Estimation of Resistance, Powering and Fuel Consumption

i. HOLTROP Statistical Method

In order to easily calculate the resistance of ships in different speeds and loading conditions, especially in ballast conditions where we do not have similar speed test curves as in full load departure, and in an attempt to validate more accurately the data from the real time consumptions of the vessels we use the semi-empirical HOLTROP method.

The semi-empirical HOLTROP method is a statistical method presented for the determination of the required propulsive power at the initial design stage of a ship. This is a statistical method and was developed through a regression analysis of random model experiments and full scale data, available at the Netherlands Ship Model Basin.

The total resistance of a ship according to this methodology breaks down in several parts:

$$R_{TOTAL} = R_F \cdot (1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A$$

Where:

R_F : Is the Frictional Resistance predicted using the ITTC formula of 1957. For large bulk carries with low Froude numbers, as these examined, is by far the major part that composing the total resistance of the vessel.

$1 + k_1$: Is a Form factor describing the viscous resistance of the hull form in relation to the frictional resistance.

R_{APP} : The Appendage Resistance, which depends on the number of rudders and other exposed surfaces like anodes, spoilers, fins and shafts.

R_W : The Wave Resistance, which is calculated using a statistically derived formula depending on the main dimensions, the entrance angle of the design waterline, the Froude number, the bulbous bow design and the prismatic coefficient of the vessel. Contrary to the frictional resistance, it plays a much smaller part calculating the total resistance in such types of vessels.

R_B : Additional pressure resistance of bulbous bow, which takes into account the pressure increase due to the presence of a bulbous bow.

R_{TR} : Additional Pressure Resistance due to immersed transom stern. It takes into account the pressure increase and increase wave at the transom area as well as the flow separation there.

R_A : Model Ship correlation resistance, which is supposed to describe primarily the effect of the hull roughness and the still air resistance.

Generally speaking the HOLTROP method is very accurate when calculating the resistance in large bulk carries with a big block coefficient numbers and low sailing speed, something validated in the process of this paper. Especially, due to the low Froude number of these vessels and the average and simple hull form, the total resistance depends mostly on the frictional resistance leaving the wave making resistance only to be a small fraction of the total resistance of these ships. Furthermore, the ITTC formula of 1957 approaches well the frictional resistance of vessels with simplified geometry like the ones we examine. At a later stage of this report we will use the SHIPFLOW computational fluid dynamics (CFD) packet in order to validate the results derived from the HOLTROP method and examine and analyze more accurately the wave resistance and wave patterns of one of the vessels in different speeds and loading conditions.

In order to use the HOLTROP method and calculate the resistance of the three vessels in different loading conditions and speeds we will use as input the values of the basic characteristics, such as main dimensions and form coefficients of the vessels, as they have been given to us. More significantly, we use the following data as input to use the HOLTROP method:

L [m]	v [m^2/s]	hb [m] (center of Abt (BULB) from keel)	LCB (% of L, from 0,5L)
B [m]	Vol [m^3]		
T [m]	Cb	Abt [m^2 of bulb]	L/B
T Aft [m]	Cm		
T fore (m)	Cp	AT [m^2] (immersed area of transom)	B/T
Disp [t]	Cwl		L/Vol^(1/3)
ρ [kg/ m^3]			g [m/s^2]

Figure 25: Input data for HOLTROP method

Regarding the propeller efficiency, which is also an input used in the HOLTROP method, we use the GRID program for all three vessels. The propeller efficiency is about 0,68% for the vessels in question.

Having all the input data we are able to use the HOLTROP method to calculate the resistance we expect the vessels to have in both full load departure and ballast conditions. As it was mentioned previously, having speed test curves only for the full load departure of the vessels, made the comparison for data obtained through ballast conditions not feasible. Using this method enables us to compare the real time consumption data also for ballast condition voyages.

ii. Computational Fluid Dynamics (CFD) packet SHIPFLOW

a) Scope of Work

In order to validate the results derived from the HOLTROP method and examine and analyze more accurately the wave resistance and wave patterns of one of the vessels, namely the vessel 'Voyager', in different speeds and loading conditions, we will use the SHIPFLOW computational fluid dynamics (CFD) packet. More significantly SHIPFLOW proves to be useful for the following reasons:

✓ Firstly, to validate our results regarding the form factor K which describes the viscous resistance of the hull form in relation to the frictional resistance and can be more accurately calculated running the viscous code in such programs.

✓ Moreover, as it is mentioned above the HOLTROP method is a statistical method and therefore cannot determine particular details of local hull form shape that might trigger irregularities and problems at the viscous pressure resistance and the wave field. SHIPFLOW is a good aid in order to identify any unexpected wave patterns, like extreme wave heights that can lead in a big deviation of the wave resistance predicted by the HOLTROP method. Consequently, in order to calculate more accurately the wave resistance and wave patterns, especially at the bow and stern areas, and compare the results with the HOLTROP method the SHIPFLOW proves to be really useful.

✓ Lastly, to attempt and optimize the vessels voyage by selecting the suitable trim, or even bulb form, which minimizes the wave resistance and consequently the total resistance and fuel consumption of the vessel.

b) How SHIPFLOW works

The computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and algorithms to analyze and solve problems involving the flow of fluids. The fundamental basis of almost all CFD problems is the equations of Navier - Stokes, which determine the flow of fluid.

The flow around a body can be described mathematically as a function of fluid pressure and the three components of velocity. This can create a series of equations of motion, such as the Range Average Navier - Stokes equation (RANS) for turbulent flow, which are solved by specific boundary conditions. These equations are often complex to solve and therefore computational fluid dynamics programs are used in that scope. Several methods have been developed based on simplified equations RANS. As the CFD codes become more reliable and efficient, the use data extracted from experimental methods becomes less necessary.

The computational fluid dynamics (CFD) program SHIPFLOW is specifically designed for the hydrodynamics of ships. Generally, the hydrodynamics of a ship differs from the other areas of fluid dynamics. This is attributed to the presence of the free surface, the sea, with immediate effect of creating waves adding resistance to the vessel. SHIPFLOW solves its computational problems of hydrodynamics by separating the vessel and the computational approach in three regions.

When equations of RANS are used from the CFD codes, there are the two different approaches available:

➢ **The Global approach**: The global approach is quite time consuming and requires high computational power. However, with this approach, the RANS equations are applied throughout the entire computational region making it possible to calculate all the necessary measurements.

➢ **The Zonal approach**: This approach was proposed by Larsson (1993) in order to reduce the computational time, using three separate methods in the calculations. Each one of them applies to the region of the fluid, which exhibits the best performance.

The three territories which define the zonal approach can be seen at the following figure.
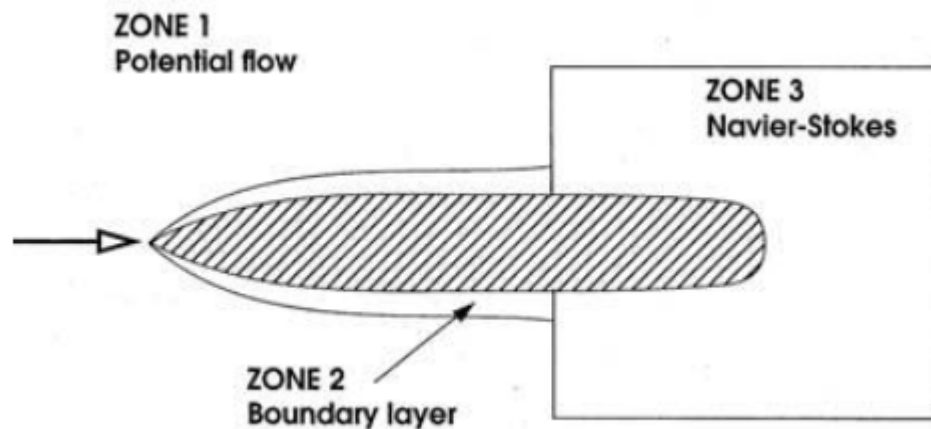
Figure 26: SHIPFLOWS zonal approach

Zone 1: Potential flow

The fluid is assumed to be non rotational, incompressible and non turbulent. These assumptions are acceptable for the flow around the ship, as the Reynolds number is relatively large and the viscous effect is limited to a thin layer near the hull and wake (see next zone). Pressures and speeds are calculated by an appropriate dynamic function. Namely, from the dynamic flow, the pressure and velocity on the wetted surface are calculated. Thus, the integration of the vertical pressures on the hull results I the calculation of the wave resistance.

This method is used to analyze the fluid flow in the remote zone from the vessel. (Zone 1). In this region the fluid is analyzed in continuous streamlines starting from the forward end of the ship and terminating at the aft.

Zone 2: Boundary layer

The area of the free surface describing the thin boundary layer along the hull is defined as Zone 2. The nature of the fluid changes as it moves along the zone and the flow characteristics are calculated using the boundary layer theory. The flow starts from the point that stops to be laminar and deviates gradually as we run along the hull. When it reaches the

transition point where viscous forces cannot keep up with the streamlines the flow becomes turbulent. In Zone 2, the boundary layer is analyzed using integral equations and the result is determined by Runge – Kutta equations. However, this method cannot be applied in the stern of the ship, where dense and converging streamlines are observed.

Zone 3: Navier – Stokes method

Zone 3 contains the stern of the ship, as shown in the above Figure. This region is characterized by a fully turbulent flow, including the wake of the vessel and extends well beyond the transition point of the flow, usually located on the midship. In this zone the Navier – Stokes theory is applied in order to calculate the energy, and therefore the resistance. In this region, the Navier-Stokes (RANS) equations and the conservation of mass theory is used to describe the flow. The computation of these complex equations requires long time and for this reason it is limited in the stern of the ship, where it is most needed.

In order to determine the Wave resistance of the ship, SHIPFLOW has two options

- ✓ The **Pressure integration** analysis determines the wave resistance through the pressure integration on the hull panel. The hull pressure consists from the hydrostatic and hydrodynamic pressure. In order to obtain the result of the wave resistance for the linear solution, the hydrostatic pressure vanishes involving the integration of only the dynamic pressure. For non-linear solutions hydrostatic pressure does not vanish and thus both pressures must be completed. The hydrostatic pressure is often higher than that of the hydrodynamics causing some problems with the accuracy of the method. The solution to this problem is to use a sufficient number of panels to the surface of the hull.

- ✓ The **Wave Cut** analysis determines the wave resistance analyzing the waveform. The wave cut analysis determines the wave height to a number of transverse wave sections at the back of the ship under two conditions.

    - ○ The wave sections must be in a region where the waveform is relatively smooth. This means that the first section cannot be too close to the stern of the ship.

- o The second condition is that the sections must cover at least one wavelength and the wavelength distribution of the wave cuts cannot be at equal distances.

The method determines the wave resistance by approximating the wave elevation in each section derived from the sum of a set of primary waves. The advantage of this method is the fact that it depend less on the number of panels in the hull. This makes the wave cut analysis more robust from the pressure integration analysis, especially for hulls with more complicated geometry and intense curvature regions. In CFD programs like SHIPFLOW coefficients for both methods are usually provided. However, the coefficients of the wave cut analysis are preferred usually for the optimization processes due to their greater robustness.

c) *Assessment procedure of the Wave Resistance in SHIPFLOW*

Due to the similarities of the three vessels it was decided to process with SHIPFLOW only one of the three vessels in question, the vessel 'Voyager'.

We were able to obtain the offsets of this vessel. However, due to the fact that not even the offsets were quite accurate, we forced to use the program AVEVA line to create a hull form as close as possible to the hydrostatics and general characteristics of the vessel. The process we followed included circles of smoothing sections, fitting them to waterlines and vice versa. We were also able to create a more accurate flat of bottom with more points. After the distortion we obtained a very close value to the block coefficient of the vessel given.

The hull form geometry constructed with the program AVEVA Lines was given in SHIPFLOW in a section xyz text file. In order the offset file to be readable in SHIPFLOW we split the sections in four different groups according to their position on the vessel as following

- ✓ Bulb

- ✓ Hull

- ✓ Boss

- ✓ Stern

The first point of each section is marked with the number 1 and the rest with 0. The last point of the last section of each group is marked as 9. The section offset file is now readable from SHIPFLOW.

The following two figures depict the constructed geometry of the vessel 'Voyager' in SHIPFLOW. The different density of the four groups (bulb, hull, boss, stern) can be distinguished.
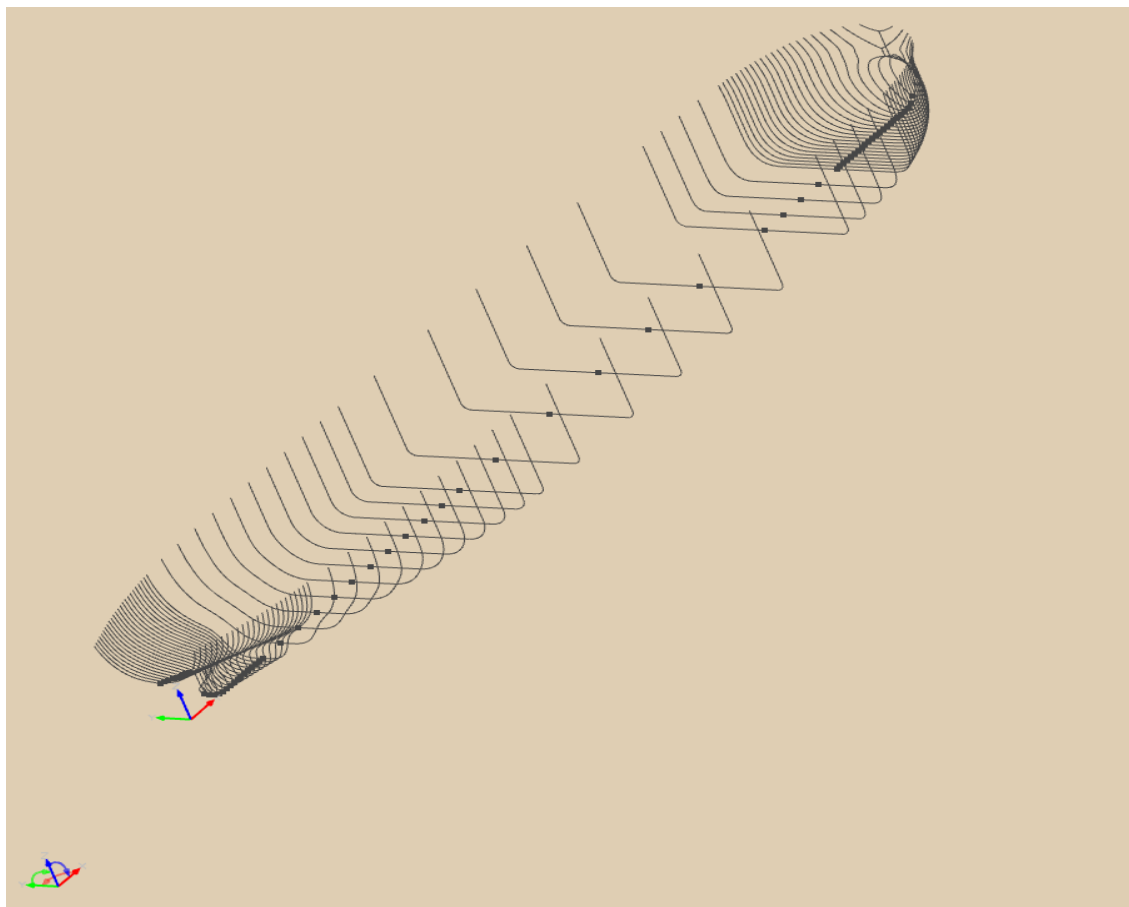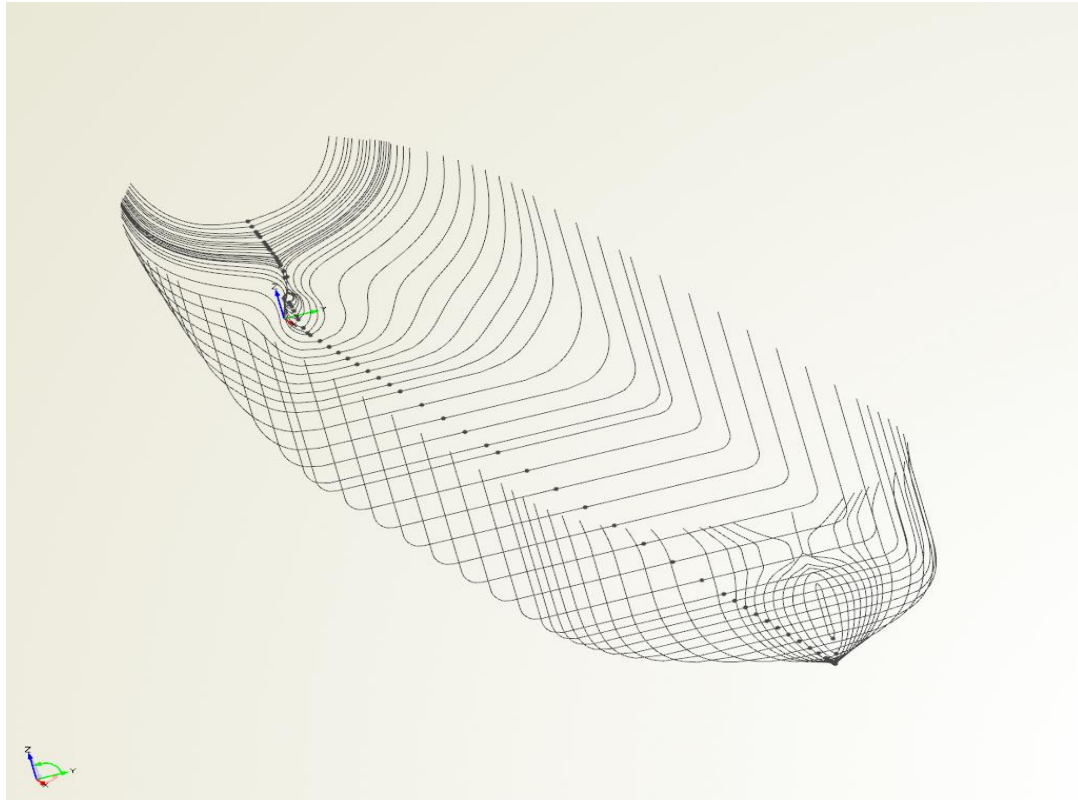
Figure 27 & 28: Constructed geometry of the vessel 'Voyager' in SHIPFLOW

Subsequently, the Configuration and Computation files were created in order to produce the panels of the hull and the free surface and to calculate the wave resistance coefficient. We should mention that for the wave resistance, SHIPFLOW gives as two coefficients.

- ➢ **Cw** which is the coefficient derived from the pressure integration analysis

- ➢ **Cwtc** the coefficient derived from the wave cut analysis

Both of the above coefficients give us the resistance of the vessel from the following formula and under normal circumstances should converge.

Rw(N) = [ρ (kg/m^3) * Cw * wetted surface S (m^2) * V (m/s) ^2]/2

In order to calculate the above resistance coefficients for the different speeds and loading conditions of the vessel we use the potential flow method as analyzed previously.

For this purpose, we use the XPAN code of the computational packet SHIPFLOW. XPAN is a program that analyzes potential flow around 3D objects by separating the surface in panels. Later on, in order to have more accurate results, the paneling procedure was manually configured using the XMESH program. The penalization was done separately, in order to cover the different specifics, on the following groups:

- ⇨ For the **hull**: Bulb – Hull – Stern – Boss

- ⇨ For the **free surface**: Free surface – Transom

The parameters of the process of the creation of panels were the following:

- The matrix density should vary depending on the different areas, in order to get more accurate results. For example in areas like the stern or bulb, where the geometry of the vessel is not so smooth, the paneling must be denser. Moreover, each created wave in the free surface must be able to be described by an appropriate number of panels so that the peaks and valleys of the wave are correctly determined. In addition, at the transom area behind the ship, the density of the panels must be increased, due to the large concentration of waves in that area.

- Moreover, at the free surface particular attention must be given to cover the entire wave system and include all wave energy.

- Lastly, the adjoining panels should be as similar in size as possible.

Theoretically speaking, the more panels we use, the more accurate results we get. In practice though this is not feasible for the reason that SHIPFLOW has a certain amount of memory and a very dense matrix would either cause the program to run for days for a single calculation or would not run at all. We were able to achieve a more than sufficiently dense paneling.

The following figures depict the paneling of the different hull areas
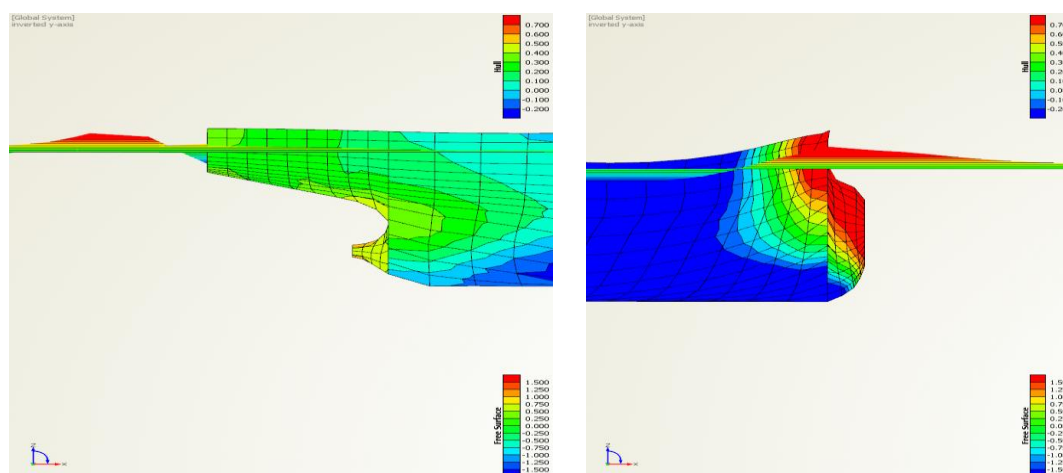
Figure 29: Bulb and stern paneling in SHIPFLOW
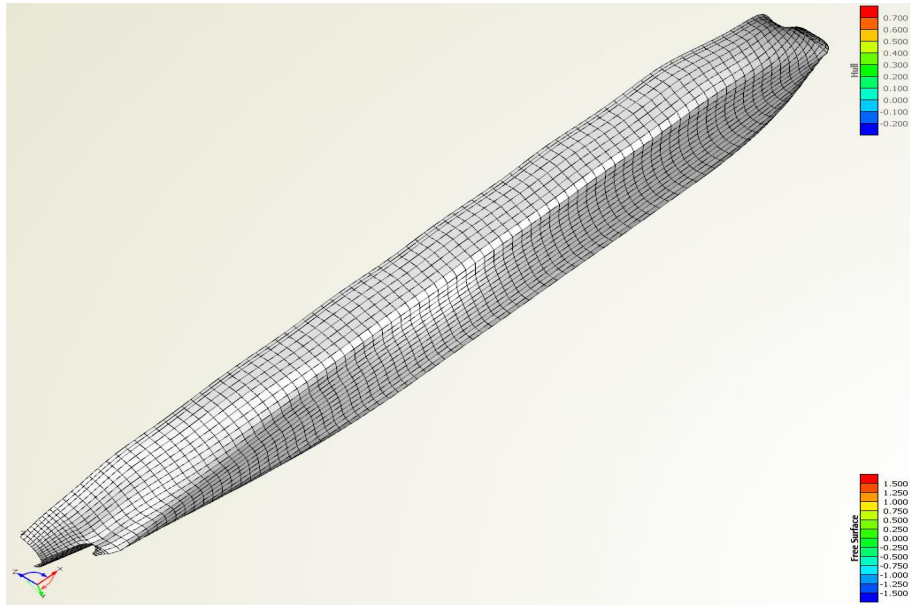
Figure 30: Hull paneling in SHIPFLOW

The following figure depicts the variations at the density of the panels in the free surface.
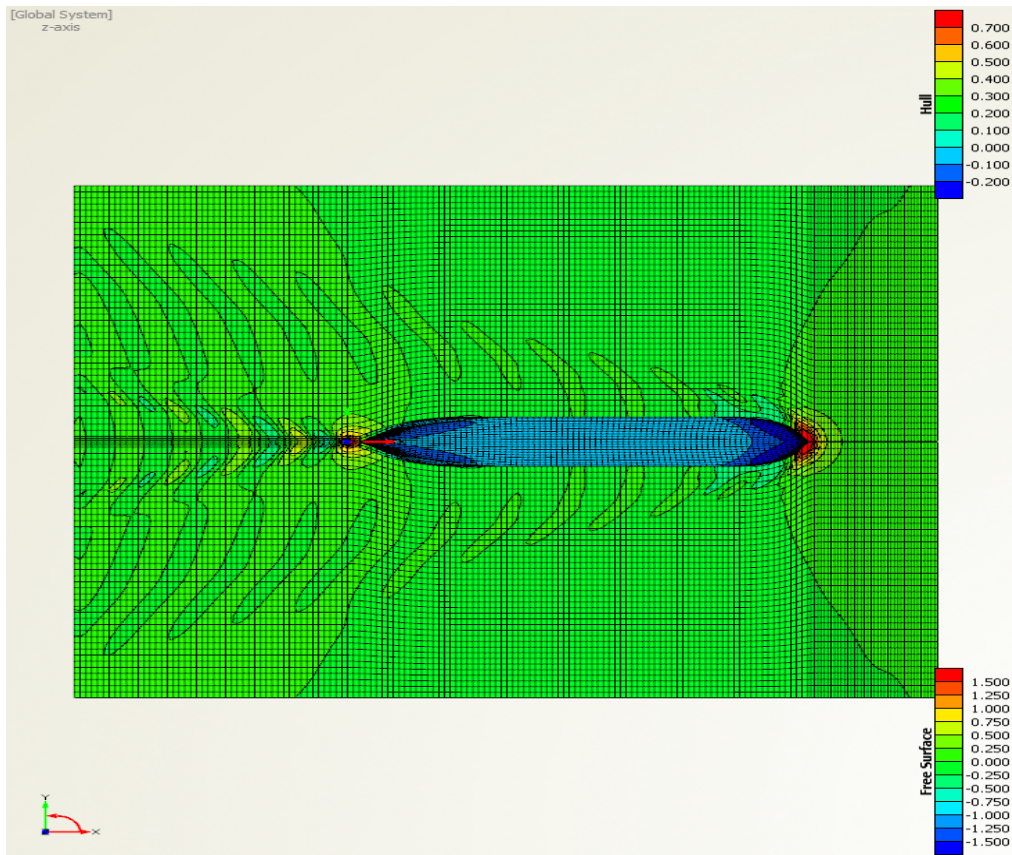
Figure 31: Free surface paneling in SHIPFLOW

Chapter four:

Onboard information of Fuel Consumption for the Three Study Ships

i. Information about Onboard recorded data of Fuel Consumption of the Three Vessels in different Voyages and Loading Conditions

One of the most significant objectives of this diploma thesis is to try and evaluate data collected on real time regarding fuel consumption for the three cape size bulk carriers mentioned previously. We were able to obtain very detailed voyage logs from different voyages and loading conditions of the vessels as well as speed test curves for all three vessels for their full load condition. The log abstracts gathered contain information from the crew members regarding the daily fuel consumption of the vessel in a particular voyage, the weather condition it encounters throughout the voyage, the average sailing speed, the forward and aft draft at departure and arrival to the port of destination and remarks on possible vessel motions due to bad weather. Regarding the weather condition, the crew gathers information about the wind (direction-force), the sea condition (waves-swell) and the currents in an attempt to accurately describe the weather and general the sea condition the vessel encounters in its voyage. Except from the vessels drafts, the rest of the information is updated in the log every 24 hours until the vessel reaches its destination. The following figure depicts a page from a certain voyage log:

Figure 32: Voyage log

In order to compare the fuel consumption given in tones per day in the voyage log with the speed tests curve of each vessel we follow the following procedure:

❖ The fuel consumption of the vessels is recorded daily in tones per day. In order to convert it in KWs, which is the module found in the speed test curve, we use the engine output diagram of the vessel and particularly the Specific Fuel Consumption (SFOC) curve.

❖ The SFOC curve gives as the KWs the engine produces when consuming a certain amount of fuel given in grams per hour. Therefore, converting the tones per day of fuel consumption of the vessels in grams per hour we can easily obtain, using the SFOC curve, the KWs the engine produces.

❖ The speed test curves are for a certain loading condition, with a certain draft and displacement, namely the full load departure. On the other hand, the real time information we have gathered refers to different conditions, loaded and ballast. For the loaded conditions, where the vessel has similar displacement and draft with the full load condition, we have to make some adjustments in order to 'transfer' the fuel measurements to the same condition as given in the speed tests enabling comparisons. The information on ballast conditions will be analyzed at the next chapter of this diploma thesis using the semi- empirical HOLTROP method.

❖ Thus, in order to be able to compare the different loading conditions with the specific condition found at the speed test curve we are able to use the Admiralty coefficient (CAD). Since we refer to similar loading conditions with similar drafts we can assume that the CAD of the vessel remains constant for the reason that no significant changes can be observed in the hull form. The Admiralty coefficient is constant for a given hull and gives the approximate relationships between the needed propulsion power P, ship speed V and displacement ∇. The CAD of a vessel is defined as follows:

CAD= $(\nabla^{(2/3)} \times V^{(3)})/P$

For the same CAD and speed we can equate the following:

$\nabla_1^{(2/3)}/P_1 = \nabla_2^{(2/3)}/P_2$

∇_1 = the displacement for full load departure, as in the speed curves

∇_2 = the actual displacement of the vessel in its voyage derived from the draft mentioned in the voyage log using the trim and stability booklet.

P_2 = the propulsion power in KWs derived from the fuel consumption of the vessel in tons per day.

P_1 = the corrected value of the propulsion power of the vessel if it was sailing at full load departure. It results while solving the above equation.

❖ In order to have more reliable results we must correct the sailing speed of the vessel based on the information we have on currents it encounters while travelling. For example an adverse current of 0,3 knots should equal in an increase of the sailing speed monitored in the log abstracts of 0,3 knots.

❖ Lastly, since the speed test curve is a theoretical approach calculating the vessels fuel consumption under ideal conditions, the speed test results should be corrected with a suitable factor taking into account the non ideal conditions the vessels encounter in their voyage. Regarding to the weather conditions, it is a normal practice to add an extra power margin, the so-called sea margin, which is traditionally about 15 %. It is obvious that when the weather is bad, with head winds and waves, the ship's resistance may increase compared to operating in calm weather conditions. Fouling, period from last dry dock and others which were analyzed previously in this diploma thesis are also factors affecting the vessels resistance and fuel consumption and should be taken under consideration.
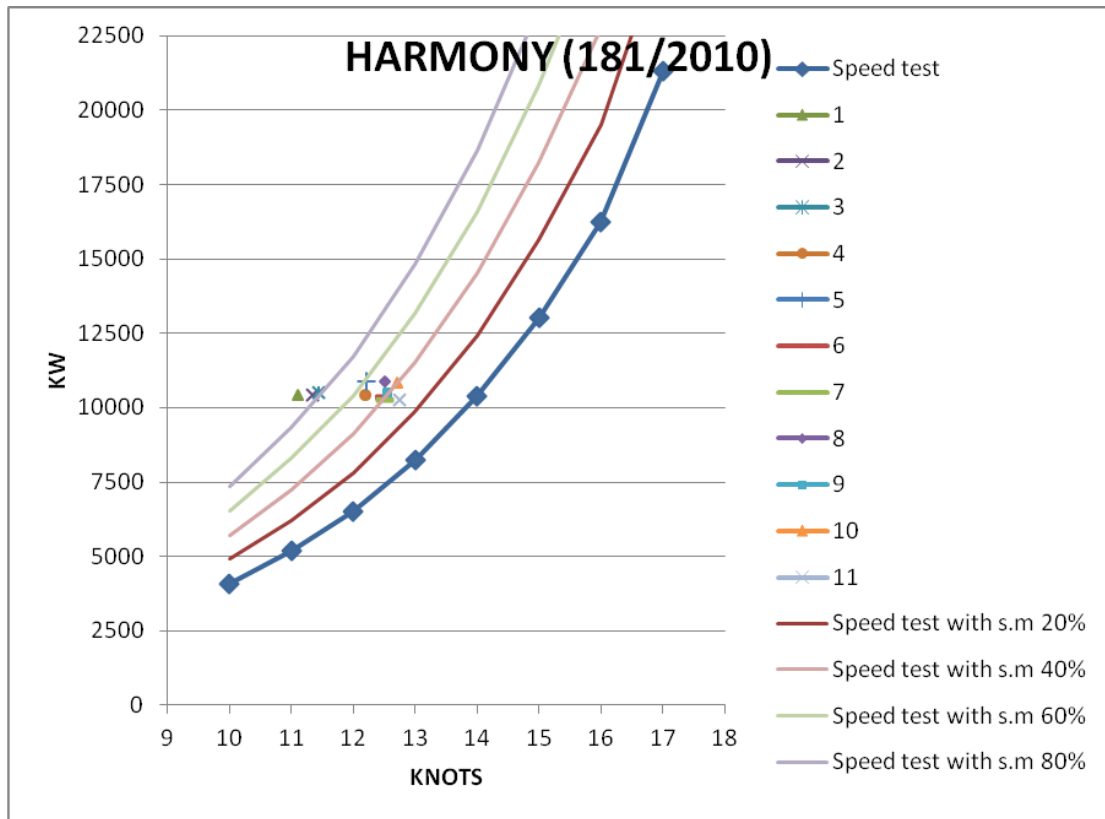
ii. Sources of Uncertainty

As we can see at the following figure regarding the real time consumption of the vessel 'HARMONY' compared with its speed test curve, with a margin of 20% the speed test results deviate tremendously from the real time consumption data collected. Most importantly though, one couldn't help to miss the fact that the results gathered from the vessels voyage log show great abnormality. The following remarks lead us to believe that most of these measurements seem to be random and not carefully gathered from the crew members.

- ✓ In some cases, the vessel seems to consume the same or even more amount of fuel when sailing without cargo (ballast condition) from sailing fully loaded without the weather conditions to differ significantly.

- ✓ In many cases the weather conditions seem not to have the expected influence on the vessels performance. Specifically, even though the weather conditions seem to be worse, the vessel consumes less fuel than other days with certainly more favorable weather conditions.

- ✓ Furthermore, we should note that the fuel consumption of the vessels remains almost constant on every trip although there are variations in the average cruising speed. More specifically, during the same voyage and with almost the same weather conditions, the vessels are being recorded to consume the same amount or sometimes even more fuel sailing in a lower speed ,even up to 2 knots, something beyond dispute non reasonable. Partly this could be attributed to the changes in the weather conditions during a voyage, although the repetitive manner of this observation and the fact that these changes frequently do not appear on the data gathered makes it impossible for us to explain and evaluate.

- ✓ Moreover, we should highlight the fact that the vessel 'Voyager' seems to have quite better daily consumptions in comparison with the other two vessels, which sometimes are even close to what expected from the speed tests with the appropriate increment taking into consideration the sea margin and the other factors that affect the vessels resistance and fuel consumption. Except from the fact

that simply the crew may have been more accurate when monitoring this vessels performance, there are two factors needed to be further outlined and commented.

- o Firstly, in the log abstracts gathered it is remarked that 'the vessel is sailing at ECO speed due charterers demand. Eco speed can be achieved with the vessel sailing at a lower percentage of its engines MCR, even down to 60%, and consequently a lower rpm rate and speed. Nevertheless, the vessel does not seem to sail at a lower speed compared with the other two vessels.

- o Furthermore, we should outline the fact that the log abstracts collected regarding voyages of the vessel 'Voyager' seem to be monitored at quite better weather and sea conditions in comparison with the other two vessels.

- ✓ Lastly, it should be mentioned that all three vessels rarely come close to sailing on their design speed of 15 knots and instead sail at a much lower speeds most of the times. It is observed though that data on fuel consumptions, recorded while the vessels are sailing closer to their design speed, are generally closer to what expected from the speed test curves. On the other hand, when sailing on lower speeds both the weather conditions and the fuel oil consumptions seem to be considerably worse. The worse weather and sea conditions could justify worse fuel consumptions, but the deviations up to 80% of the expected, from the speed test curve, consumptions certainly cannot be explained.

The following figure and its explanatory table, depict the real time consumption of the vessel 'HARMONY' compared with its speed test curve at full load departure. The above remarks and observations, as well as the real time consumptions of all three vessels compared with their speed test curves, are more clearly and analytically presented at the APPENDIX which follows.

HARMONY			WEATHER CONDITION						
POINTS	V(KNOTS)	TONNES PER DAY	WIND(bofort)	SEA	REMARKS (CURRENT)	TRIM (+aft)	Tmd	DISPLACEMENT	KW for fld
1	11,1	45,1	7	HIGH	STRONG ADVERSE CURRENT 0,8 KNOTS	0,01	17,25	195590,2	10436,84
2	11,33	45,1	6	V.ROUGH	ADVERSE CURRENT 0,5 KNOTS	0,01	17,25	195590,2	10436,84
3	11,43	45	6	V.ROUGH	STRONG ADVERSE CURRENT 1,0 KNOTS&VESSEL ROLLING HEAVILY	0,18	17	192495,8	10523,63
4	12,2	45,1	6	V.ROUGH	ADVERSE CURRENT 0,5 KNOTS&VESSEL ROLLING HEAVILY IN TIMES	0,01	17,25	195590,2	10436,84
5	12,22	47	5	ROUGH	ADVERSE CURRENT 0,8 KNOTS	0,01	17,25	195590,2	10900,46
6	12,37	45	4	MODERATE	VESSEL ROLLING AND PITCHING&STRONG ADVERSE CURRENT 0,5 knots	0,08	17,4	197448,8	10345,49
7	12,5	46	4	MODERATE	NONE	0,02	18,19	207382,9	10248,98
8	12,5	47	5	ROUGH	VESSEL ROLLING	0,9	17,25	195590,2	10900,46
9	12,54	45	4	MODERATE	ADVERSE CURRENT 0,5 KNOTS&VESSEL ROLLING HEAVILY IN TIMES	0,18	17	192495,8	10523,63
10	12,71	47	4	MODERATE	ADVERSE CURRENT 0,5 KNOTS	0,08	17,4	197448,8	10830,49
11	12,75	46	4	MODERATE	NONE	0,02	18,19	207382,9	10248,98

Figure 33: Vessels 'Harmony' speed test curve and real time consumption on full load condition and explanatory table

Trying to determine the reasons behind the generally not accurate and in some cases abnormal measurements we can assume that the crew members responsible for this job are not properly trained or simply do not care enough to collect accurate measurements. It is beyond dispute that the abstract logs contain very detailed information on fuel consumption, speed, weather and sea conditions that will probably won't be the most pleasant matter to be done daily by the crew members. Furthermore, it is important to note that the inaccurate results may rely on the fact that the measurements collected may be documented from the side of the owners to be presented to the charterers. It is common knowledge that in conditions that the fuel oil is to be paid from the charterers, the ship owners may show increased consumption results in their benefit. It is also possible that the weather and sea conditions are not monitored properly from the vessels sensors. Lastly, we should mention that in some cases in the past it has been observed that the measurements of fuel consumption were deliberately increased from the crew members, in order to enable oil smuggling in the port of destination from them, something that seems unlikely in this case.

In an attempt to cut down costs and generally to try and monitor the vessels performance accurately, even more ship owners use different knowledge systems and software tools. As outlined previously in this diploma thesis, this kind of equipment not only try to optimize the vessels voyage, but also send through satellite measurements of fuel consumption and so on at the on shore offices of the shipping company at real time. In that case, not only the reliability of the measurements is guaranteed, but also an ease of processing and evaluating these data is on real time offered to the shipping company employees that is something undisputedly of great importance.

Chapter five:

Calculation of Ship's Resistance and Powering – Effect of Trim and Loading conditions – Comments on the Results for both Full Load and Ballast condition

I.   *Holtrop Results*

The first step we used to estimate the resistance of the ships examined was to use the HOLTROP method. At the following figure we can see the results we obtain using the HOLTROP method for the full load departure for the vessel 'Dynasty' in comparison with the corresponding speed test results. We can observe that the HOLTROP resistance curve presents the same trend as the speed test curve. Moreover, both predictions give back similar results, with the HOLTROP method giving back slight lower predictions. The above observations are similar for all three vessels.
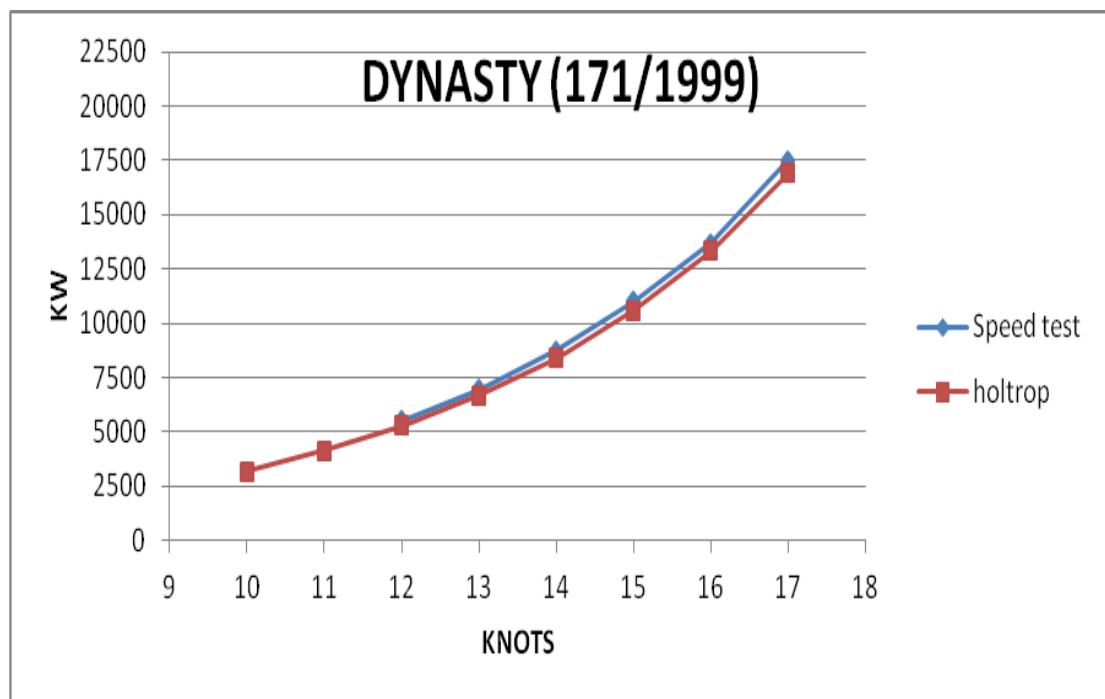

Figure 34: Vessels 'Harmony' speed test curve compared with the corresponding HOLTROP results for full load departure

In order to compare the real time data on consumption of the three vessels sailing fully loaded with the HOLTROP results, we follow the exact procedure analyzed on the previous chapter of this report.

For the ballast conditions, due to the deviations on drafts found on the different voyages of the vessels, we do not use the Admiralty coefficient (CAD). Since we do not refer to similar loading conditions and the drafts deviate we cannot assume that the CAD of the vessel remains constant, due to the possible changes in the hull form. Instead, we calculate and obtain predictions using the HOLTROP method for each of the ballast conditions separately. It should be mentioned that, as in the speed test curve, the HOLTROP predictions assume no wind, waves and swell, and a clean hull and propeller. The service power can be predicted by multiplying with a factor due to the non ideal conditions.

Being the HOLTROP predictions quite similar with the corresponding speed test predictions validates the fact that the methodology we have used seems to be correct and the HOLTROP method of calculating resistance seems to be the right choice for these type of vessels. On the other hand, it is obvious that the conclusions from the comparison with the real time fuel consumptions are the same as analyzed on the previous chapter of this report.

The following figure, and its explanatory table, depict a diagram containing the speed test curve, the HOLTROP calculation and the real time data gathered of a voyage of the vessel 'Dynasty' being fully loaded.
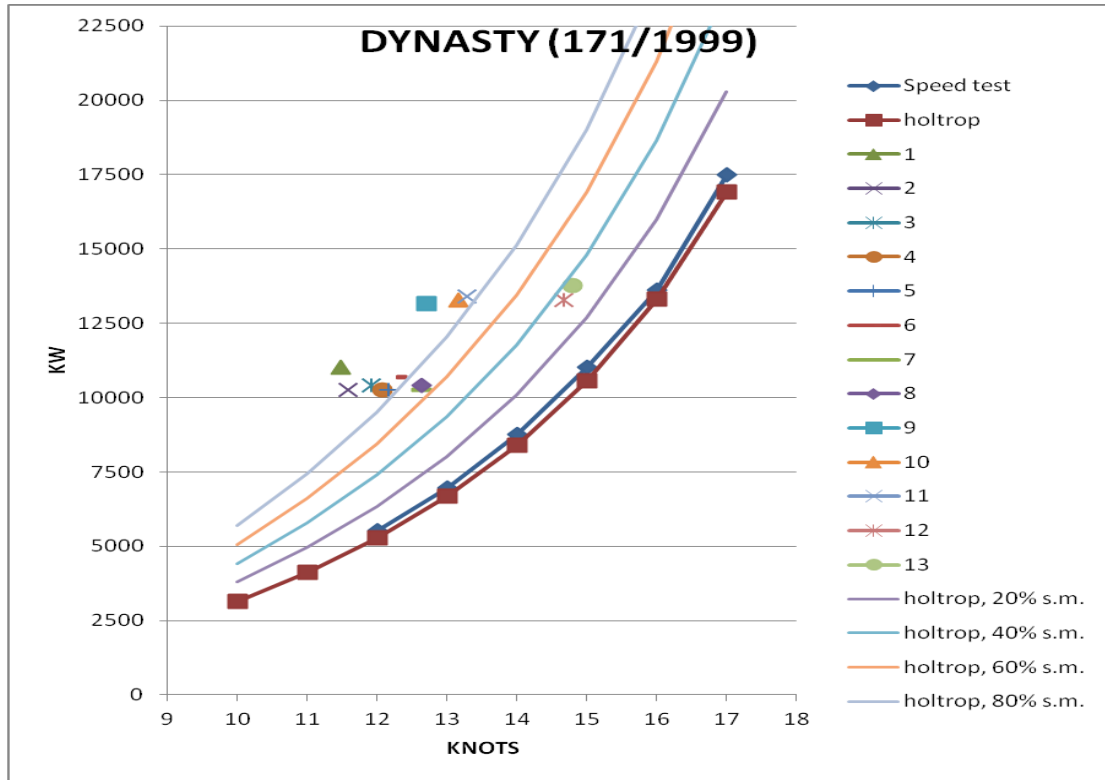
DYNASTY			Tonnes/day estimation from	WEATHER CONDITION						
ΣHMEIA	V(KNOTS)	TONNES PER DAY	holtrop with 35% s.m.	WIND(bofor	SEA	REMARKS	TRIM (+aft)	Tmd	DISPLACEMENT	KW for fld
1	11,47	47,2	27,4	7	HIGH	ECO SPEED-VESSEL ROLLING AND PITCHING	0,73	17,48	190566	11031,61
2	11,58	44	28	5	ROUGH	ECO SPEED-STRONG ADVERSE CURRENT 1,0 KNOTS	0,15	17,49	190685,5	10249,47
3	11,92	44,7	29,96	5	ROUGH	ECO SPEED-ADVERSE CURRENT 1,0 KNOTS	0,73	17,48	190566	10425,08
4	12,08	44	30,94	5	ROUGH	ECO SPEED-STRONG ADVERSE CURRENT 1,2 KNOTS	0,15	17,49	190685,5	10249,47
5	12,17	44	31,51	6	V.ROUGH	ECO SPEED-ADVERSE CURRENT 0,5 KNOTS	0,73	17,48	190566	10253,76
6	12,28	45,8	32,22	4	MODERATE	ECO SPEED-ADVERSE CURRENT 1,0 KNOTS	0,15	17,49	190685,5	10688,51
7	12,63	44	34,59	4	MODERATE	ECO SPEED-ADVERSE CURRENT 0,5 KNOTS	0,15	17,49	190685,5	10249,47
8	12,63	44,7	34,59	5	ROUGH	ECO SPEED-ADVERSE CURRENT 0,5 KNOTS	0,73	17,48	190566	10425,08
9	12,71	56	35,16	6	V.ROUGH	FULL SPEED-ADVERSE CURRENT 1,0 KNOTS	0,01	17,36	189135	13166,34
10	13,17	56,5	38,68	5	ROUGH	FULL SPEED-ADVERSE CURRENT 1,0 KNOTS	0,01	17,36	189135	13281,36
11	13,29	57	39,66	5	ROUGH	FULL SPEED-ADVERSE CURRENT 0,5 KNOTS	0,01	17,36	189135	13396,05
12	14,67	56,5	53,56	4	MODERATE	FULL SPEED-ADVERSE CURRENT 0,5 KNOTS	0,01	17,36	189135	13281,36
13	14,8	58,7	55,17	4	MODERATE	FULL SPEED-ADVERSE CURRENT 0,8 KNOTS	0,01	17,36	189135	13783,47

Figure 35: Vessels 'Dynasty' speed test curve real time consumption and HOLTROP powering results on full load condition as well as the corresponding explanatory table

Regarding the ballast conditions, the following figure depicts the deviations on the HOLTROP and speed test predictions for the vessel 'Voyager' from sailing fully loaded to the different ballast conditions met at the voyage logs gathered.
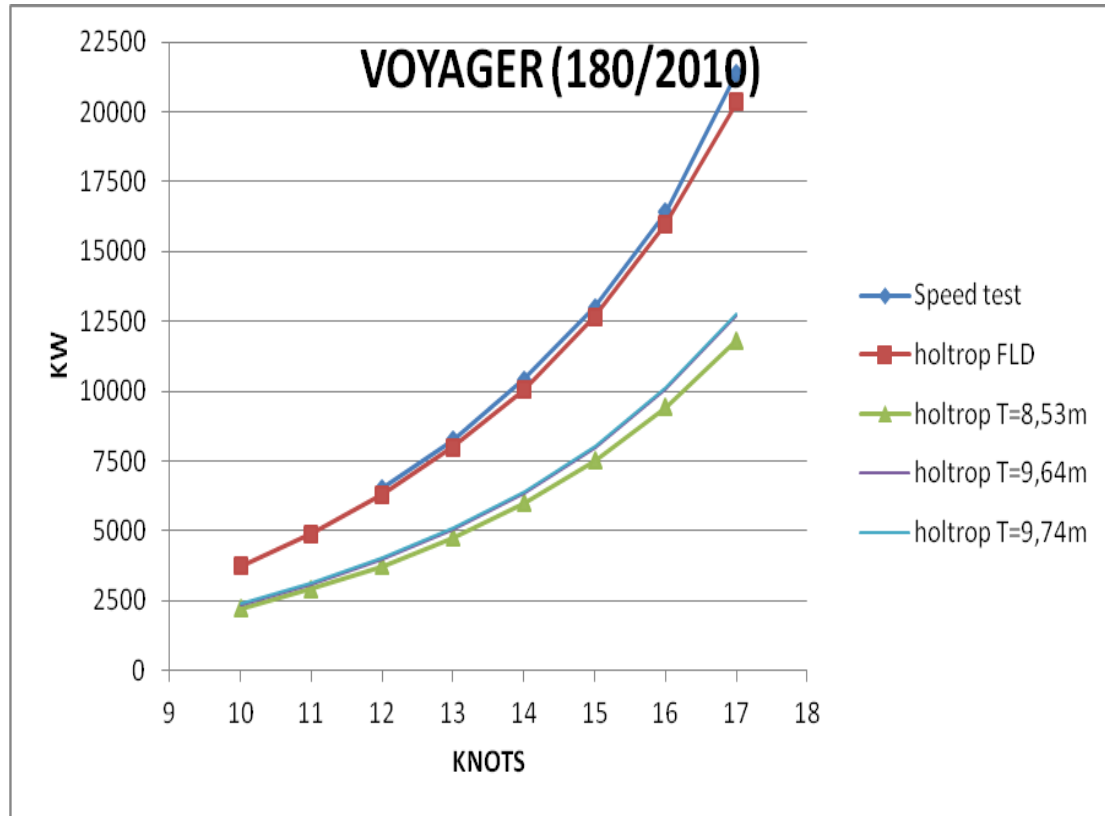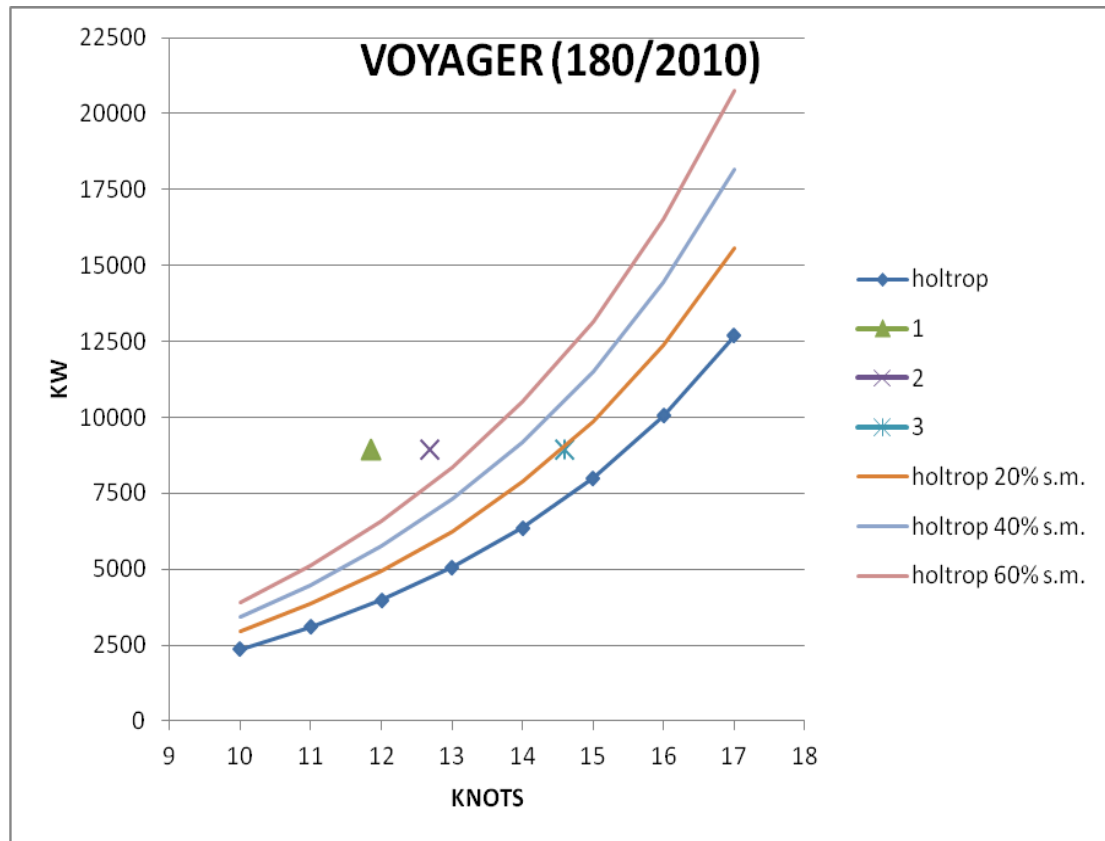

Figure 36: Deviations of the HOLTROP and speed test predictions for the vessel 'Voyager' from sailing at fully loaded to ballast condition

It is obvious that the HOLTROP predictions for ballast conditions are much lower than the corresponding fully loaded. Furthermore, as outlined in the conclusions of the previous chapter, it is often observed in the voyage consumption reports for the vessels to have similar or even higher consumption travelling at ballast contrary to traveling fully loaded. Beyond from the fact that this does not make any sense and cannot be explained nor further analyzed, it causes even more deviations to be observed in the comparison of the ballast condition real time consumption results with the HOLTROP predictions. As outlined in the conclusions of the previous chapter, only the vessels 'Voyager' fuel consumptions seem to be close to some of the service power predictions.

The following diagram, and its explanatory table, contains the HOLTROP predictions and the real time data gathered of a voyage of the vessel 'Voyager' sailing at a certain ballast condition (T=9,64m).

VOYAGER			Tonnes/day estimation	WEATHER CONDITION						
ΣΗΜΕΙΑ	V(KNOTS)	TONNES PER DAY	from holtrop with 35% s.m.	WIND(bofort)	SEA	REMARKS (CURRENT)	TRIM (+aft)	Tmd	DISPLACEMENT(TON)	KW for fld
1	11,85	37	23,89	7	V. ROUGH	ECO SPEED-ADVERSE CURRENT 1,1 KNOTS	2,06	9,64	103884	8954,21
2	12,68	37	27,98	6	ROUGH-V.ROUGH	ECO SPEED-ADVERSE CURRENT 0,3 KNOTS	2,06	9,64	103884	8954,21
3	14,59	37	41,26	3	MODERATE	ECO SPEED-ADVERSE CURRENT 0,8 KNOTS	2,06	9,64	103884	8954,21

Figure 37: Vessels 'Voyager' real time consumption and HOLTROP powering predictions as well as the corresponding explanatory table at ballast condition voyage (T=9,64m)

We can observe that the real time fuel consumptions seem to be really close to the HOLTROP predictions when the vessel sails close to its design speed. As outlined on the previous chapter the vessels seem not to sail near their design speed and instead sail at much lower speeds most of the times. We must underline the fact though, that at the ballast voyages of the vessels, all seem to sail at a higher speed compared with the information on the fully loaded voyages especially when the weather conditions seem to allow it.

More detailed diagrams and analysis for all three vessels can be found at the APPENDIX which follows.

II.   *SHIPFLOW Results and comparisons*

Using the potential flow theory in SHIPFLOW, and more specifically the XPAN code, we perform several runs for both full load and ballast conditions and for the range of speeds a similar vessel as the vessel 'Voyager' is due to sail.

After completing the above runs and comparing the wave resistance coefficients derived with this analysis with the ones we had already calculated using the HOLTROP method, we are lead to the following conclusions:

✓ The variance of the Cw wave resistance coefficients based on the wave cut analysis is significant compared with the equivalent coefficients derived from the HOLTROP method especially in the ballast conditions. More significantly, we can observe that the SHIPFLOW analysis underestimates the Cw for about 20-30% compared with the HOLTROP analysis.

✓   Apart from the deviations in the wave resistance coefficients produce by the two different methods, we can observe that the Cw – Speed curve show the same trend for both methods.

✓ Although the two methods produce Cw – speed curves with the same trend, for the speed of 15 and especially 16 knots in full load departure, the wave coefficient derived from SHIPFLOW is significant lower than the one calculated from the HOLTROP method. It would be interesting to have real time measurements, especially accurate ones, from the vessel sailing at this speed in full load departure and validate this observation. However, as mentioned previously in this report, not only the real time data seem to be inaccurate, but also all vessels sail at much lower speeds in their full loaded voyages.

✓ Generally speaking, we should also underline the fact that the wave resistance coefficients from both methods are found to have very small values. Especially, in ballast conditions and at a lower range of speed (10-12 knots) there are very close to zero as if the vessel produces no waves at all. (see following figure). This is obviously a weakness of the program to perceive the wave patterns for low wave resistance

values. Therefore, especially for the non loaded conditions, using SHIPFLOW to calculate the wave resistance may not produce accurate results.

✓ Therefore, we can conclude to the fact that for large vessels, with large Cb, a simple geometry, a low speed sail and consequently a low Froude, as the vessel 'Voyager' in question, the statistical HOLTROP method seems to be able to produce more accurate results.

The following figures depicts the above observations when comparing the HOLTROP with the SHIPFLOW results on the wave resistance coefficient for the vessel 'Voyager' for both full load and ballast condition (T= 9,74m).
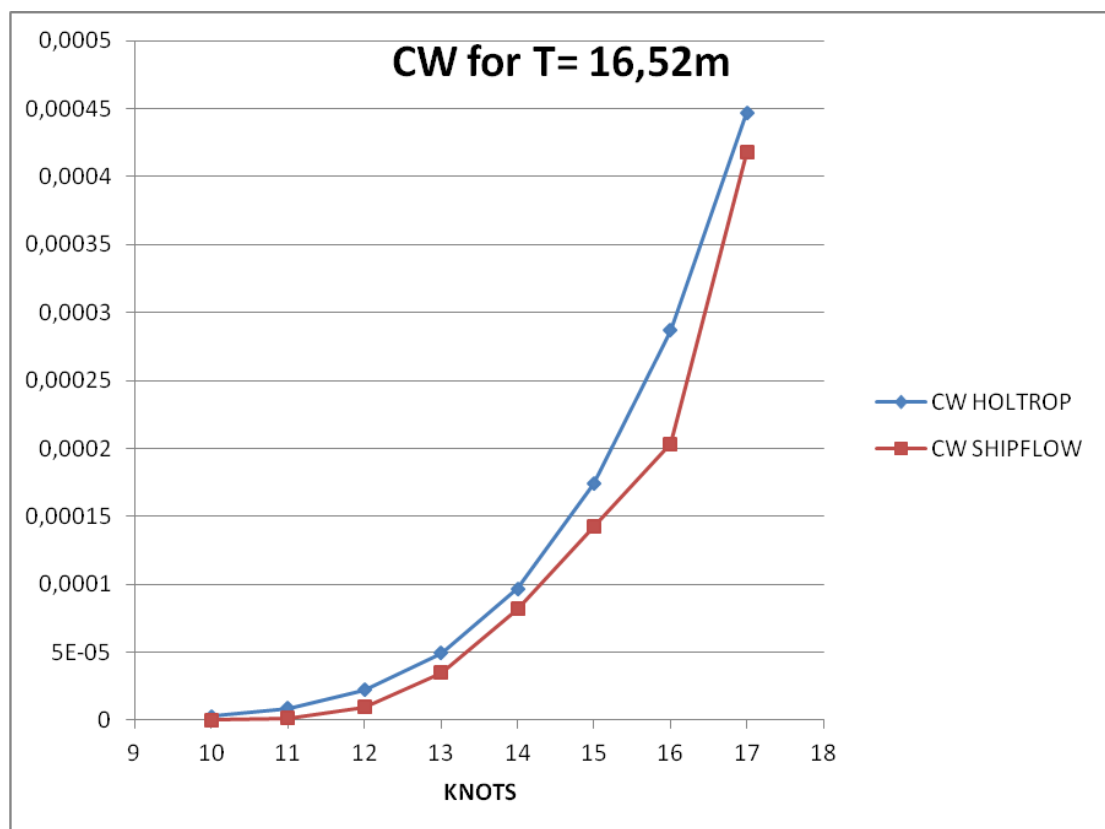
Figure 38: Wave resistance coefficient for the vessel 'Voyager' in full load departure calculated by both SHIPFLOW and HOLTROP method
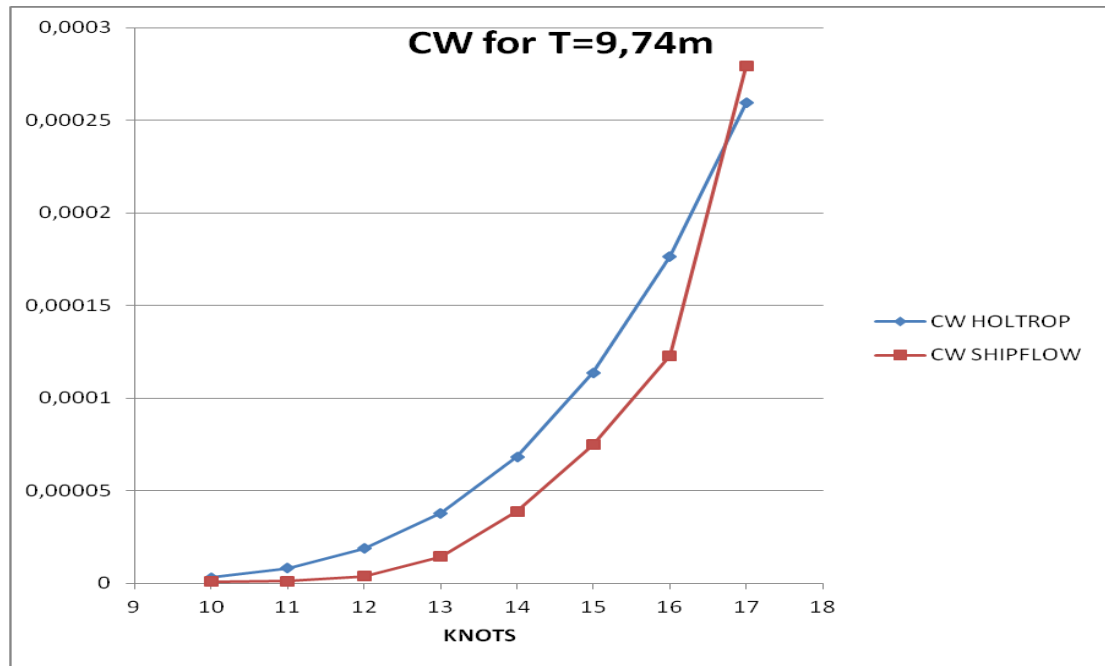
Figure 39: Wave resistance coefficient for the vessel 'Voyager' in ballast condition (T=9,74m) calculated by both SHIPFLOW and HOLTROP method

The following figure depict the deviations in the wave patterns as computed in SHIPFLOW for the vessel 'Voyager' sailing at a draft of 9,74 m (Ballast Condition) for 12 and 15 knots respectively. One can easily notice that in the lower speed the vessel seems not to produce remotely any kind of wave pattern.
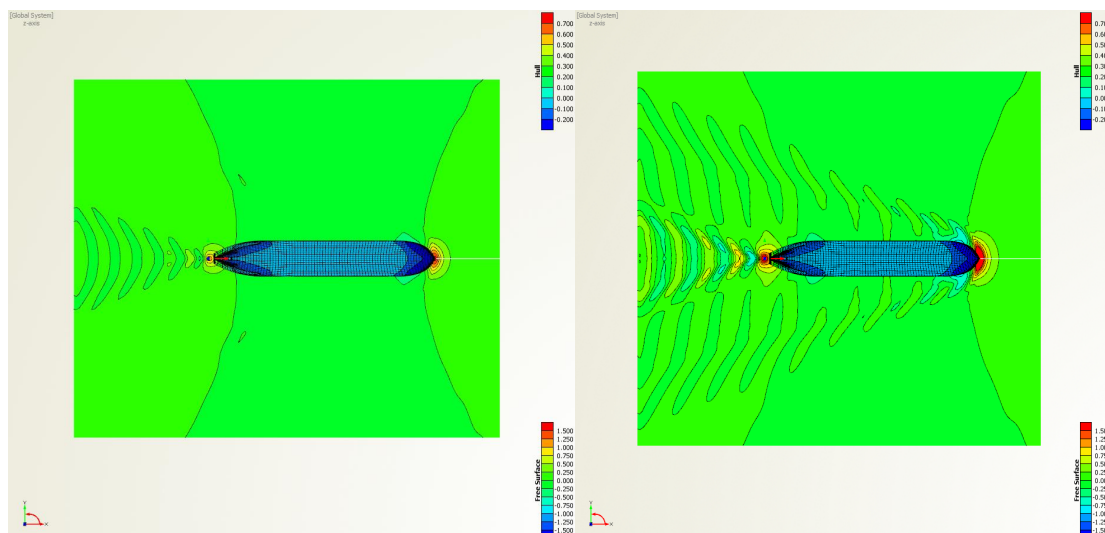

Figure 40: Deviations in wave patterns, as calculated in SHIPLOW, for the vessel 'Voyager' sailing at ballast condition (T=9,74m) with a speed of 12 (left) and 15 knots (right) respectively

The following figure depicts the wave pattern, as computed in SHIPFLOW, for the vessel 'Voyager' sailing fully loaded (T=16,52 m) at a speed of 15 knots (design speed).
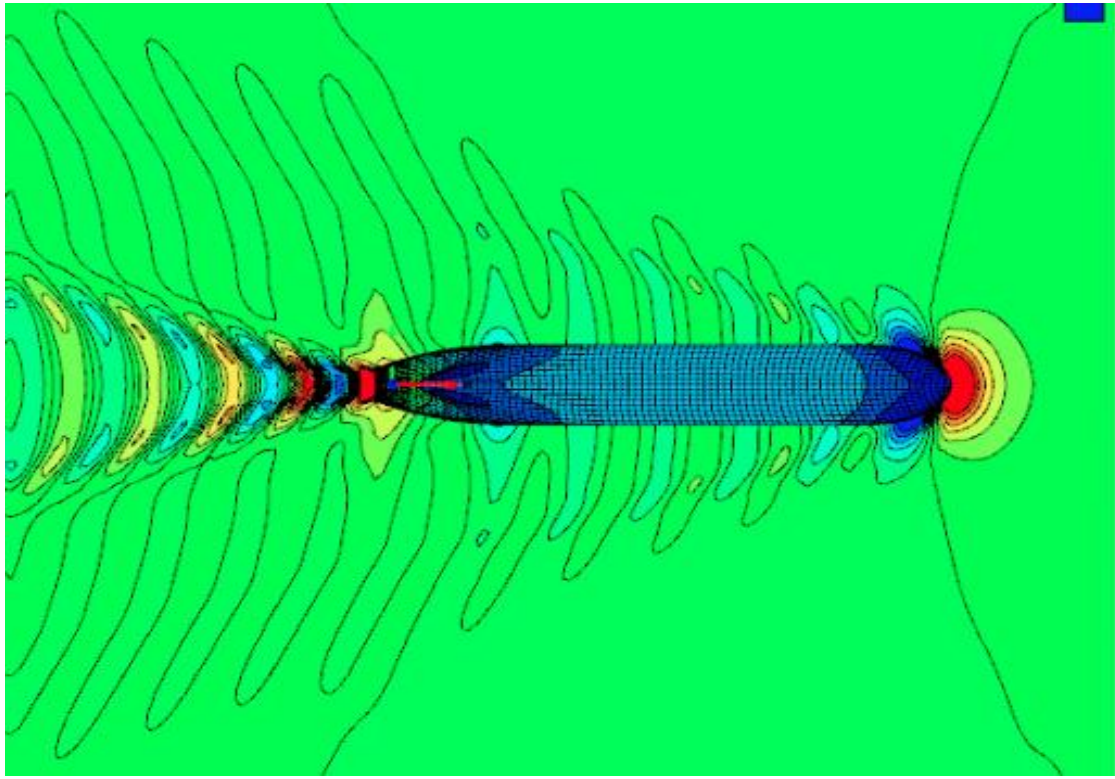

Figure 41: Wave pattern, as computed in SHIPFLOW, for the vessel ' Voyager' sailing fully loaded at its design speed (15 knots)

More snapshots of the SHIPFLOW runs carried out for both full load conditions and ballast conditions and for the range of speeds examined can be found at the APPENDIXES of this report.

III.   *Viscous Resistance and Calculations the Form Factor K*

Conducting this report it was found appropriate to use the Navier- Stokes analysis and calculate the viscous flow to perfectly validate the accuracy of the HOLTROP method calculating the total resistance of the vessel 'Voyager', something of paramount importance to us. More specifically, we were able to validate our results regarding the form factor K which describes the viscous resistance of the hull form in relation to the frictional resistance and is used in the HOLTROP method. In order to be able to run the viscous flow effectively, due to the complexity of the calculations we had to install and use the latest available SHIPFLOW edition (SHIPFLOW 5.0). Due to the huge number of iterations for the program to converge, and therefore large computational time and power, this method was only used to validate two conditions.

- o   The full load departure (T = 16,52 m) with the vessel sailing at its design speed of 15 knots.

- o   One of the ballast conditions (T = 9,74 m) with the vessel again sailing at its design speed of 15 knots.

After running the Viscous flow analysis for the above two conditions, we came to realize that the two methods converge satisfactorily calculating the form factor K.

VOYAGER	Form Factor K (V = 15 knots)	
	FLD T=16,52m	Ballast T=9,74m
HOLTROP	0,353	0,276
SHIPFLOW	0,346	0,252

Table 6: Form factor K calculated at SHIPFLOW and using the HOLTROP method

It is therefore obvious that the HOLTROP is the easiest and most accurate method to calculate the resistance of this kind of vessels. In cases of vessels with a higher Froude number or more complex geometry (twin skeg), it is recommended that assessment of the wave resistance should be done using computational fluid dynamics codes and the potential flow theory, as in SHIPFLOW.

Lastly, we must add that no deviations in the wave pattern or wave resistance were observed comparing the potential flow and the viscous flow analysis for the above two conditions.

The following figures depict the wave pattern analysis of the new edition of SHIPFLOW (5.0) derived from the viscous analysis for the above two conditions.
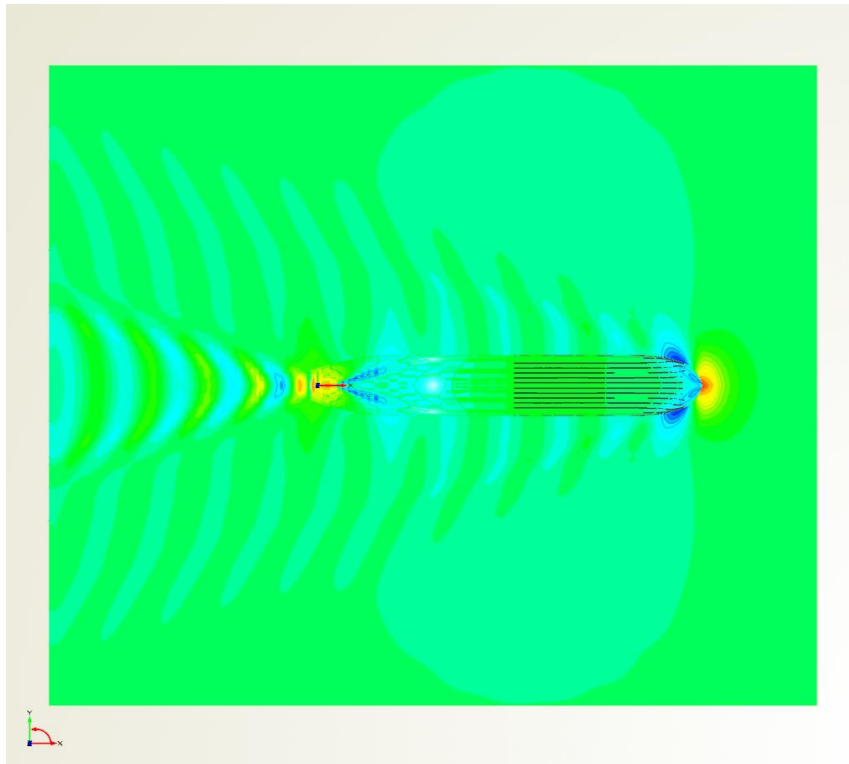

Figure 42: Wave patterns of the vessel 'Voyager' for the design speed of 15 knots and being full loaded, as computed from SHIPFLOWS 5.0 viscous resistance analysis
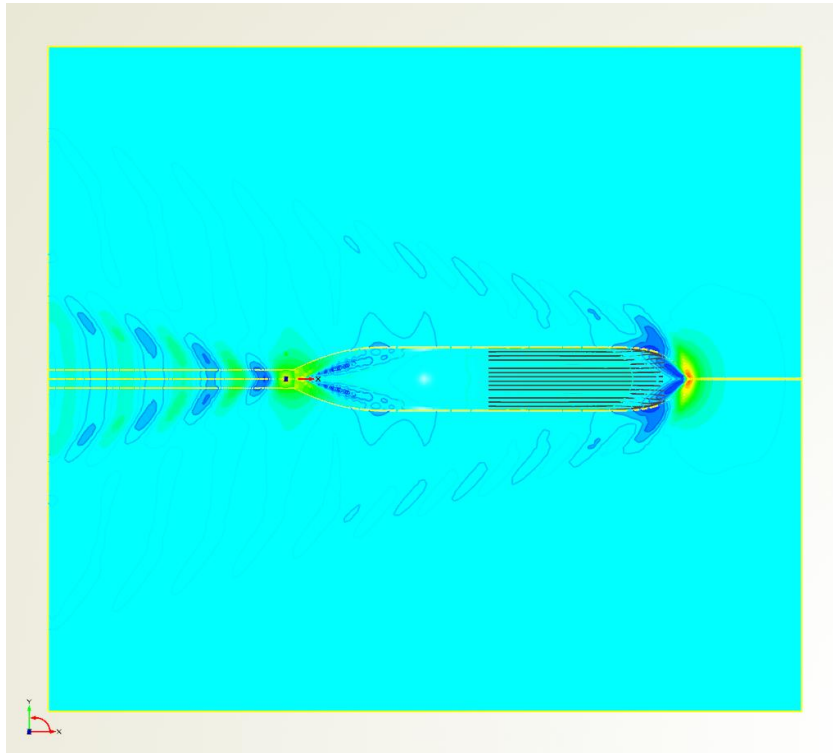
Figure 43: Wave patterns of the vessel 'Voyager' sailing at a ballast condition (T=9,74m) and at the design speed of 15 knots, as computed from SHIPFLOWS 5.0 viscous resistance analysis

IV.   *Optimization attempt - the Significance of the Wave Resistance compared to the Total Resistance for the Ships examined – effect of Trim and environmental conditions*

At this stage of the report, an attempt was made to reduce, the already reduced compared with the HOLTROP method, wave resistance of the vessel 'Voyager'. This was basically attempted by running the potential flow code for different trims and comparing the wave resistance coefficient for the range of speed the vessel is due to sail. The scope of this attempt was to find a trim suitable for the different loading conditions (full load and ballast) that would minimize the wave resistance of the vessel each time. This could be achieved by comparing the Cw coefficients produced in the XPAN runs for the different trims and most importantly the wave patterns calculated. Especially for the ballast conditions, where we are able to process a wider range of trims, it would prove very useful in an attempt to run the vessel optimized at all conditions and minimize costs and environmental emissions. Unfortunately, although we observe some deviations in the Cw coefficient for the different trim runs, when calculating the total resistance of the vessel this small deviations on the wave resistance seem to have no effect in the total resistance.

The following figures depict the deviations in the wave resistance coefficient for different trims applied both in full load and ballast condition.
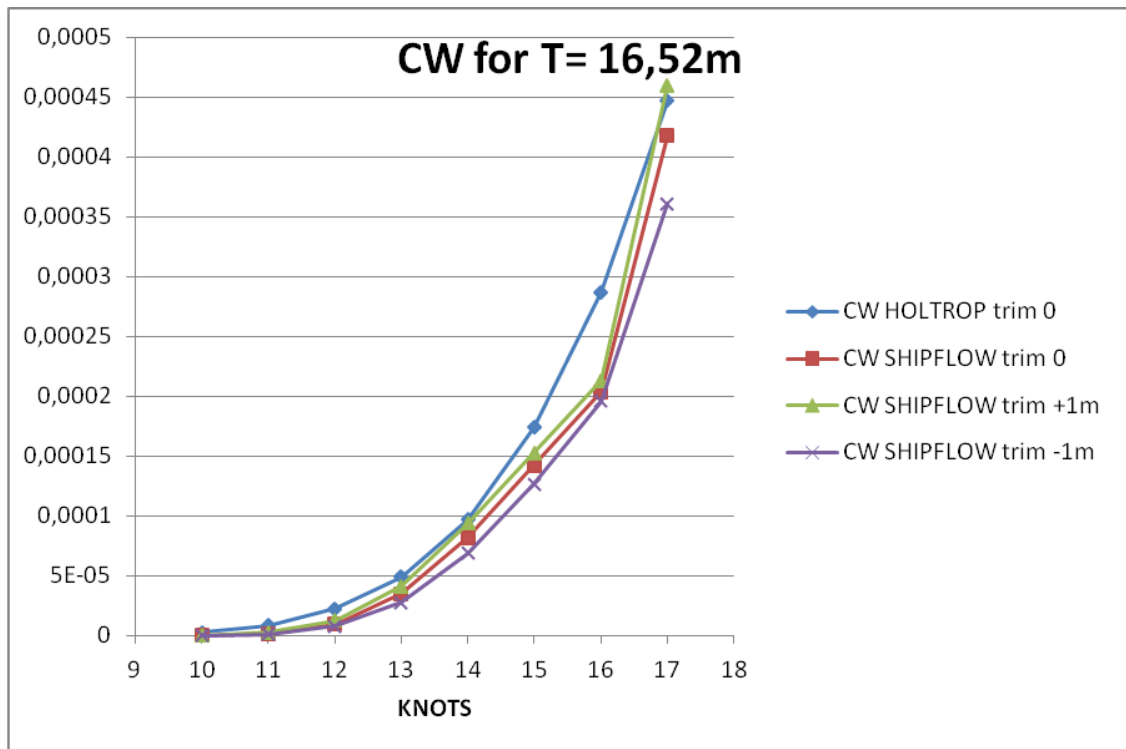
Figure 44: Deviations in the wave resistance coefficient for the vessel 'Voyager' for different trims for a full load sail as computed by SHIPFLOW
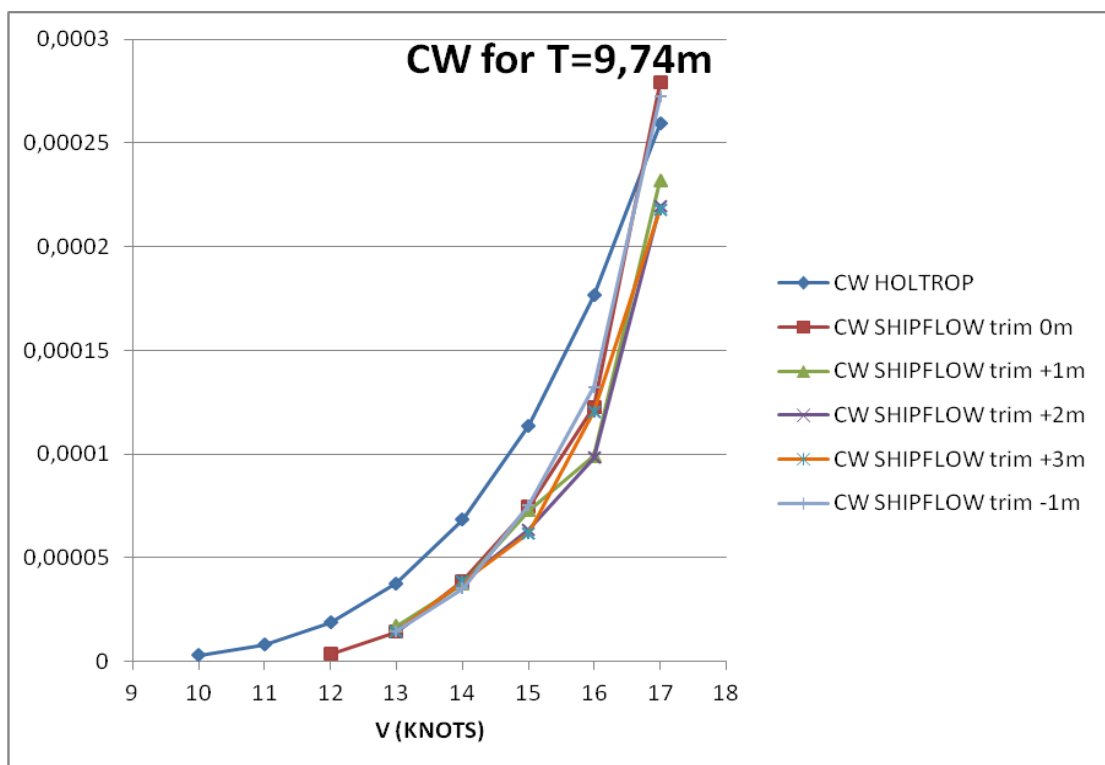

Figure 45: Deviations in the wave resistance coefficient for the vessel 'Voyager' for different trims for a ballast sail (T=9,74m) as computed by SHIPFLOW

The wave patterns produced by SHIPFLOW in the different trim runs seem not to be affected. The only condition that seems to have minor changes in the wave patterns, due to the trim changes, is when the vessel has a speed of 16 and especially 17 knots. Apart from the fact that this type of vessels will probably never sail in so high speeds, as 17 knots, this minor changes of course cannot lead to any useful conclusion regarding the trim selection of the vessel.

At this point we must underline again the fact that the wave resistance, for this type of vessels, is only a small portion of the total resistance. Consequently, even if we were able to observe significant deviations in Cw coefficient or wave patterns, they would probably have no impact on the total resistance of the vessel, especially in the low speeds.

More significantly, for the vessel 'Voyager' the percentages of the wave resistance to the total resistance as calculated in the HOLTROP method for both full load and ballast conditions and for the different speeds of the vessels can be seen at the following figure. As we can notice at 17 knots, especially in the full load condition, the wave resistance begins to play an important role affecting the Total Resistance of the vessel.
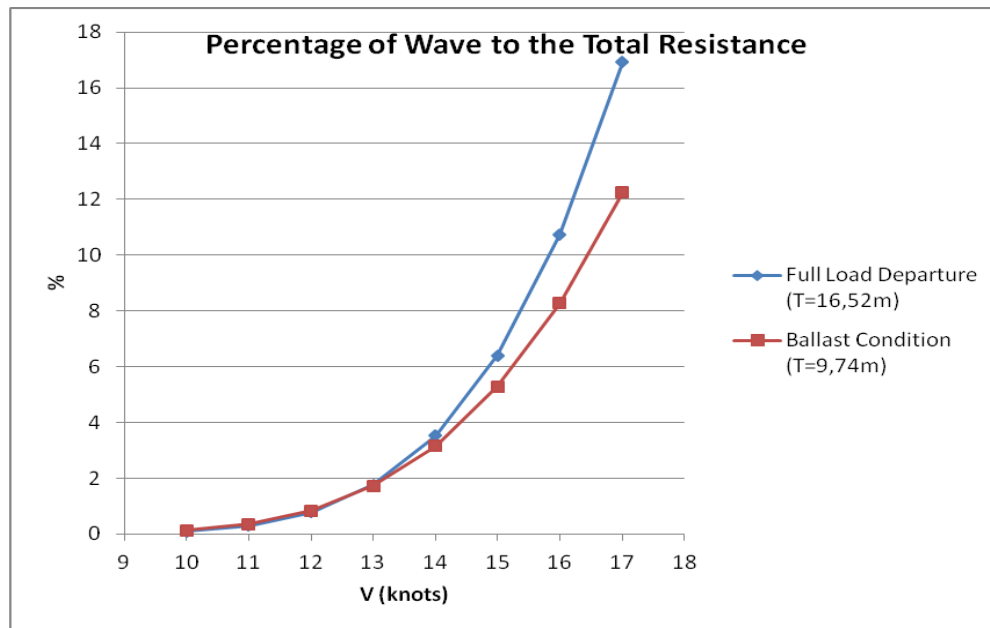
	Full Load Departure (T=16,52m)		Ballast Condition (T=9,74m)	
V(knots)	Wave Resistance (kn)	Percentage to Total Resistance	Wave Resistance (KN)	Percentage to Total Resistance
10	0,743428831	0,095315981	0,63562677	0,130881832
11	2,812499944	0,302435447	2,099504614	0,362831656
12	8,61097793	0,789145786	5,734704125	0,844668601
13	22,37186401	1,770996299	13,51662519	1,71894759
14	51,03507272	3,530055976	28,34676014	3,147253247
15	104,8360241	6,399197469	54,10746047	5,291507965
16	197,6541496	10,73934134	95,62325771	8,278484525
17	347,0782825	16,91454388	158,5423737	12,23966128

Figure 46: Percentage of wave to the total resistance of the vessel 'Voyager' as calculated with the HOLTROP method

In an attempt to possibly observe some more obvious changes in the wave patterns and try to process them, we run the code by changing the bulb of the vessel. In order not to have a change in the frictional resistance of the vessel we tried to modify the existing bulb without changing its volume and consequently the wetted surface of the vessel. To achieve this we used the program AVEVA lines again to create the form of the bulb we were to try. The concept was to make the trial bulb longer and shorter in order to be by all times in the water, even in the cases that the vessel sails at light ballast. In order to achieve this we had to 'cut' in height the same amount of surface from the existing bulb with the one to be placed at the trial bulb lengthwise. In order to achieve this, without changing the vessels hydrostatics, we used again the program AVEVA lines to fix the geometry of this trial design.

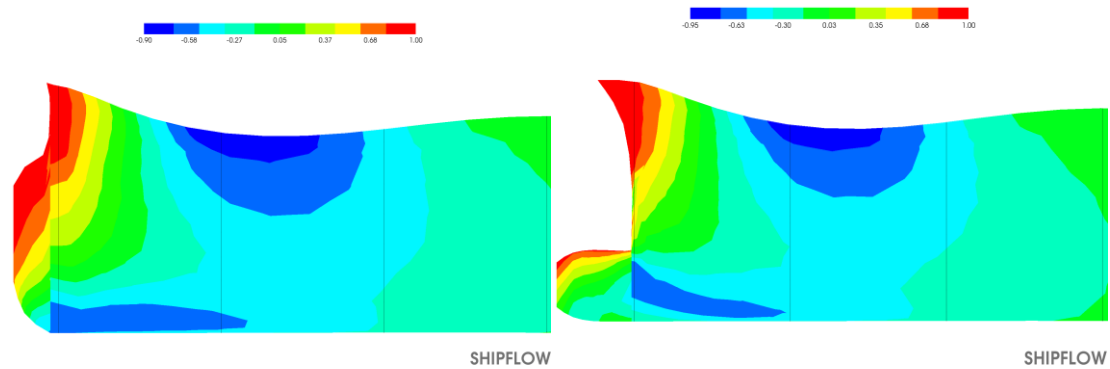The following figure depicts the changes occurred in the bulb of the vessel.

Figure 47: Attempt to change the bulb type of the vessel 'Voyager' (right new design)

Unfortunately, when running the code for the new bulbous bow design we realized that the wave pattern was not obviously affected again for the same speeds and loading conditions. Therefore, it seems that minor design changes do not affect the wave pattern of large vessels as the vessel 'Voyager'.

Despite this fact, in my opinion a change in the design of the bulb, even in this type of vessels, should definitely cause a change in the waves produced. Either way, throughout our experience with SHIPFLOW we come to conclude and validate its general weakness and non sensitivity to accurately calculate the wave resistance and wave patterns of vessels with high Block coefficients (Cb) and low Froude numbers.

We can therefore conclude that for these kind of vessels the most important parameter affecting their consumption of fuel is the actual sea state and the additional resistance in waves, rough sea and currents. Additional resistance may also be attributed to shallow waters (squatting) and of course due to wind, which beyond dispute plays a significant role, however little can be done to optimize the vessels voyage in that scope. We were unfortunate enough to have inaccurate onboard information, regarding the fuel consumptions of the vessels examined, making it impossible for us to reach conclusions on how exactly these parameters affect the vessels consumption. As previously mentioned in this diploma thesis, when evaluating the onboard information gathered, in some cases the vessel seems to consume the same or even more amount of fuel when sailing without cargo (ballast condition) from sailing fully loaded without the weather conditions to differ

significantly. Moreover, in many cases the weather conditions seem not to have the expected influence on the vessels performance. Specifically, even though the weather conditions seem to be worse, the vessel consumes less fuel than other days with certainly more favorable weather conditions. On the other hand, based on the minor dependence of the wave resistance to the total resistance of such type of vessels and the weakness of SHIPFLOW to accurately depict the wave patterns in such low Froude numbers, we were unable to come to a significant conclusion regarding the best trim for each condition. Of course, as we observed using SHIPFLOW, the trim should be such in order for the bulb to be completely immersed in the water and work in favor of the ships resistance otherwise the wave resistance produced is dramatically increased.

Summary – Conclusions and Way Ahead: Summary of Findings and Future Perspectives

In today's environment, with constantly changing political, technological and cultural needs, globalization plays a very important role in the everyday lives of people. This international integration and exchange of information, leads to advanced knowledge of the negative effects fuel consumption has on the environment, and subsequently on the flora and the fauna of the world. Keeping in mind that the world and the elements that comprise it are strongly interconnected and interrelated, every act has an effect somewhere.

When shipping companies are ignorant about pollution and its effects, and embark vessels that consume uncontrollably, this leads to a chain of events that end up to humans being indirectly harmed. For this reason, international organizations have taken action, and now regulate the emissions of ships. Consequently, this leads to further pressure from the people, and this goes on, in a continuous attempt to optimize fuel oil consumption in vessels.

The global warming is the rise in the average temperature of the earth, caused by the greenhouse gases that are produced by human activities, such as the burning of fossil fuels. The average temperature rise of the Earth's atmosphere leads to the melting of ice, and therefore the increase of the sea level. If global warming continues to increase uncontrollably, this will lead to the flooding of certain parts of the world. Through globalization, people exchange worldviews and cultural aspects and become more aware about all the above negative effects of heavy fuel oil consumption.

In a nutshell, the reason behind the incentives of this diploma thesis was the need for a solution to the problem of global warming, greenhouse gas emissions and pollution. It is a topic of rising importance, and a concern each one of us should have. Looking forward into the future, it is obvious that global warming will be solved. The question is, who will participate in the query for the solution?

In retrospect, due to the ever increasing heavy fuel oil prices and the relatively low freight rates, being fuel consumption the basic cost of embarking it is significantly important to attempt and lower its cost. In addition to the negative effects of high costs for the shipping company, there is an incentive to lower fuel consumption due to environmental factors, and in order to meet the strict government and IMO regulations.

As seen before, fuel consumption depends upon many variable factors. In order to take measures to reduce fuel consumption, it must firstly be accurately monitored. Monitoring fuel consumption and the variables that affect it is not an easy procedure, and it requires

specialization. The responsible crew must be motivated and dedicated in order to achieve the accurate measuring of the usage. Unfortunately, in our case the data collected from the crew on real time consumption and the factors that affected it, presented some irregularities and were considered inaccurate. This was a negative element to our effort to analyze (based on real time fuel consumption) the actual effect of every factor on the consumption levels.

Due to the importance of accurate monitoring, and the growing need to improve the voyage in means of cutting down costs, even more shipping companies seek professional help in companies like "Eniram". This kind of companies provide efficient systems in that scope, as it not only collects accurate data and sends them at real time through satellite to the onshore offices where the data is being properly analyzed, but also constantly attempts to optimize the sail of the vessel by optimizing the trim and speed in the different loading conditions. Furthermore, it has been observed lately that shipping companies install systems or patents like a "wake equalizing system" or a "speed nuzzle" at the propeller, in order to further increase the efficiency of fuel consumption and to cut down costs. In addition, these companies, in order to meet the strict regulatory framework for gas emissions, install relatively large and pricy components like exhaust gas scrubbers, that aim at "cleaning" the fuel from its negative elements, and waste heat recovery systems, that aim in utilizing better the power derived from the engine and lead to better performance of the engines and consequently to a reduction of fuel consumption.

In an attempt to calculate the resistance that was expected in the three vessels under investigation, we used the HOLTROP method, which although it is based on statistic calculations, it is a quick, accurate and trustworthy method for ships with simplified geometry, small Froude number and large block coefficient as the ones in question. On the other hand, in our attempt to validate the aforementioned results and attempt to optimize one of the three vessels in order to minimize its wave resistance, we used the computational fluid dynamics program SHIPFLOW, and unfortunately proved the weakness of this kind of programs for accurate results when examining slow steaming ships with high Block Coefficients (Cb) and small Froude numbers. The estimates of wave resistance that were derived from SHIPFLOW were 20-30% lower than the HOLTROP method. In addition, running the code for different trims did not lead to any sort of alteration to the wave pattern produced by SHIPFLOW, and which resulted to the attempt of optimization being unsuccessful. It is important to note that in these type of vessels, the wave resistance is a relatively small portion of the total resistance, therefore an improvement to the wave resistance would probably not have an effect on the total resistance. In the opposite case, in examples of vessels with a higher Froude number or more complex geometry, it is recommended to assess the wave pattern and wave resistance, using computational fluid dynamic codes, as in SHIPFLOW. In that case, trim optimization, beyond dispute, would act actively towards fuel saving, and optimizing voyage.

In order to decrease fuel oil consumption for these types of vessels, technology must turn towards alternative solutions, such as concentrating on how to increase the propeller and engine efficiency and of course on the installation of fuel cleansing devices. Besides the

solution of decreasing the speed, which would have immediate results in fuel consumption, optimization should be based on an attempt to decrease the wetted surface for the vessels in question. This would beyond dispute have an immediate effect in minimizing the total resistance of such vessels as the frictional resistance, which directly depends on the wetted surface, is by far the major factor affecting it. Therefore, design alterations and different bulb and stern types should be the focus of future studies and reports.

Future perspectives for the optimization of heavy fuel oil consumption would include not only changes in design and engine and propeller efficiency, but also the optimization of fuel itself. This would indicate fuels that contain lower Greenhouse Gas elements that cause pollution. Through time, it is believed that solar energy and seawater will be key aspects of pollution reduction.

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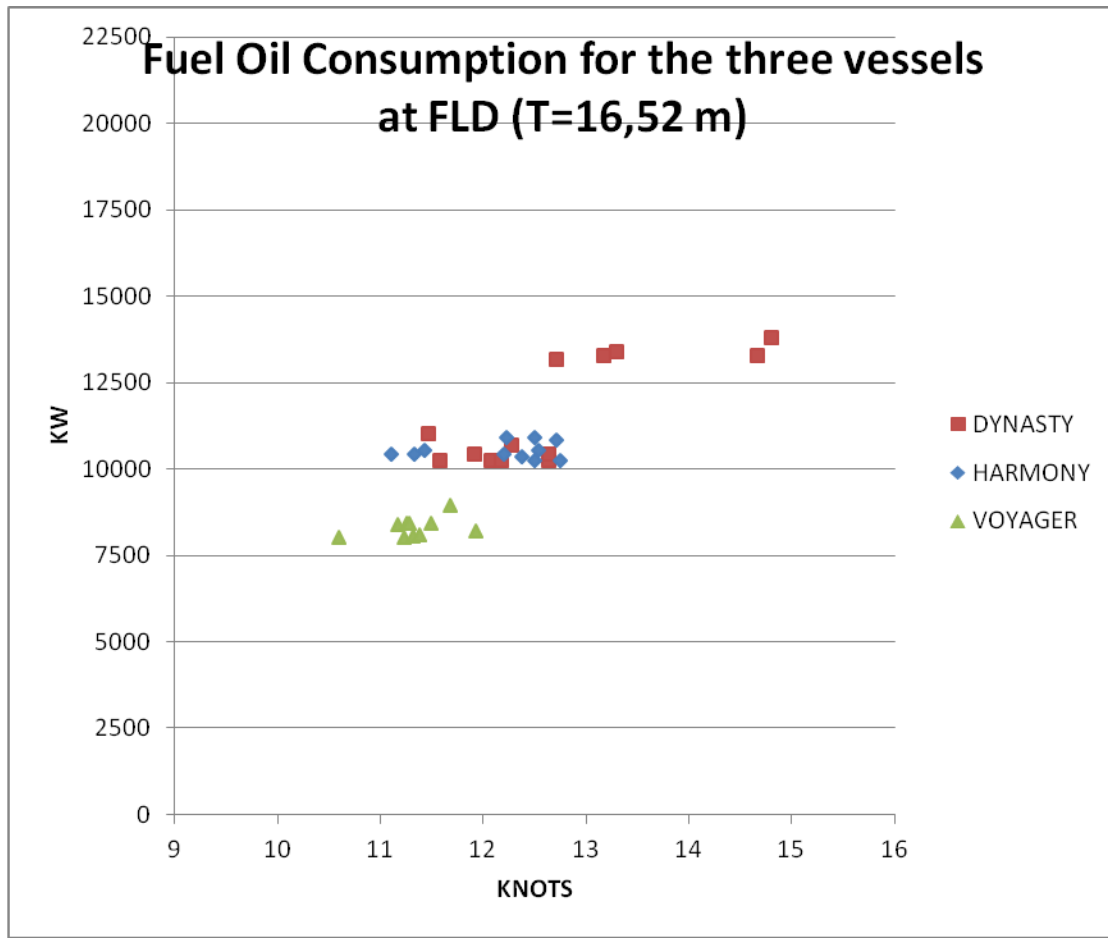
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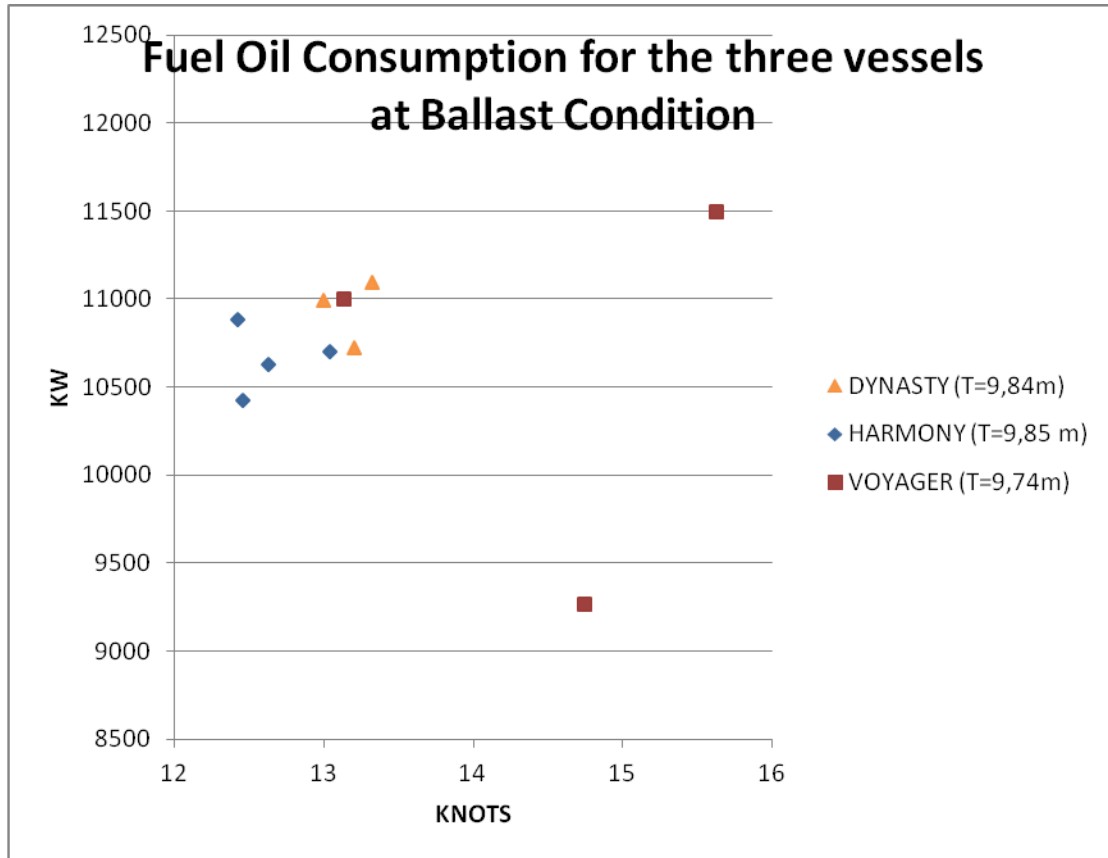
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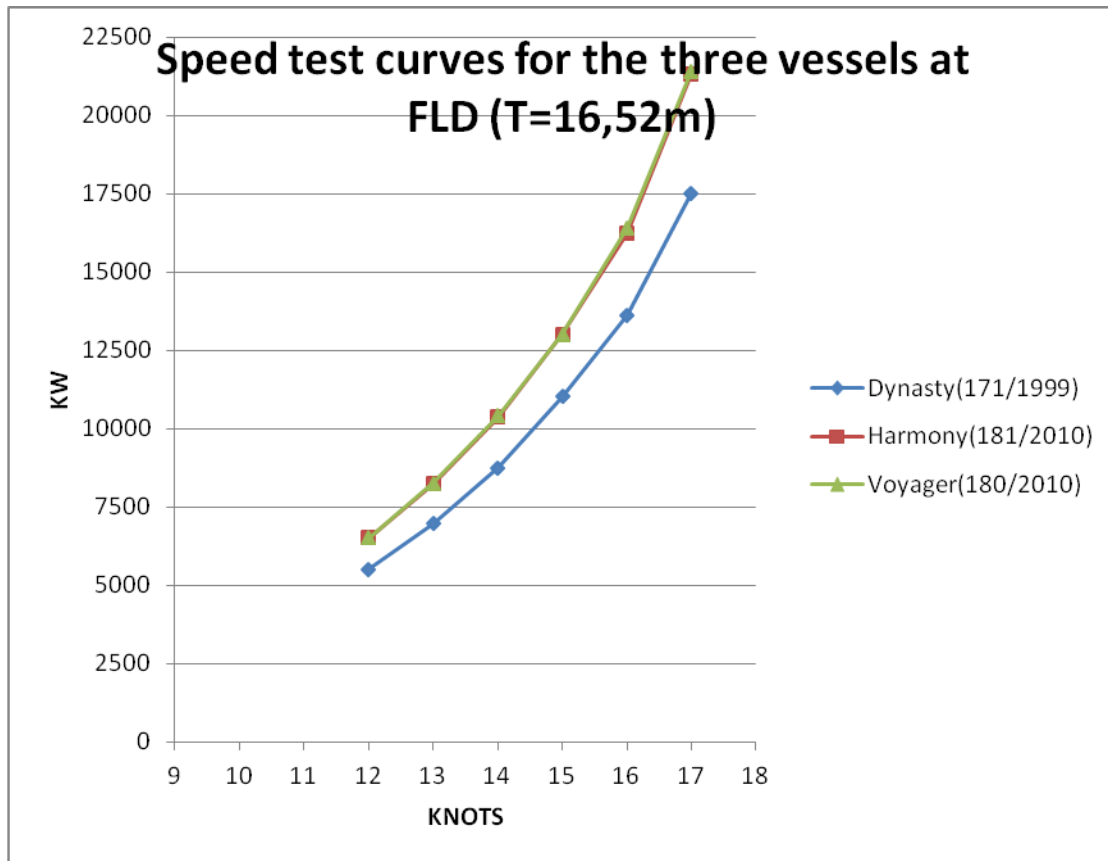
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APPENDIX I:

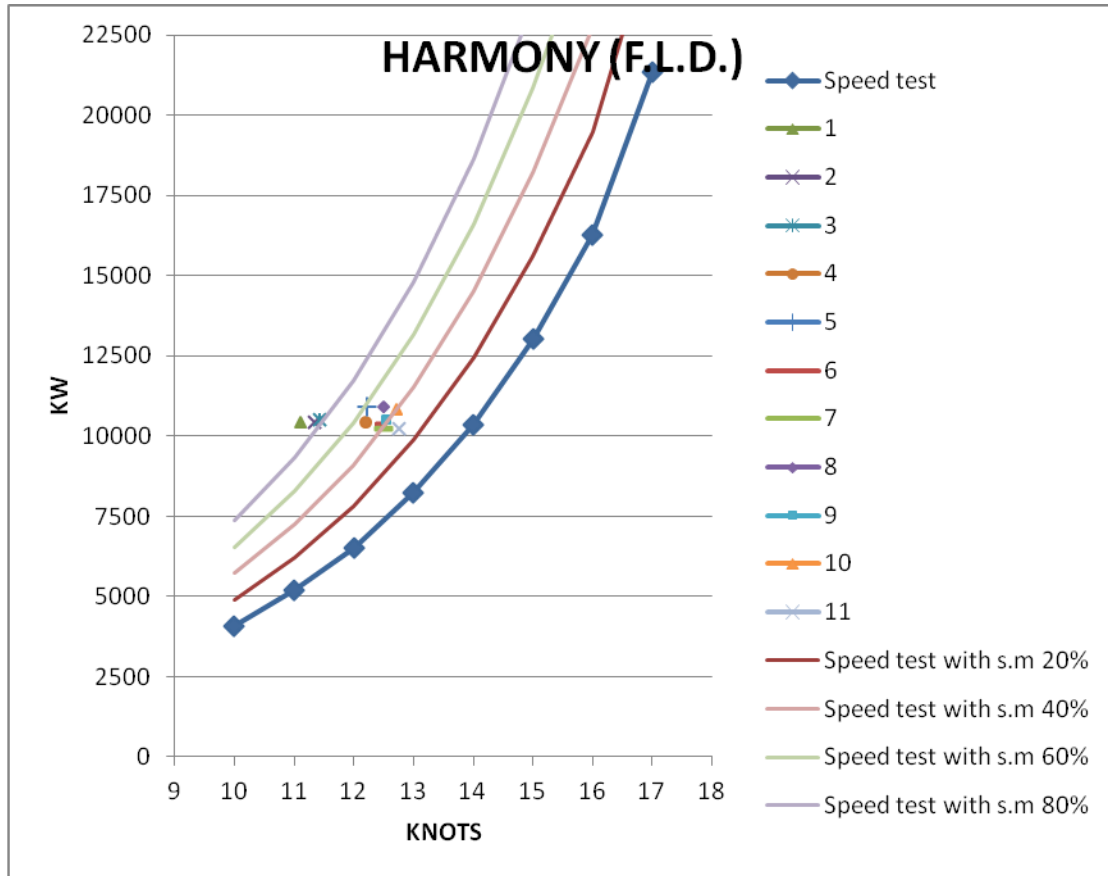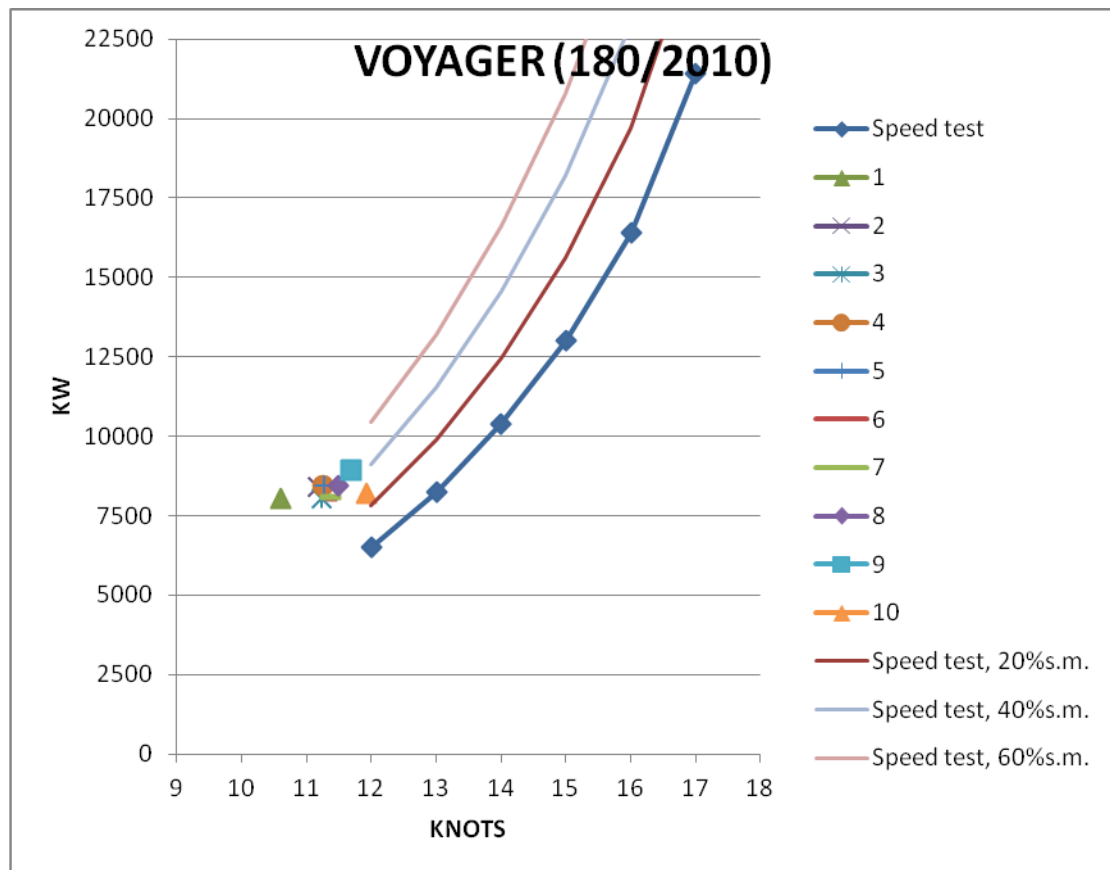# Fuel Oil Consumption – Speed – Powering – Fuel Consumption Data Records and Curves

Fuel Oil Consumption for the three vessels at FLD (T=16,52 m)

Fuel Oil Consumption for the three vessels at Ballast Condition

DYNASTY (T=9,84m)
HARMONY (T=9,85 m)
VOYAGER (T=9,74m)

Speed test curves for the three vessels at FLD (T=16,52m)
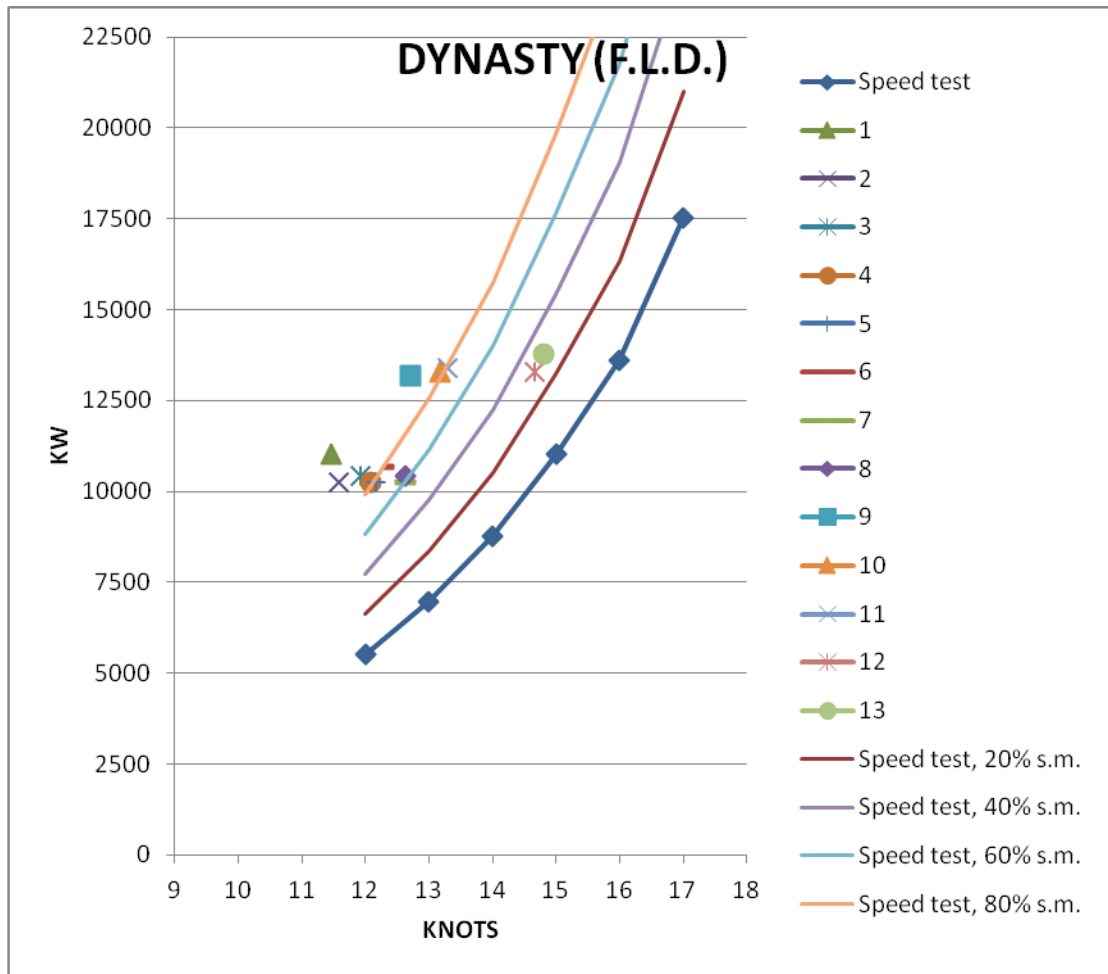
DYNASTY			WEATHER CONDITION						
ΣHMEIA	V(KNOTS)	TONNES PER DAY	WIND(bofor	SEA	REMARKS	TRIM (+aft)	Tmd	DISPLACEMENT	KW for fld
1	11,47	47,2	7	HIGH	ECO SPEED-VESSEL ROLLING AND PITCHING	0,73	17,48	190566	11031,61
2	11,58	44	5	ROUGH	ECO SPEED-STRONG ADVERSE CURRENT 1,0 KNOTS	0,15	17,49	190685,5	10249,47
3	11,92	44,7	5	ROUGH	ECO SPEED-ADVERSE CURRENT 1,0 KNOTS	0,73	17,48	190566	10425,08
4	12,08	44	5	ROUGH	ECO SPEED-STRONG ADVERSE CURRENT 1,2 KNOTS	0,15	17,49	190685,5	10249,47
5	12,17	44	6	V.ROUGH	ECO SPEED-ADVERSE CURRENT 0,5 KNOTS	0,73	17,48	190566	10253,76
6	12,28	45,8	4	MODERATE	ECO SPEED-ADVERSE CURRENT 1,0 KNOTS	0,15	17,49	190685,5	10688,51
7	12,63	44	4	MODERATE	ECO SPEED-ADVERSE CURRENT 0,5 KNOTS	0,15	17,49	190685,5	10249,47
8	12,63	44,7	5	ROUGH	ECO SPEED-ADVERSE CURRENT 0,5 KNOTS	0,73	17,48	190566	10425,08
9	12,71	56	6	V.ROUGH	FULL SPEED-ADVERSE CURRENT 1,0 KNOTS	0,01	17,36	189135	13166,34
10	13,17	56,5	5	ROUGH	FULL SPEED-ADVERSE CURRENT 1,0 KNOTS	0,01	17,36	189135	13281,36
11	13,29	57	5	ROUGH	FULL SPEED-ADVERSE CURRENT 0,5 KNOTS	0,01	17,36	189135	13396,05
12	14,67	56,5	4	MODERATE	FULL SPEED-ADVERSE CURRENT 0,5 KNOTS	0,01	17,36	189135	13281,36
13	14,8	58,7	4	MODERATE	FULL SPEED-ADVERSE CURRENT 0,8 KNOTS	0,01	17,36	189135	13783,47

HARMONY (F.L.D.)

HARMONY			WEATHER CONDITION						
POINTS	V(KNOTS)	TONNES PER DAY	WIND(bofort)	SEA	REMARKS (CURRENT)	TRIM (+aft)	Tmd	DISPLACEMENT	KW for fld
1	11,1	45,1	7	HIGH	STRONG ADVERSE CURRENT 0,8 KNOTS	0,01	17,25	195590,2	10436,84
2	11,33	45,1	6	V.ROUGH	ADVERSE CURRENT 0,5 KNOTS	0,01	17,25	195590,2	10436,84
3	11,43	45	6	V.ROUGH	STRONG ADVERSE CURRENT 1,0 KNOTS&VESSEL ROLLING HEAVILY	0,18	17	192495,8	10523,63
4	12,2	45,1	6	V.ROUGH	ADVERSE CURRENT 0,5 KNOTS&VESSEL ROLLING HEAVILY IN TIMES	0,01	17,25	195590,2	10436,84
5	12,22	47	5	ROUGH	ADVERSE CURRENT 0,8 KNOTS	0,01	17,25	195590,2	10900,46
6	12,37	45	4	MODERATE	VESSEL ROLLING AND PITCHING&STRONG ADVERSE CURRENT 0,5 knots	0,08	17,4	197448,8	10345,49
7	12,5	46	4	MODERATE	NONE	0,02	18,19	207382,9	10248,98
8	12,5	47	5	ROUGH	VESSEL ROLLING	0,9	17,25	195590,2	10900,46
9	12,54	45	4	MODERATE	ADVERSE CURRENT 0,5 KNOTS&VESSEL ROLLING HEAVILY IN TIMES	0,18	17	192495,8	10523,63
10	12,71	47	4	MODERATE	ADVERSE CURRENT 0,5 KNOTS	0,08	17,4	197448,8	10830,49
11	12,75	46	4	MODERATE	NONE	0,02	18,19	207382,9	10248,98

VOYAGER			WEATHER CONDITION						
ΣΗΜΕΙΑ	V(KNOTS)	TONNES PER DAY	WIND(bofort)	SEA	REMARKS (CURRENT)	TRIM (+aft)	Tmd	DISPLACEMENT	KW for fld
1	10,6	35,8	5	ROUGH	ECO SPEED&CURRENT 0,3 KNOTS	0,08	18,27	206713	8028,36
2	11,17	37,2	4	MODERATE	ECO SPEED&CURRENT 0,5 KNOTS	0,14	18,19	205950	8389,6
3	11,23	35,8	4	MODERATE	ECO SPEED&CURRENT 0,4 KNOTS	0,08	18,27	206713	8028,36
4	11,26	37,4	5	ROUGH	ECO SPEED&CURRENT 0,8 KNOTS	0,14	18,19	205950	8438,17
5	11,28	37,4	4	MODERATE	ECO SPEED&CURRENT 0,2 KNOTS	0,1	18,23	206350	8427,26
6	11,32	35,8	4	MODERATE	ECO SPEED&CURRENT 0,1 KNOTS	0,14	18,19	205950	8048,18
7	11,38	36	5	MODERATE	ECO SPEED&CURRENT 0,5 KNOTS	1,17	18,24	206500	8082,72
8	11,49	37,4	3	MODERATE	ECO SPEED&CURRENT 0,2 KNOTS	0,14	18,19	205950	8438,17
9	11,68	39,5	5	ROUGH	ECO SPEED&CURRENT 0,3 KNOTS	1,17	18,24	206500	8929,12
10	11,93	36,5	3	SLIGHT	ECO SPEED&CURRENT 0,3 KNOTS	1,17	18,24	206500	8204,61

APPENDIX II:

Predictions based on the Statistical HOLTROP Method

Holtrop powering estimations on the three vessels for their full load departure (T=16,52m)

DYNASTY			Tonnes/day estimation	WEATHER CONDITION						
ΣΗΜΕΙΑ	V(KNOTS)	TONNES PER DAY	from holtrop with 35% s.m.	WIND(bofort)	SEA	REMARKS	TRIM(+aft)	Tmd	DISPLACEMENT	KW for fld
1	11,47	47,2	27,4	7	HIGH	ECO SPEED-VESSEL ROLLING AND PITCHING	0,73	17,48	190566	11031,61
2	11,58	44	28	5	ROUGH	ECO SPEED-STRONG ADVERSE CURRENT 1,0 KNOTS	0,15	17,49	190685,5	10249,47
3	11,92	44,7	29,96	5	ROUGH	ECO SPEED-ADVERSE CURRENT 1,0 KNOTS	0,73	17,48	190566	10425,08
4	12,08	44	30,94	5	ROUGH	ECO SPEED-STRONG ADVERSE CURRENT 1,2 KNOTS	0,15	17,49	190685,5	10249,47
5	12,17	44	31,51	6	V.ROUGH	ECO SPEED-ADVERSE CURRENT 0,5 KNOTS	0,73	17,48	190566	10253,76
6	12,28	45,8	32,22	4	MODERATE	ECO SPEED-ADVERSE CURRENT 1,0 KNOTS	0,15	17,49	190685,5	10688,51
7	12,63	44	34,59	4	MODERATE	ECO SPEED-ADVERSE CURRENT 0,5 KNOTS	0,15	17,49	190685,5	10249,47
8	12,63	44,7	34,59	5	ROUGH	ECO SPEED-ADVERSE CURRENT 0,5 KNOTS	0,73	17,48	190566	10425,08
9	12,71	56	35,16	6	V.ROUGH	FULL SPEED-ADVERSE CURRENT 1,0 KNOTS	0,01	17,36	189135	13166,34
10	13,17	56,5	38,68	5	ROUGH	FULL SPEED-ADVERSE CURRENT 1,0 KNOTS	0,01	17,36	189135	13281,36
11	13,29	57	39,66	5	ROUGH	FULL SPEED-ADVERSE CURRENT 0,5 KNOTS	0,01	17,36	189135	13396,05
12	14,67	56,5	53,56	4	MODERATE	FULL SPEED-ADVERSE CURRENT 0,5 KNOTS	0,01	17,36	189135	13281,36
13	14,8	58,7	55,17	4	MODERATE	FULL SPEED-ADVERSE CURRENT 0,8 KNOTS	0,01	17,36	189135	13783,47

HARMONY F.L.D. (T=16,52m)

ΣΗΜΕΙΑ	V(KNOTS)	TONNES PER DAY	Tonnes/day estimation from holtrop with 35% s.m.	WIND(bofort)	SEA	REMARKS (CURRENT)	TRIM (+aft)	Tmd	DISPLACEMENT	KW for fld
HARMONY				WEATHER CONDITION						
1	11,1	45,1	28,44	7	HIGH	STRONG ADVERSE CURRENT 0,8 KNOTS	0,01	17,25	195590,2	10436,84
2	11,33	45,1	29,86	6	V.ROUGH	ADVERSE CURRENT 0,5 KNOTS	0,01	17,25	195590,2	10436,84
3	11,43	45	30,5	6	V.ROUGH	STRONG ADVERSE CURRENT 1,0 KNOTS&VESSEL ROLLING HEAVILY	0,18	17	192495,8	10523,63
4	12,2	45,1	35,97	6	V.ROUGH	ADVERSE CURRENT 0,5 KNOTS&VESSEL ROLLING HEAVILY IN TIMES	0,01	17,25	195590,2	10436,84
5	12,22	47	36,12	5	ROUGH	ADVERSE CURRENT 0,8 KNOTS	0,01	17,25	195590,2	10900,46
6	12,37	45	37,31	4	MODERATE	VESSEL ROLLING AND PITCHING&STRONG ADVERSE CURRENT 0,5 knots	0,08	17,4	197448,8	10345,49
7	12,5	46	38,37	4	MODERATE	NONE	0,02	18,19	207382,9	10248,98
8	12,5	47	38,37	5	ROUGH	VESSEL ROLLING	0,9	17,25	195590,2	10900,46
9	12,54	45	38,7	4	MODERATE	ADVERSE CURRENT 0,5 KNOTS&VESSEL ROLLING HEAVILY IN TIMES	0,18	17	192495,8	10523,63
10	12,71	47	40,17	4	MODERATE	ADVERSE CURRENT 0,5 KNOTS	0,08	17,4	197448,8	10830,49
11	12,75	46	40,52	4	MODERATE	NONE	0,02	18,19	207382,9	10248,98
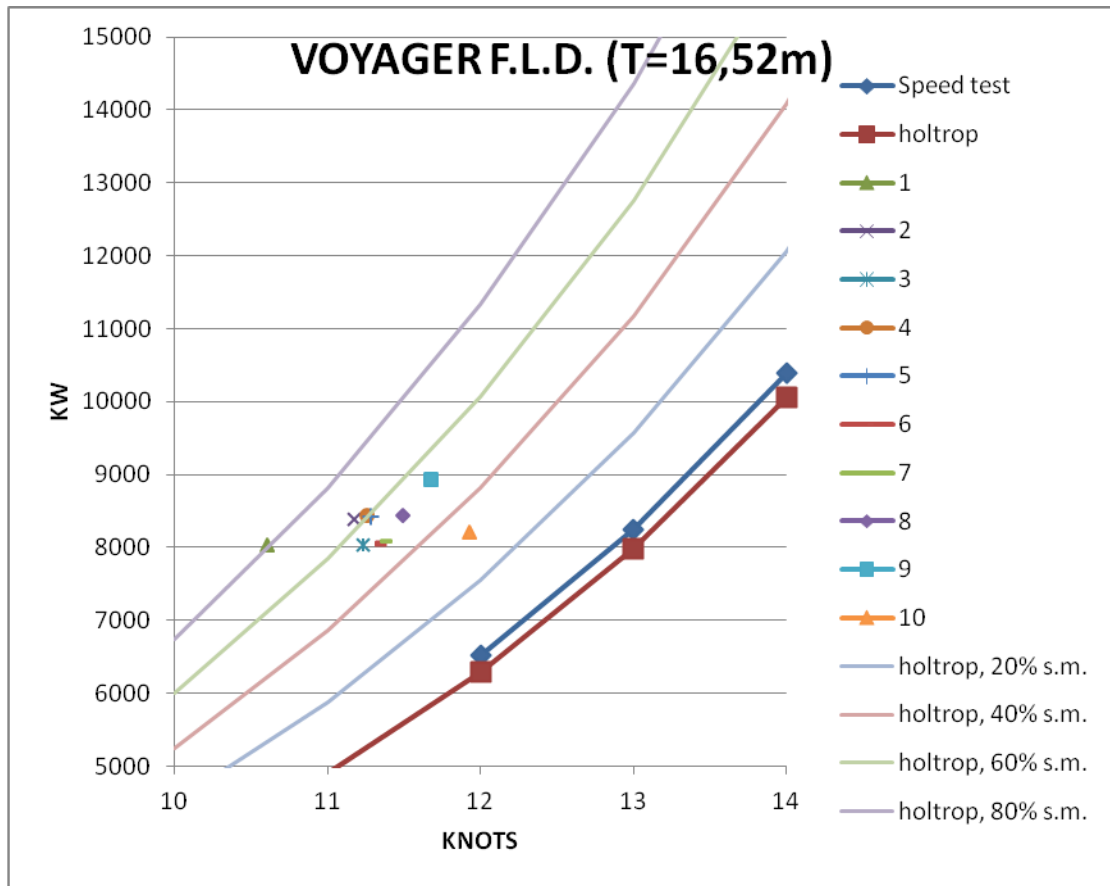
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VOYAGER			Tonnes/day estimation	WEATHER CONDITION						
ΣΗΜΕΙΑ	V(KNOTS)	TONNES PER DAY	from holtrop with 35% s.m.	WIND(bofort)	SEA	REMARKS (CURRENT)	TRIM (+aft)	Tmd	DISPLACEMENT	KW for fld
1	10,6	35,8	25,96	5	ROUGH	ECO SPEED&CURRENT 0,3 KNOTS	0,08	18,27	206713	8028,36
2	11,17	37,2	29,31	4	MODERATE	ECO SPEED&CURRENT 0,5 KNOTS	0,14	18,19	205950	8389,6
3	11,23	35,8	29,69	4	MODERATE	ECO SPEED&CURRENT 0,4 KNOTS	0,08	18,27	206713	8028,36
4	11,26	37,4	29,88	5	ROUGH	ECO SPEED&CURRENT 0,8 KNOTS	0,14	18,19	205950	8438,17
5	11,28	37,4	30,01	4	MODERATE	ECO SPEED&CURRENT 0,2 KNOTS	0,1	18,23	206350	8427,26
6	11,32	35,8	30,27	4	MODERATE	ECO SPEED&CURRENT 0,1 KNOTS	0,14	18,19	205950	8048,18
7	11,38	36	30,67	5	MODERATE	ECO SPEED&CURRENT 0,5 KNOTS	1,17	18,24	206500	8082,72
8	11,49	37,4	31,4	3	MODERATE	ECO SPEED&CURRENT 0,2 KNOTS	0,14	18,19	205950	8438,17
9	11,68	39,5	32,72	5	ROUGH	ECO SPEED&CURRENT 0,3 KNOTS	1,17	18,24	206500	8929,12
10	11,93	36,5	34,55	3	SLIGHT	ECO SPEED&CURRENT 0,3 KNOTS	1,17	18,24	206500	8204,61
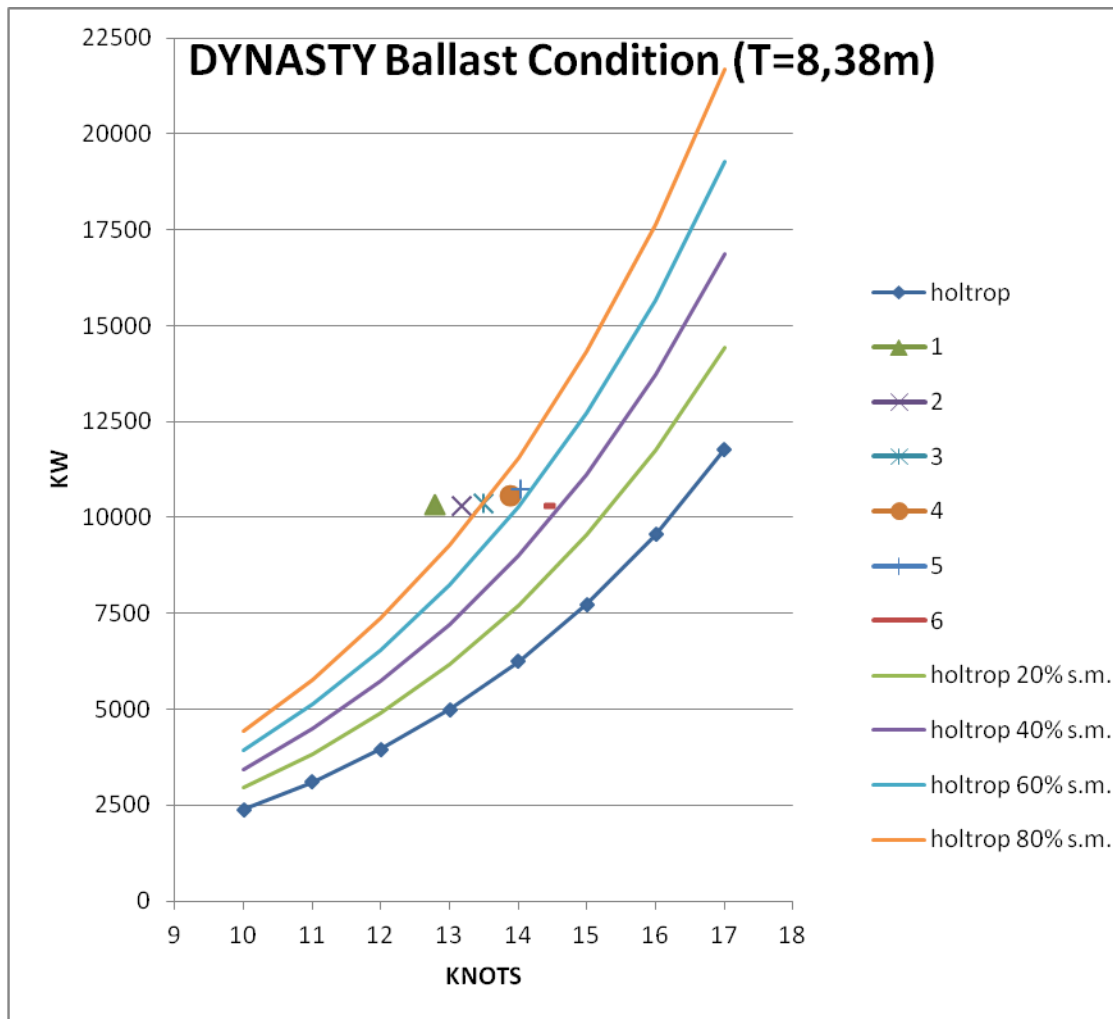
DYNASTY Ballast Condition (T=8,38m)

DYNASTY			Tonnes/day estimation	WEATHER CONDITION						
ΣHMEIA	V(KNOTS)	TONNES PER DAY	from holtrop with 35% s.m.	WIND(bofort)	SEA	REMARKS	TRIM (+aft)	Tmd	DISPLACEMENT(TON)	KW for fld
1	12,78	42,6	28,68	6	V.ROUGH	ADVERSE CURRENT 0,4 KNOTS	2,35	8,38	86040	10327,15
2	13,17	42,5	30,83	5	ROUGH	ADVERSE CURRENT 1,5 KNOTS	2,35	8,38	86040	10301,39
3	13,5	42,7	32,8	5	ROUGH	ADVERSE CURRENT 0,5 KNOTS	2,35	8,38	86040	10352,89
4	13,88	43,5	35,25	5	ROUGH	ADVERSE CURRENT 0,5 KNOTS	2,35	8,38	86040	10558,34
5	14,04	44,2	36,34	5	ROUGH	NONE	2,35	8,38	86040	10737,37
6	14,38	42,5	38,8	4	MODERATE	ADVERSE CURRENT 0,5 KNOTS	2,35	8,38	86040	10301,39
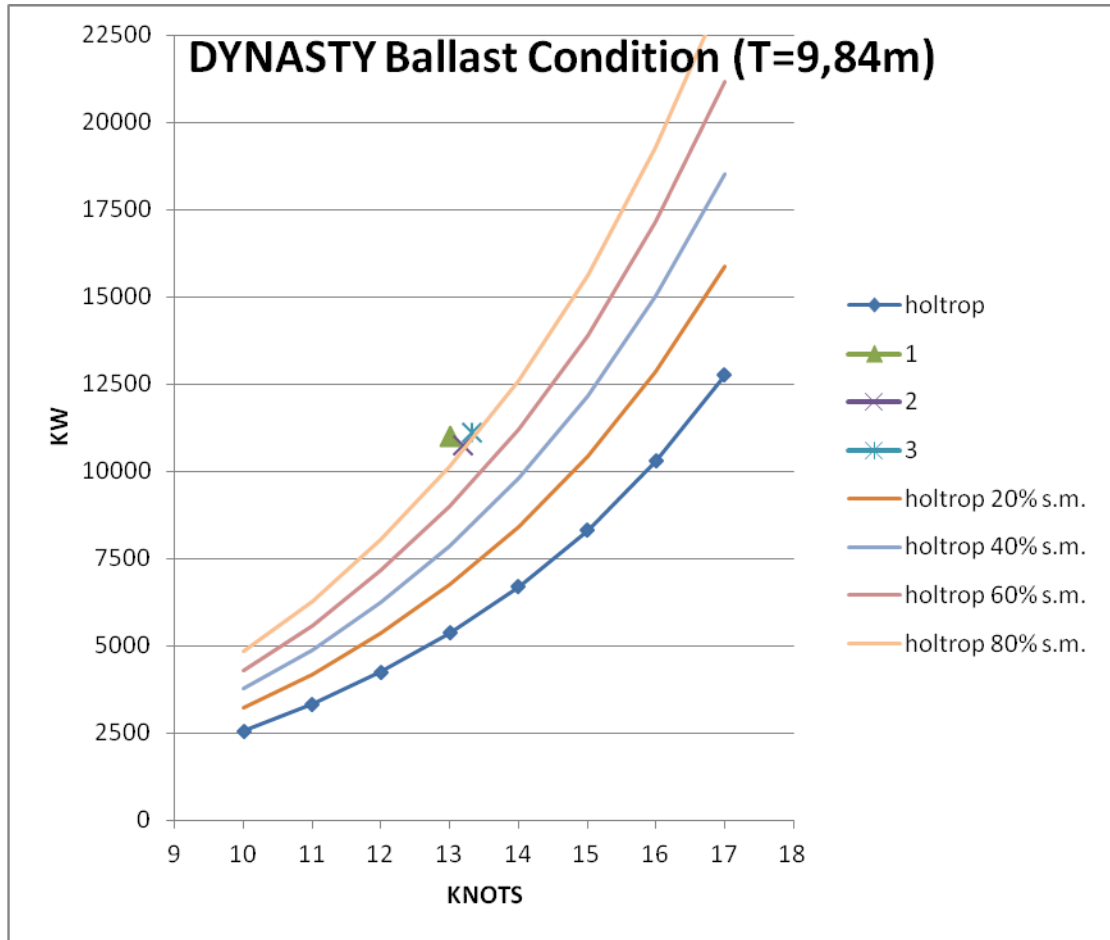
DYNASTY Ballast Condition (T=9,84m)

ΣΗΜΕΙΑ	V(KNOTS)	TONNES PER DAY	Tonnes/day estimation from holtrop with 35% s.m.	WIND(bofort)	SEA	REMARKS	TRIM (+aft)	Tmd	DISPLACEMENT(TON)	KW for fld
DYNASTY			Tonnes/day estimation	WEATHER CONDITION						
1	13	45,2	32,07	4	MODERATE	ADVERSE CURRENT 0,5 KNOTS	3,42	9,84	102125	10991,86
2	13,2	44,4	33,32	4	MODERATE	NONE	3,42	9,84	102125	10722,4
3	13,32	45,6	34,1	4	MODERATE	ADVERSE CURRENT 0,3 KNOTS	3,42	9,84	102125	11093,4
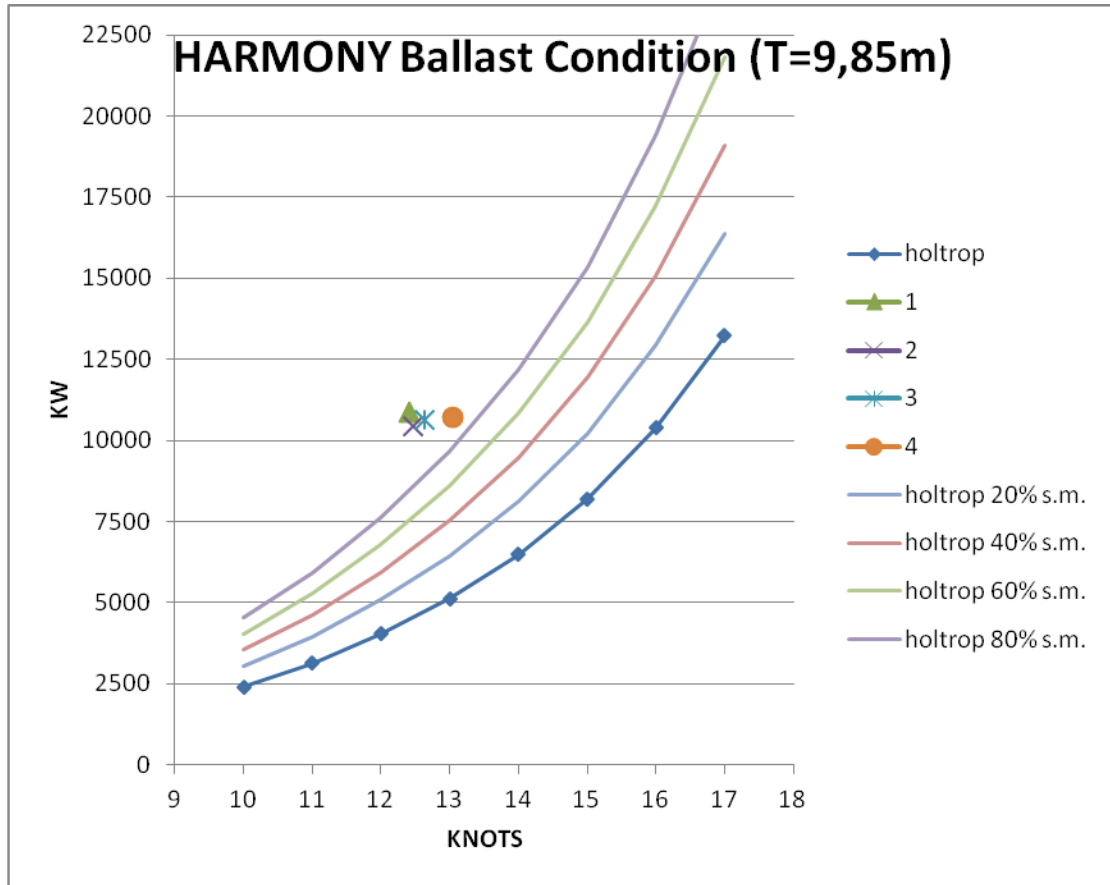
HARMONY Ballast Condition (T=9,85m)

ΣΗΜΕΙΑ	V(KNOTS)	TONNES PER DAY	Tonnes/day estimation from holtrop with 35% s.m.	WIND(bofort)	SEA	REMARKS (CURRENT)	TRIM (+aft)	Tmd	DISPLACEMENT(TON)	KW for fld
HARMONY				WEATHER CONDITION						
1	12,42	45,5	27,9	5	ROUGH	ADVERSE CURRENT 0,5 KNOTS	3,08	9,85	106895,8	10880,94
2	12,46	43,7	28,12	4	MODERATE	NONE	3,08	9,85	106895,8	10424,57
3	12,63	44,5	29,08	4	MODERATE	NONE	3,08	9,85	106895,8	10627,82
4	13,04	44,8	31,56	4	MODERATE	NONE	3,08	9,85	106895,8	10703,87

HARMONY Ballast Condition (T=9,05m)

ΣΗΜΕΙΑ	V(KNOTS)	TONNES PER DAY	Tonnes/day estimation from holtrop with 35% s.m.	WIND(bofort)	SEA	REMARKS (CURRENT)	TRIM (+aft)	Tmd	DISPLACEMENT(T	KW for fld
				WEATHER CONDITION						
1	14,13	58	37,42	5	ROUGH	ADVERSE CURRENT 0,3 KNOTS-VESSEL ROLLING HEAVILY	1,9	9,05	97725,6	13957,12
2	14,9	60,5	43,99	5	ROUGH	ADVERSE CURRENT 0,5 KNOTS-VESSEL ROLLING HEAVILY	1,9	9,05	97725,6	14552,82
3	15	58	44,97	5	ROUGH		1,9	9,05	97725,6	13957,12
4	15,04	60,4	45,36	4	MODERATE	STRONG ADVERSE CURRENT 1,0 KNOTS	1,9	9,05	97725,6	14529,12
5	15,17	58,5	46,67	4	MODERATE	ADVERSE CURRENT 0,5 KNOTS-VESSEL ROLLING AND PITCHING	1,9	9,05	97725,6	14076,78

VOYAGER Ballast Condition (T=9,64m)

VOYAGER			Tonnes/day estimation	WEATHER CONDITION						
ΣΗΜΕΙΑ	V(KNOTS)	TONNES PER DAY	from holtrop with 35% s.m.	WIND(bofort)	SEA	REMARKS (CURRENT)	TRIM (+aft)	Tmd	DISPLACEMENT(TON)	KW for fld
1	11,85	37	23,89	7	V. ROUGH	ECO SPEED-ADVERSE CURRENT 1,1 KNOTS	2,06	9,64	103884	8954,21
2	12,68	37	27,98	6	ROUGH-V.ROUGH	ECO SPEED-ADVERSE CURRENT 0,3 KNOTS	2,06	9,64	103884	8954,21
3	14,59	37	41,26	3	MODERATE	ECO SPEED-ADVERSE CURRENT 0,8 KNOTS	2,06	9,64	103884	8954,21

ΣΗΜΕΙΑ	V(KNOTS)	TONNES PER DAY	Tonnes/day estimation from holtrop with 35% s.m.	WIND(bofort)	SEA	REMARKS (CURRENT)	TRIM (+aft)	Tmd	DISPLACEMENT(TON)	KW for fld
1	11,62	38,3	21,94	5	ROUGH	ECO SPEED-ADVERSE CURRENT 0,2 KNOTS	2,17	8,53	90900	9292,48
2	11,81	36,7	22,71	4	MODERATE	ECO SPEED-ADVERSE CURRENT 0,6 KNOTS	2,17	8,53	90900	8875,81
3	13,49	36,8	31,2	4	SLIGHT	ECO SPEED-ADVERSE CURRENT 0,7 KNOTS	2,17	8,53	90900	8901,96
4	13,54	36,6	31,51	4	SLIGHT	ECO SPEED-ADVERSE CURRENT 0,8 KNOTS	2,17	8,53	90900	8849,65
5	13,67	42	32,33	4	MODERATE	ECO SPEED-ADVERSE CURRENT 0,5 KNOTS	2,17	8,53	90900	10242,4
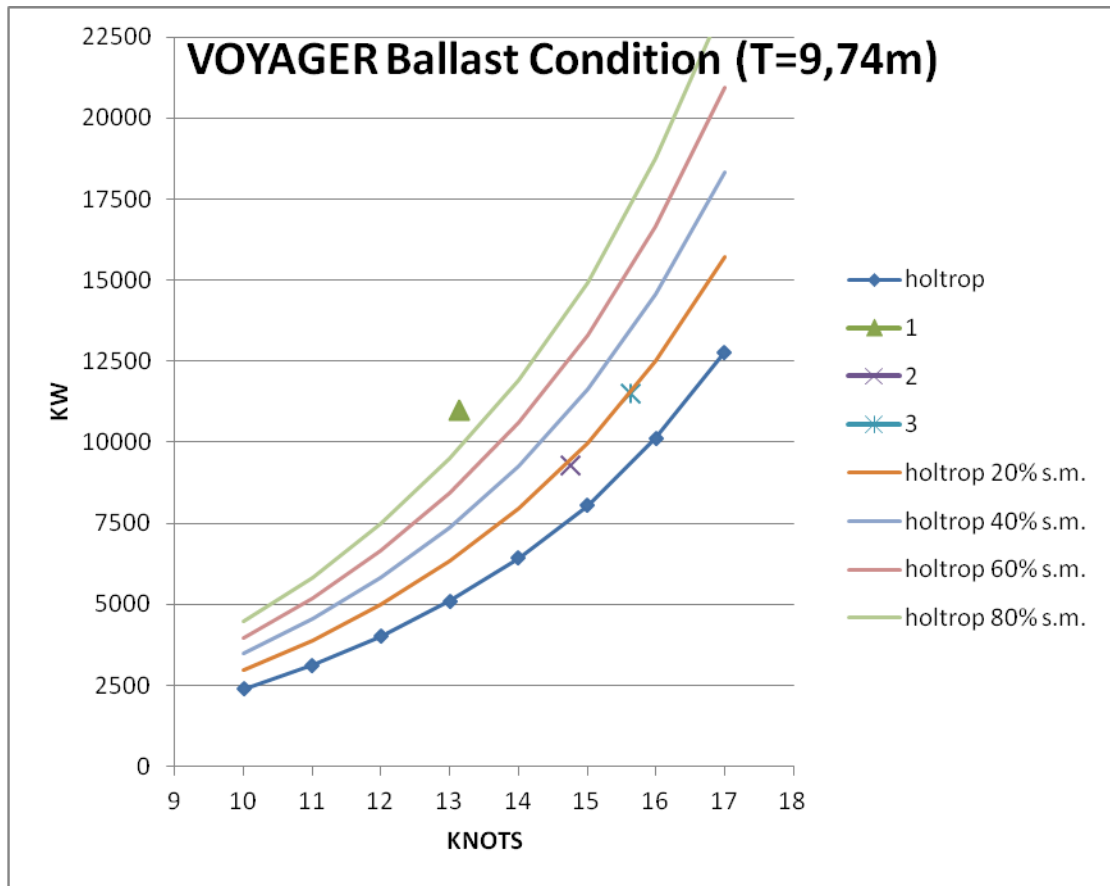
VOYAGER — Tonnes/day estimation — WEATHER CONDITION

VOYAGER Ballast Condition (T=9,74m)

Legend:
- holtrop
- 1
- 2
- 3
- holtrop 20% s.m.
- holtrop 40% s.m.
- holtrop 60% s.m.
- holtrop 80% s.m.

X-axis: KNOTS
Y-axis: KW

VOYAGER			Tonnes/day estimation	WEATHER CONDITION						
ΣΗΜΕΙΑ	V(KNOTS)	TONNES PER DAY	from holtrop with 35% s.m.	WIND(bofort)	SEA	REMARKS (CURRENT)	TRIM (+aft)	Tmd	DISPLACEMENT(TON)	KW for fld
1	13,13	45	30,84	5	ROUGH	ECO SPEED-ADVERSE CURRENT 0,3 KNOTS	2,35	9,74	105024	10998,65
2	14,75	38,2	43,12	3	SLIGHT	ECO SPEED-ADVERSE CURRENT 0,6 KNOTS	2,35	9,74	105024	9266,54
3	15,63	47	52,61	4	MODERATE	ECO SPEED-ADVERSE CURRENT 1,0 KNOTS	2,35	9,74	105024	11495,87

APPENDIX III:

Computations using the Computational Fluid Dynamics (CFD) packet, SHIPFLOW

CW for T= 16,52m

CW for T=9,74m
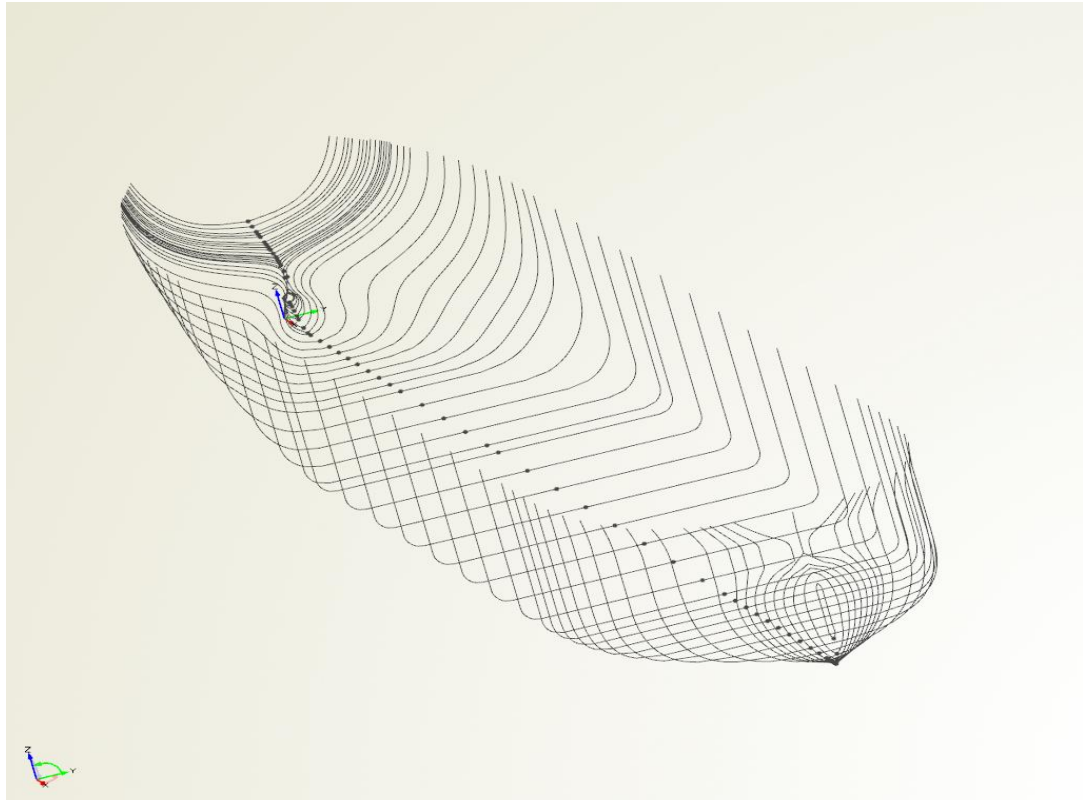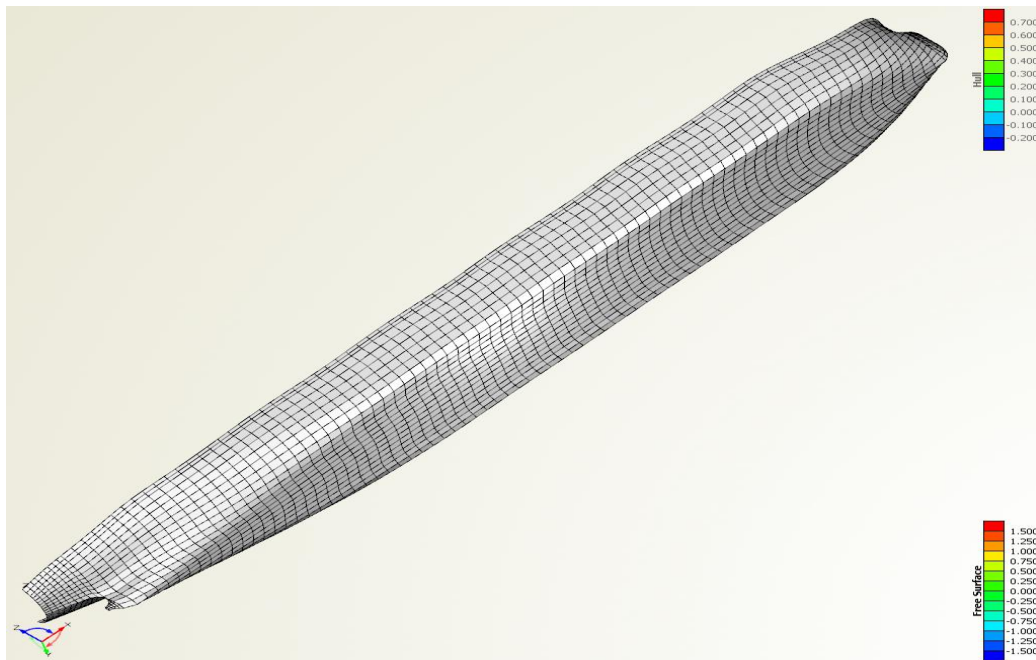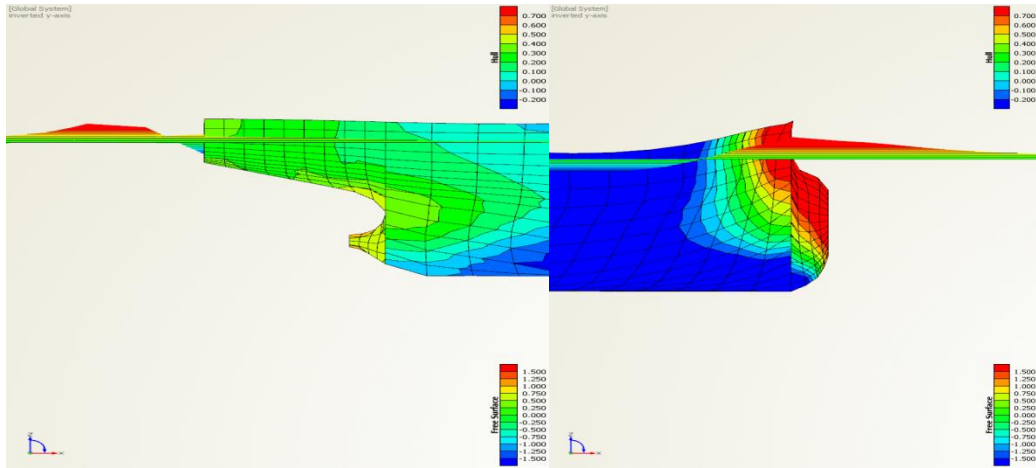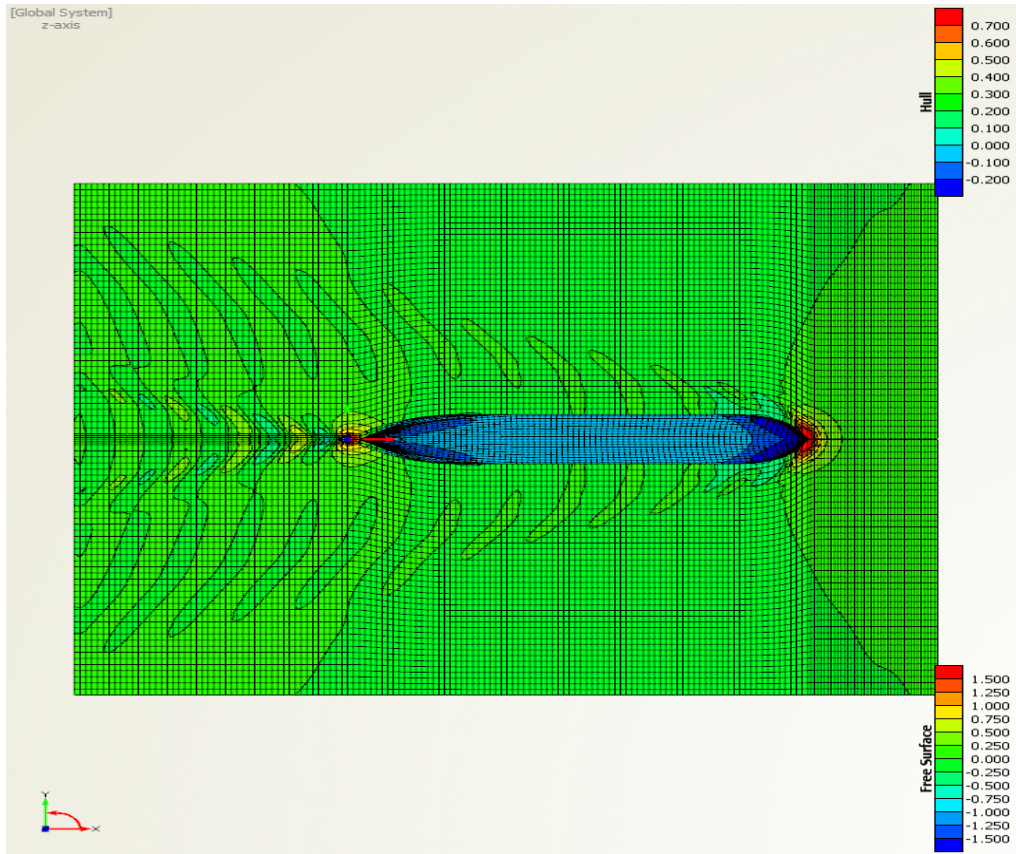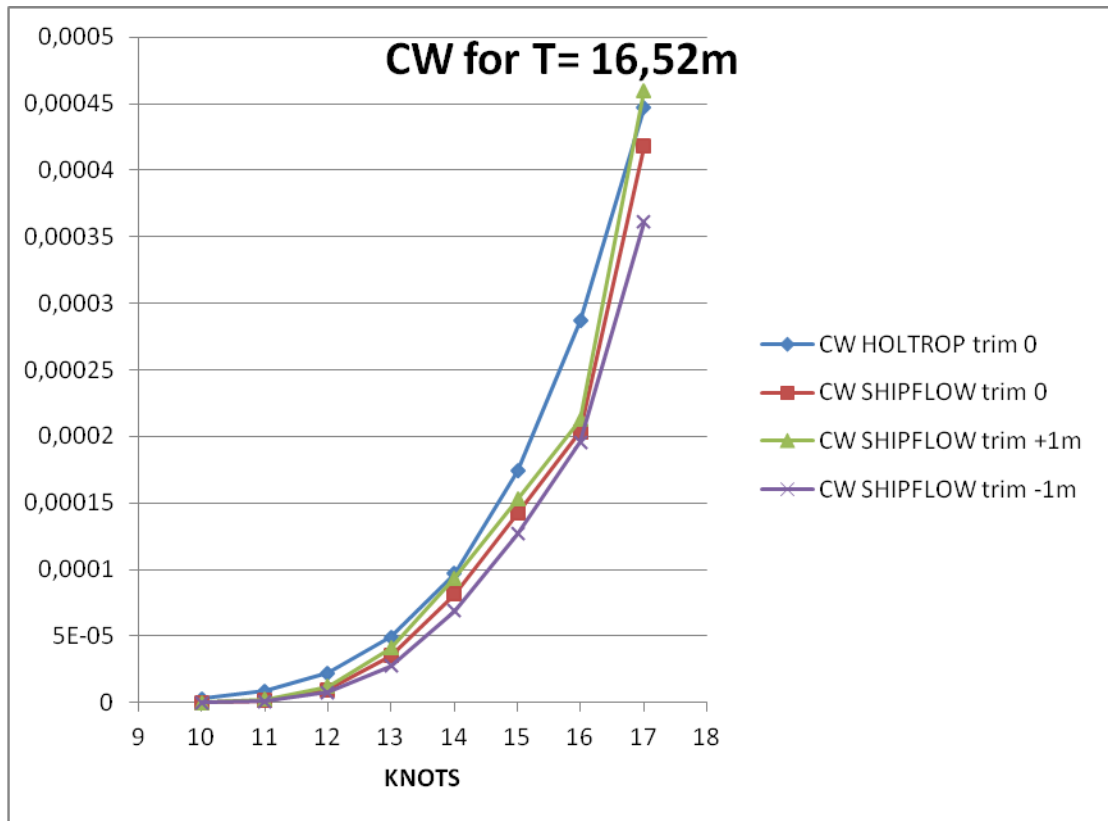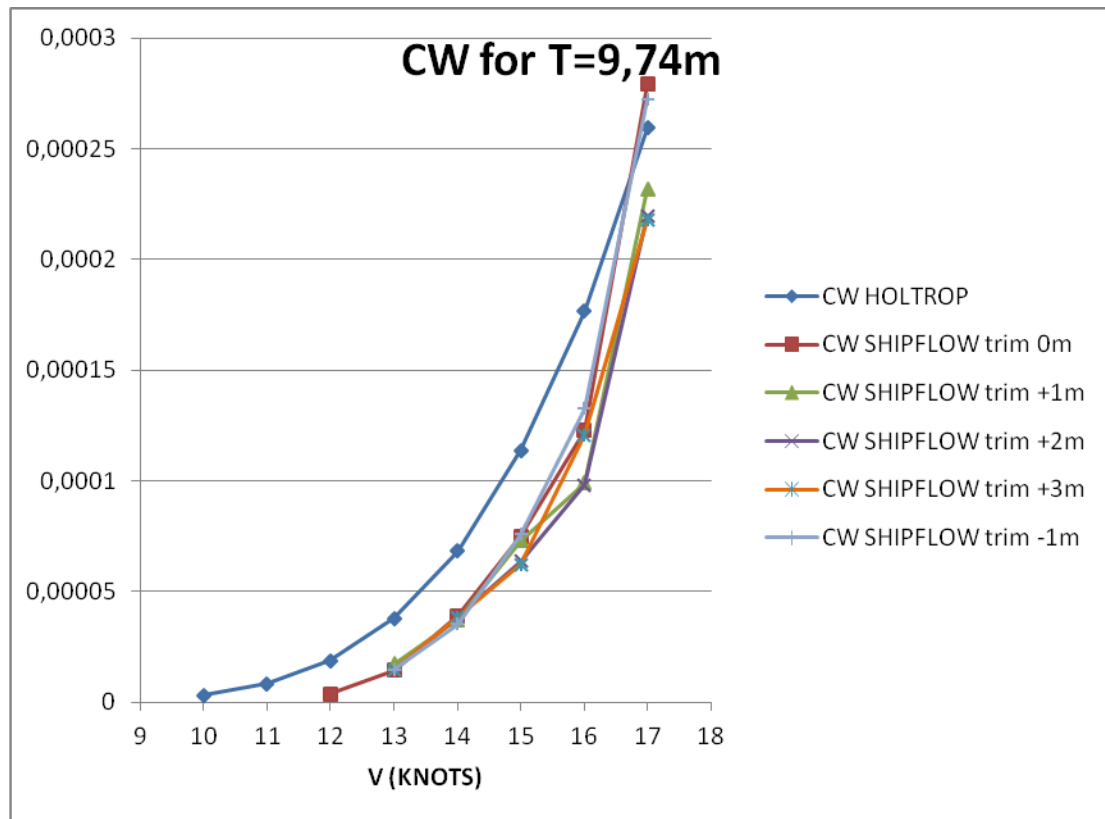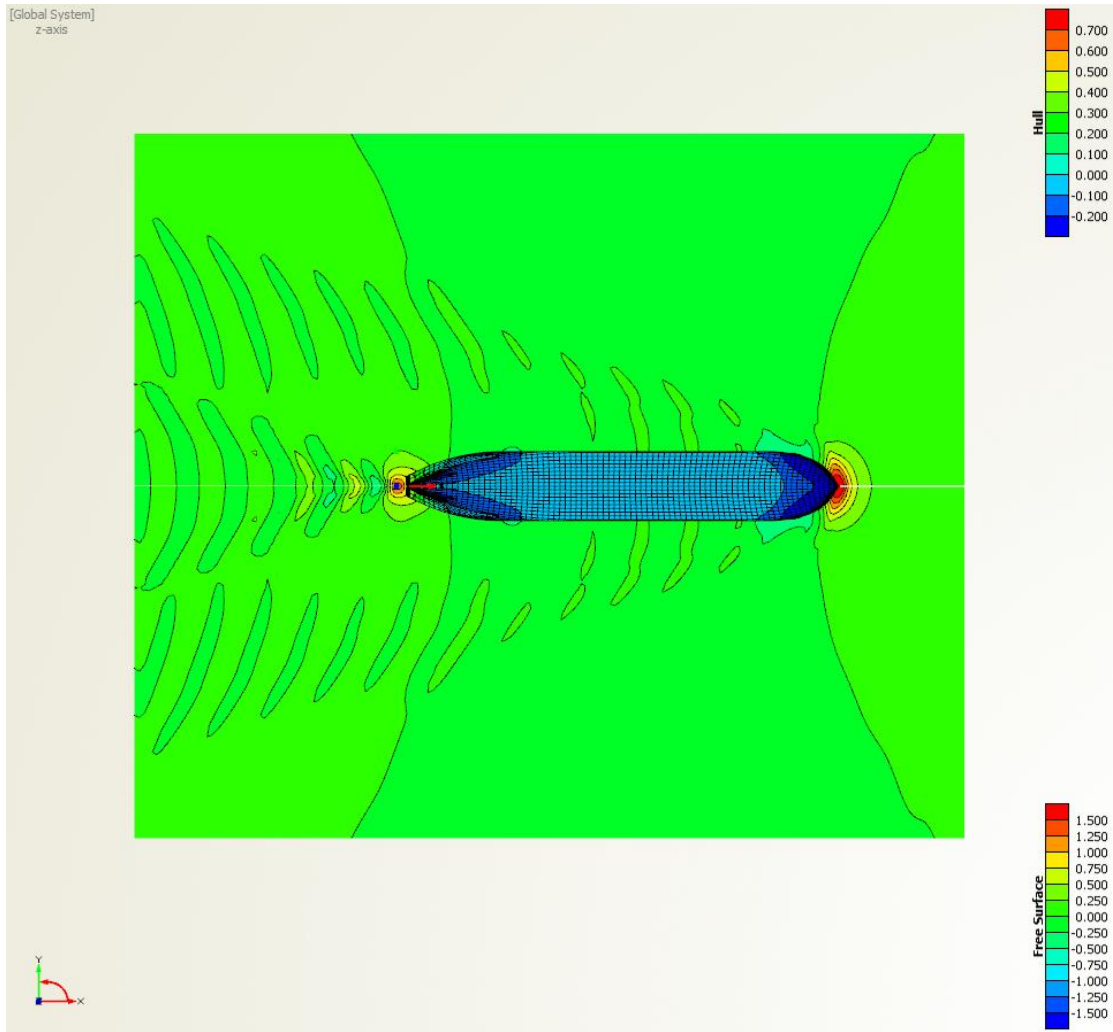
FLD T=16.52 V=10knots
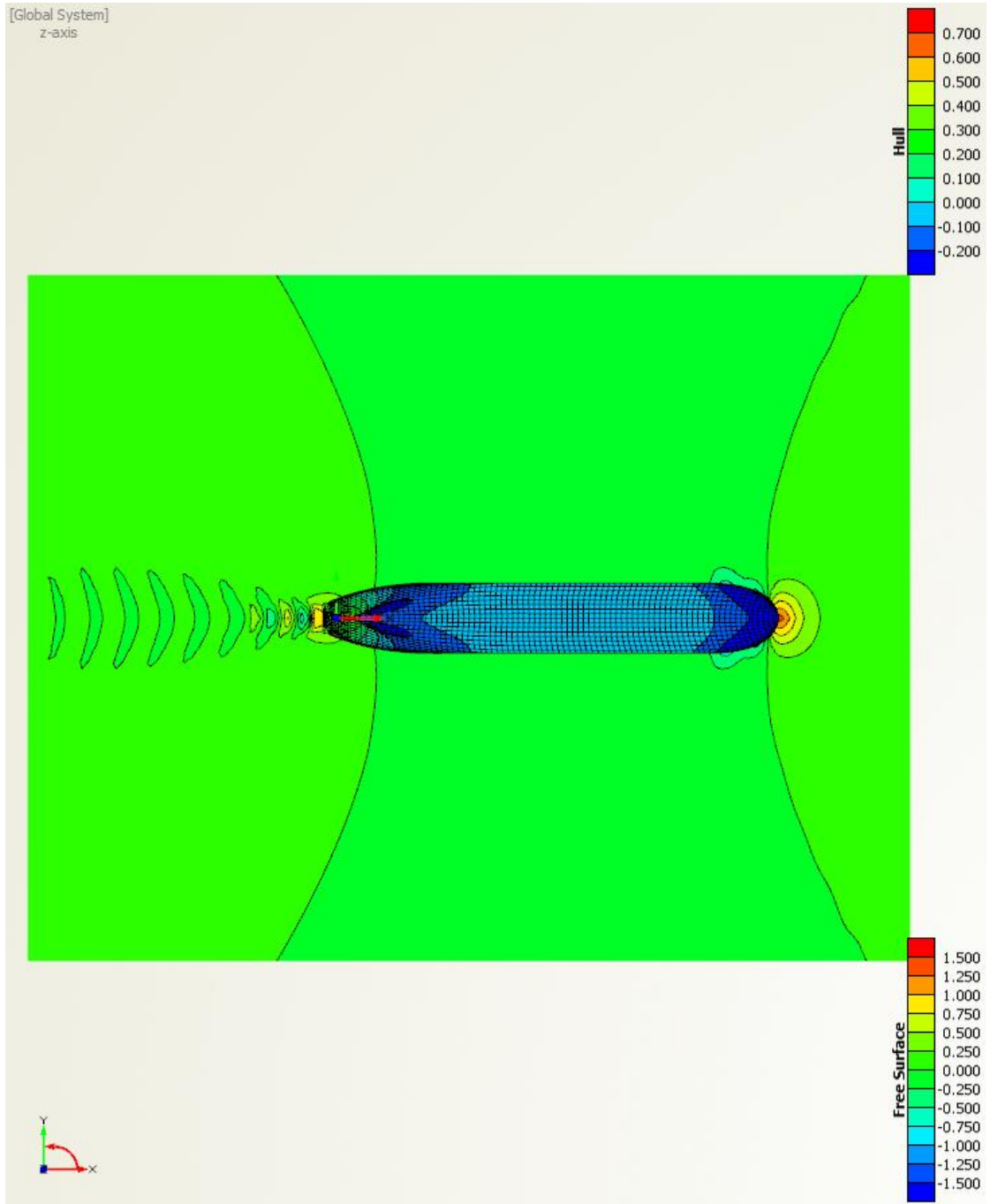
V=11knots
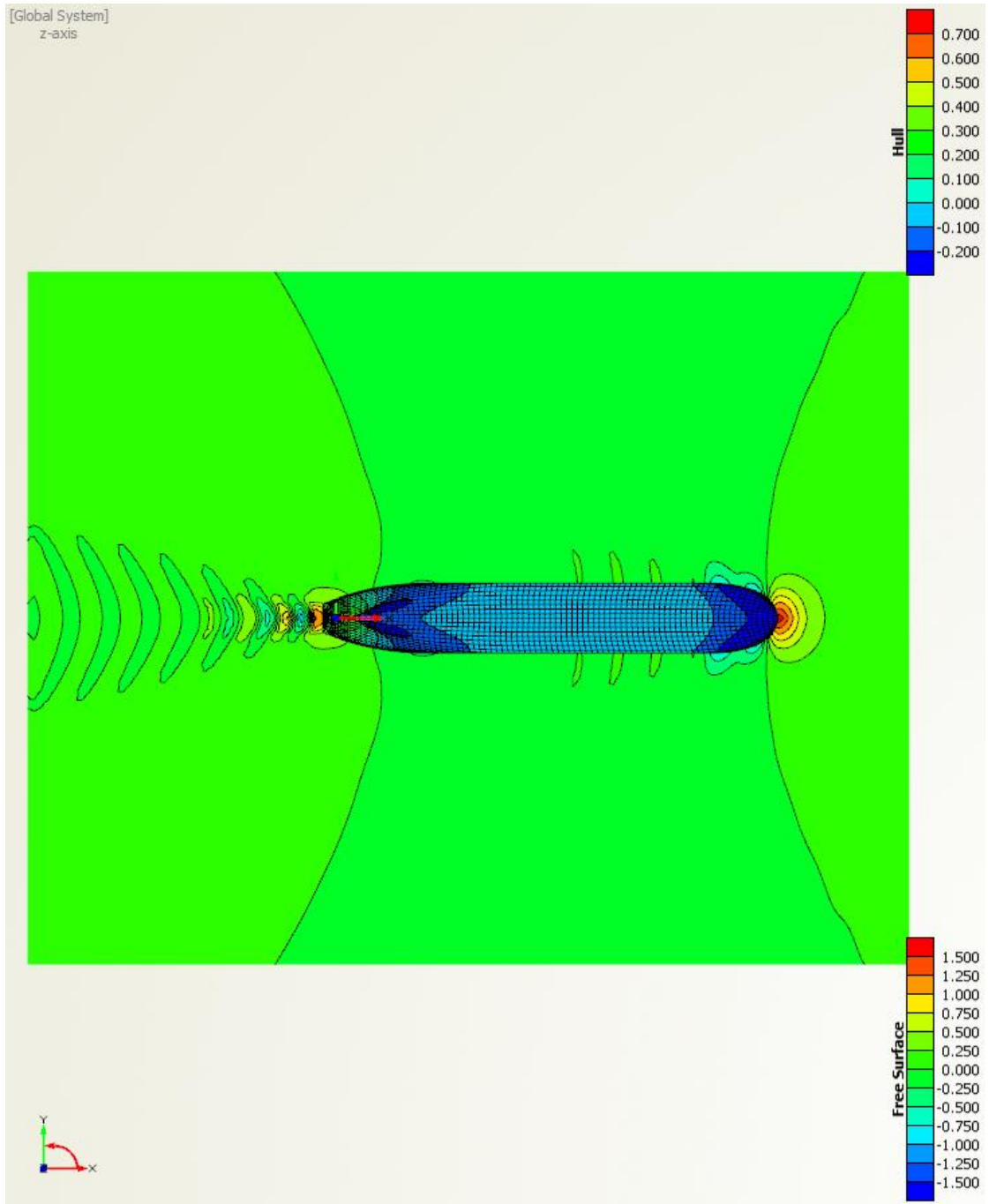
V=12knots
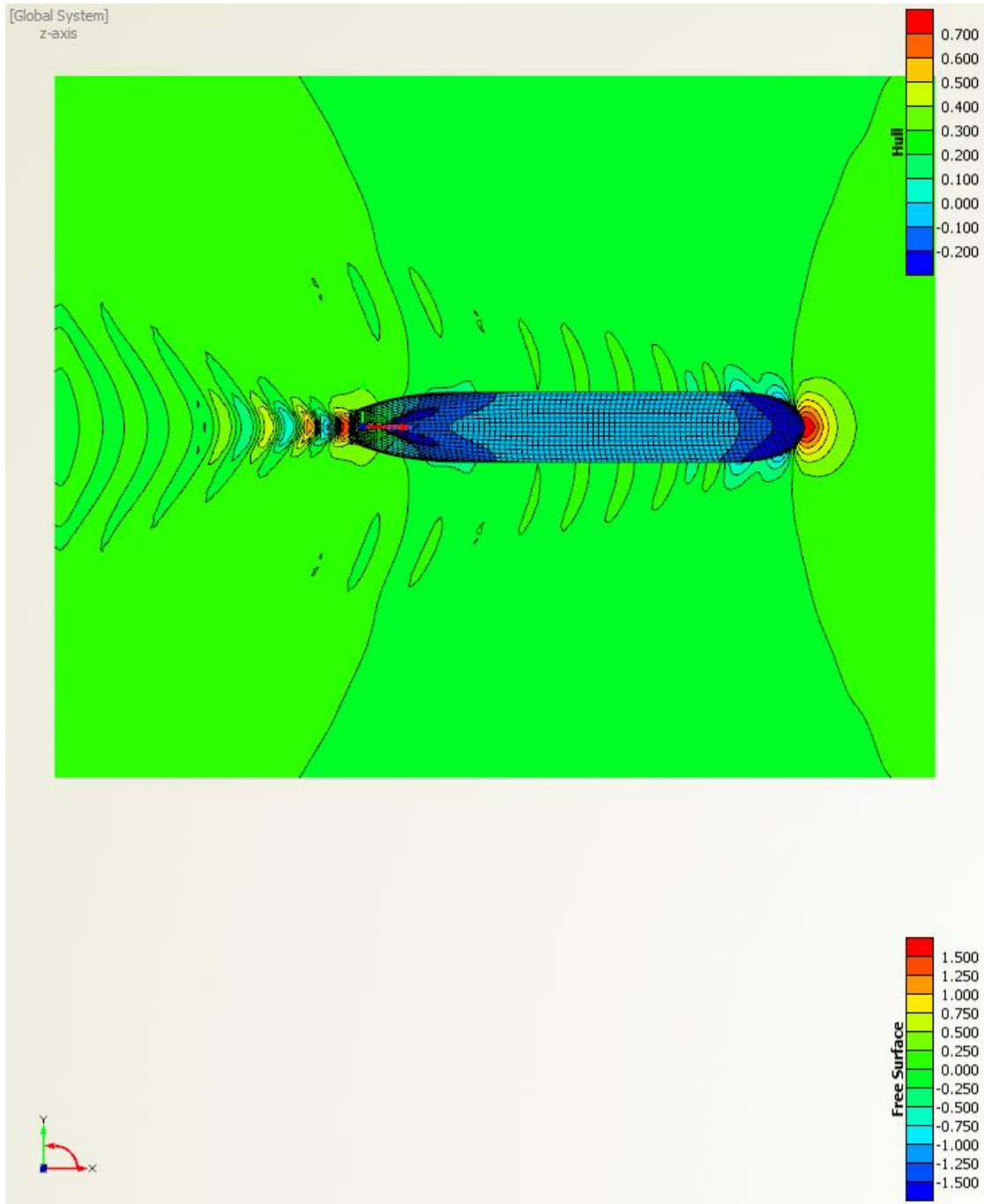
V=13 knots
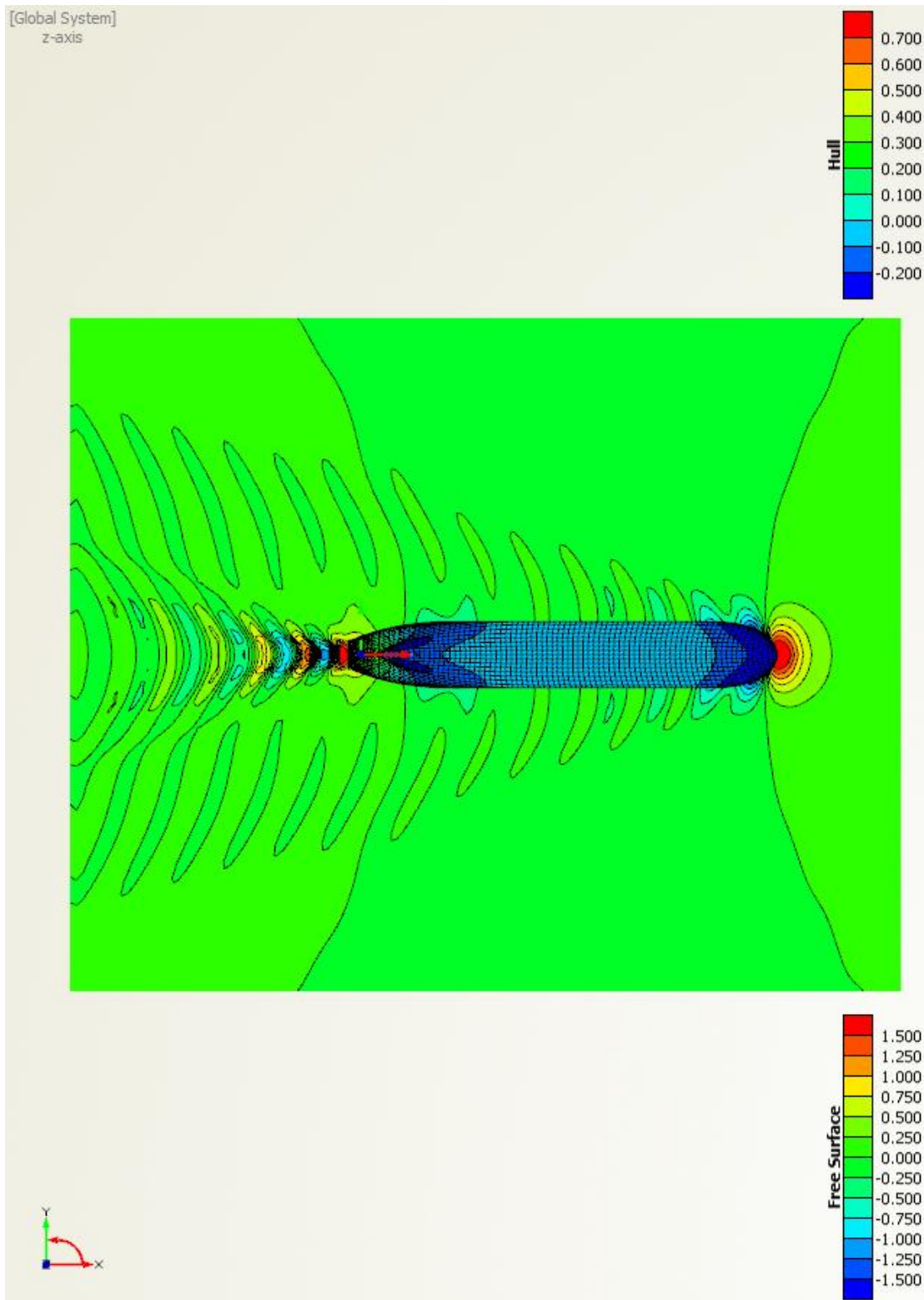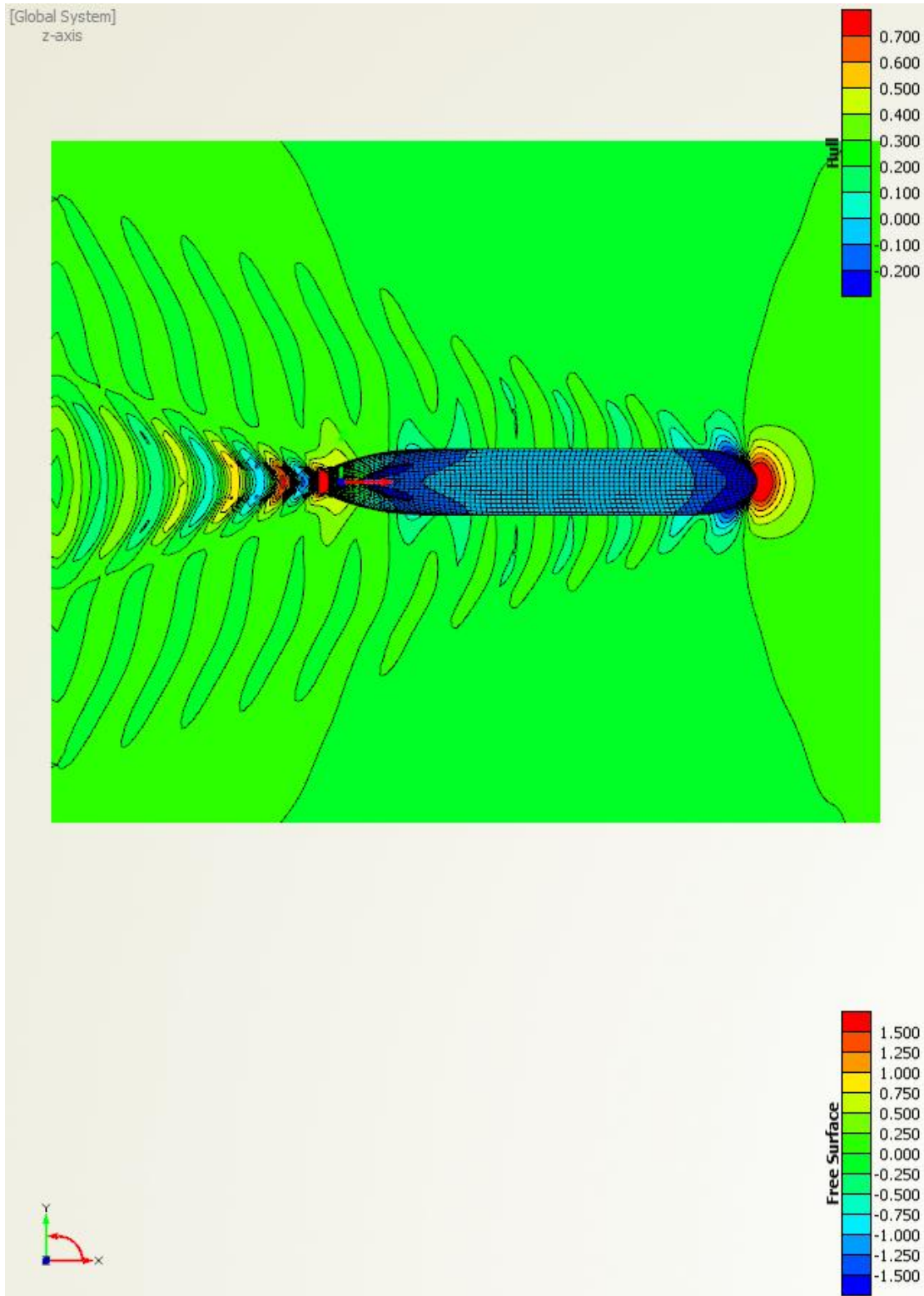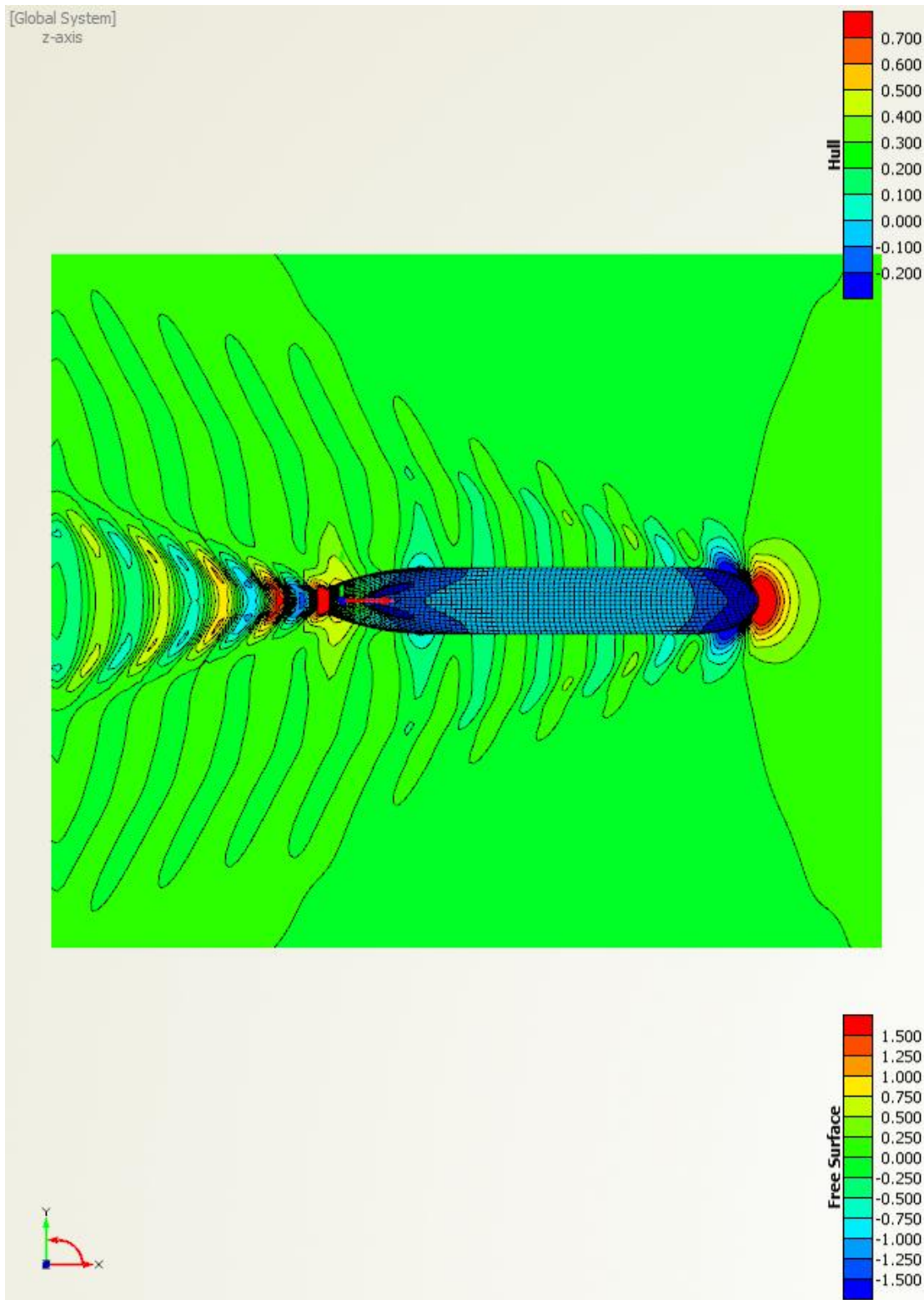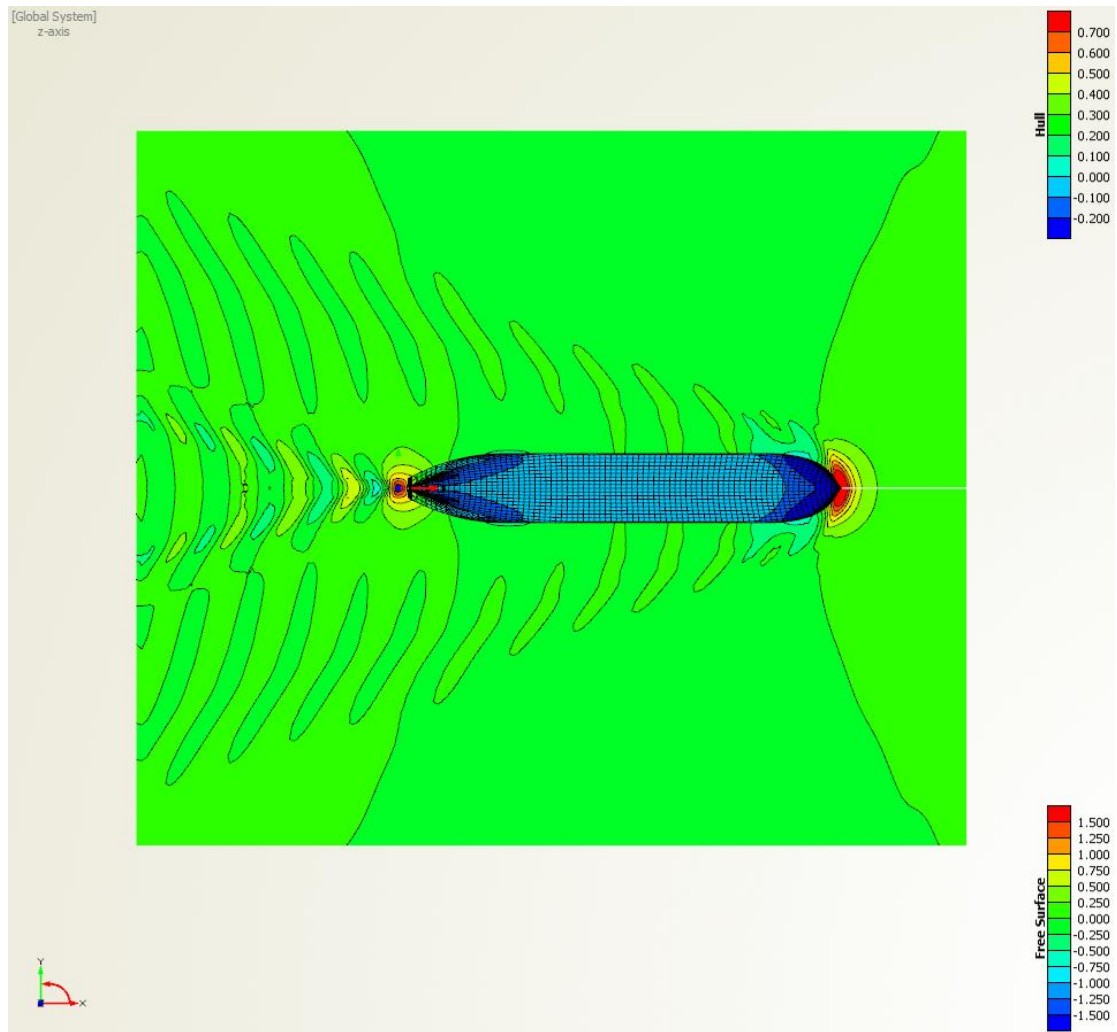
V=14knots
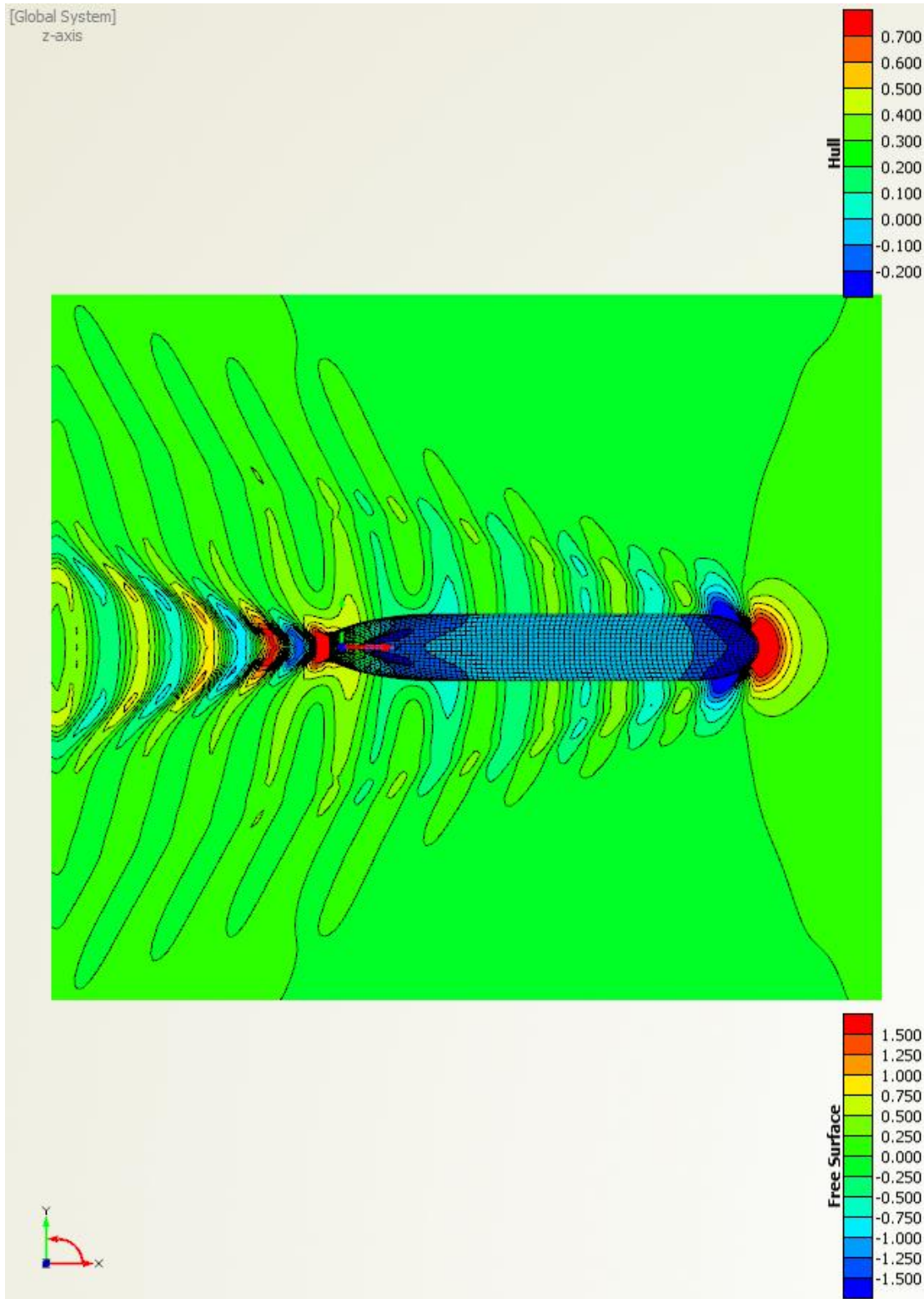
V=15knots
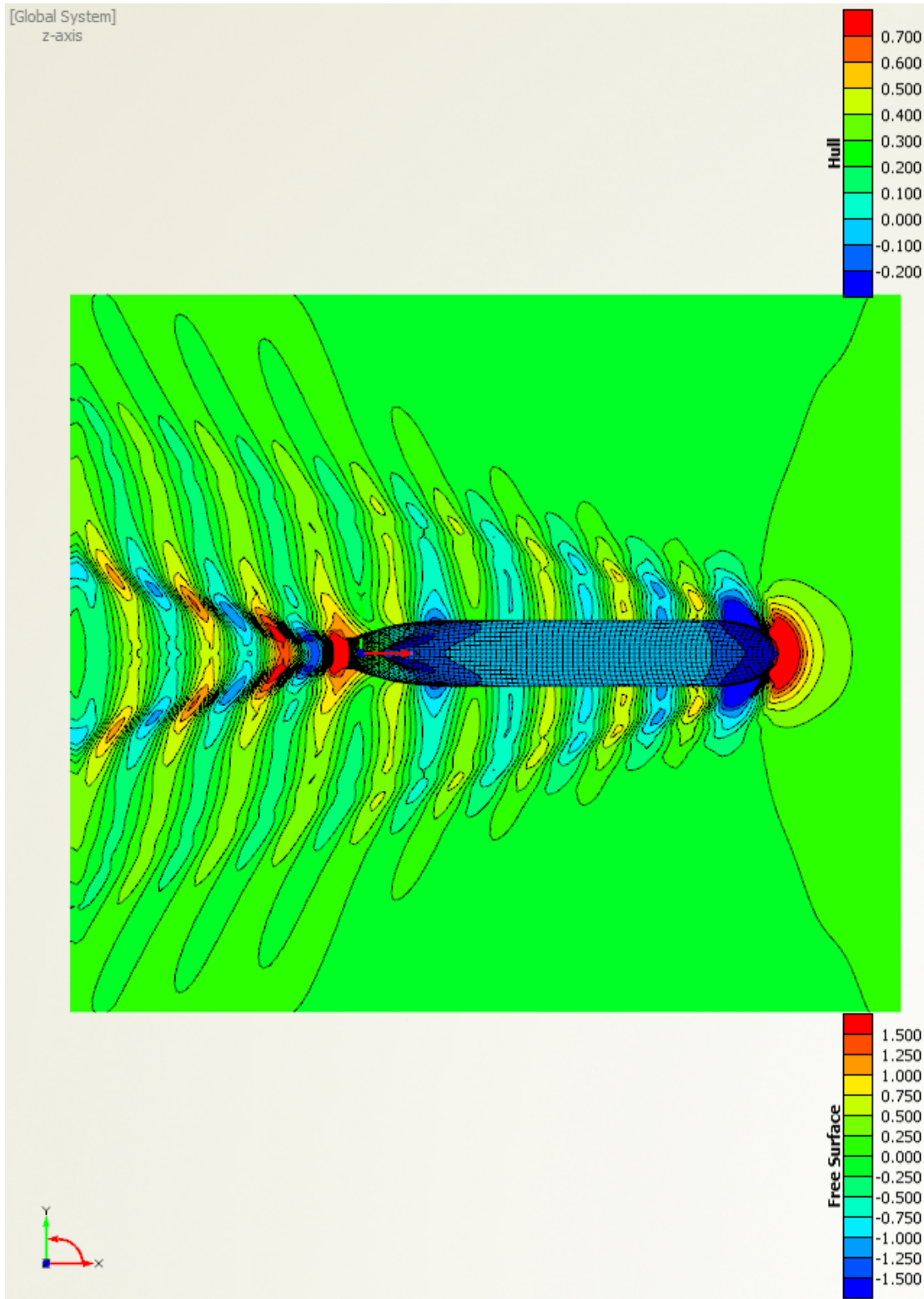
V=16knots
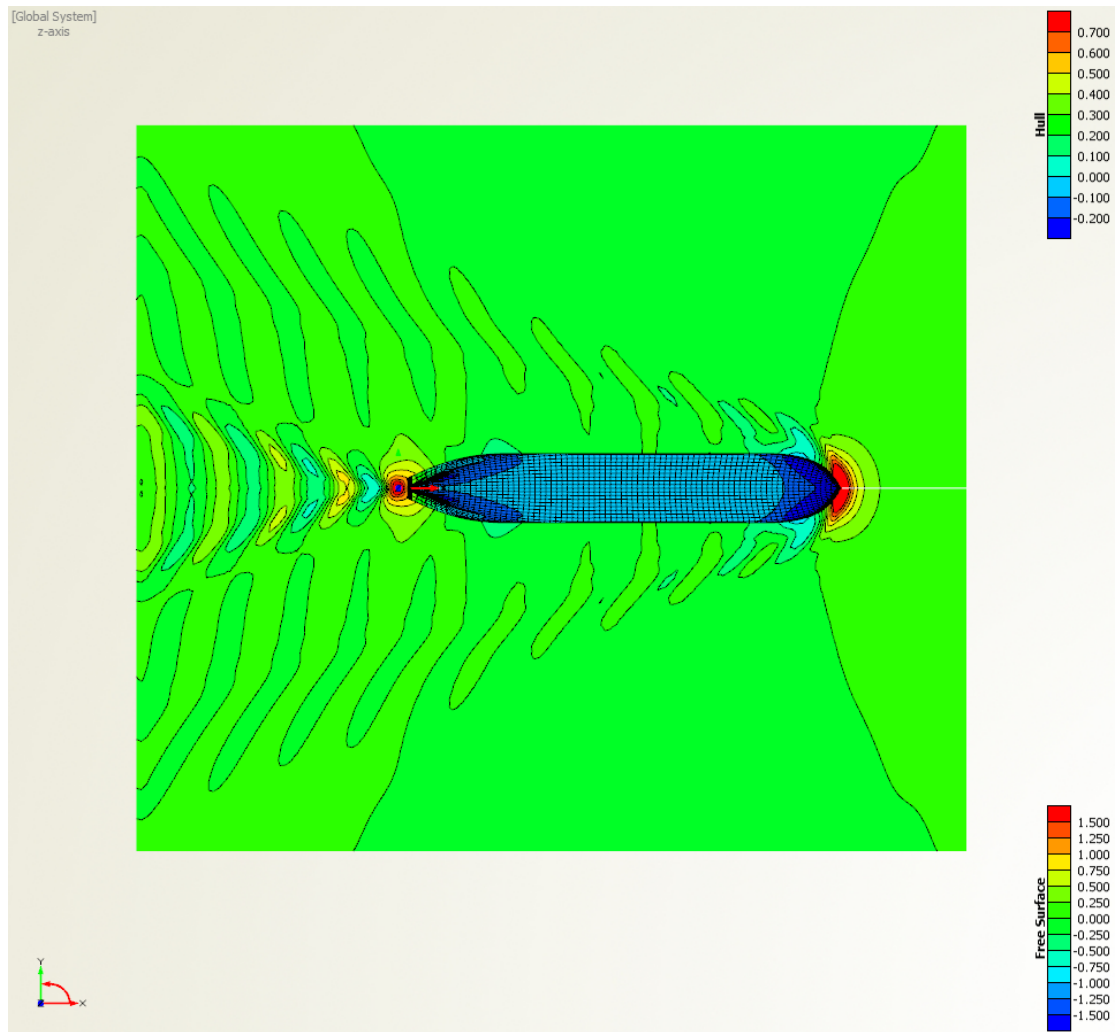
V=17knots

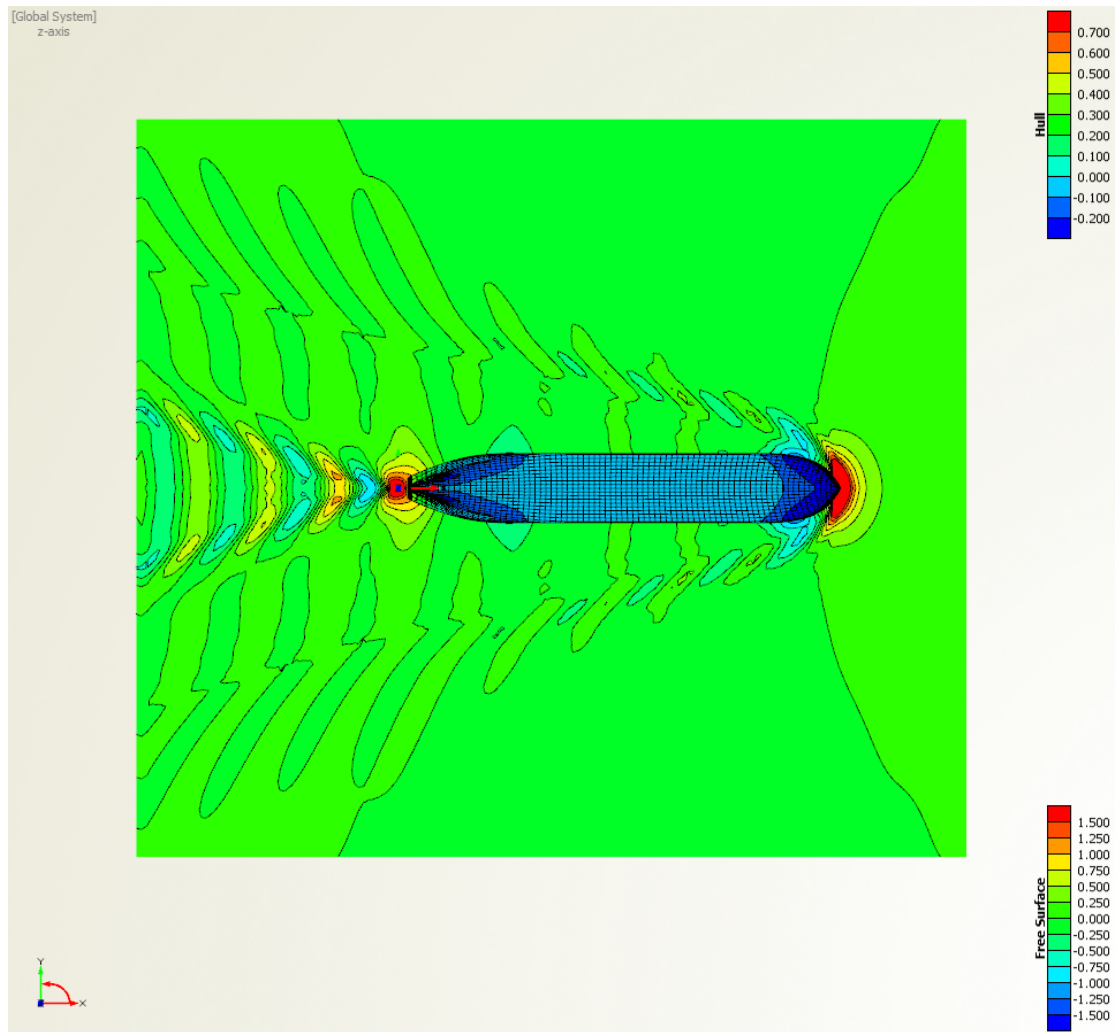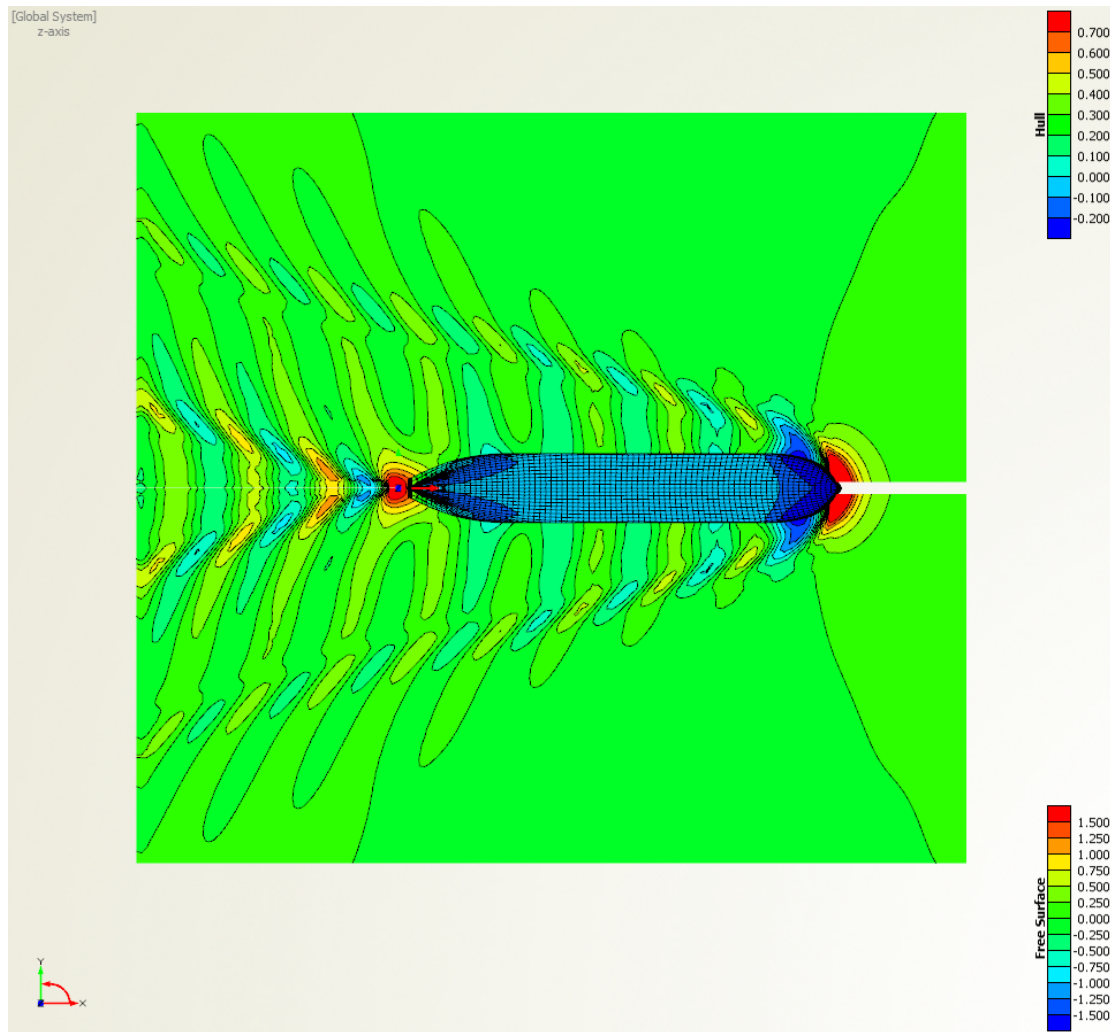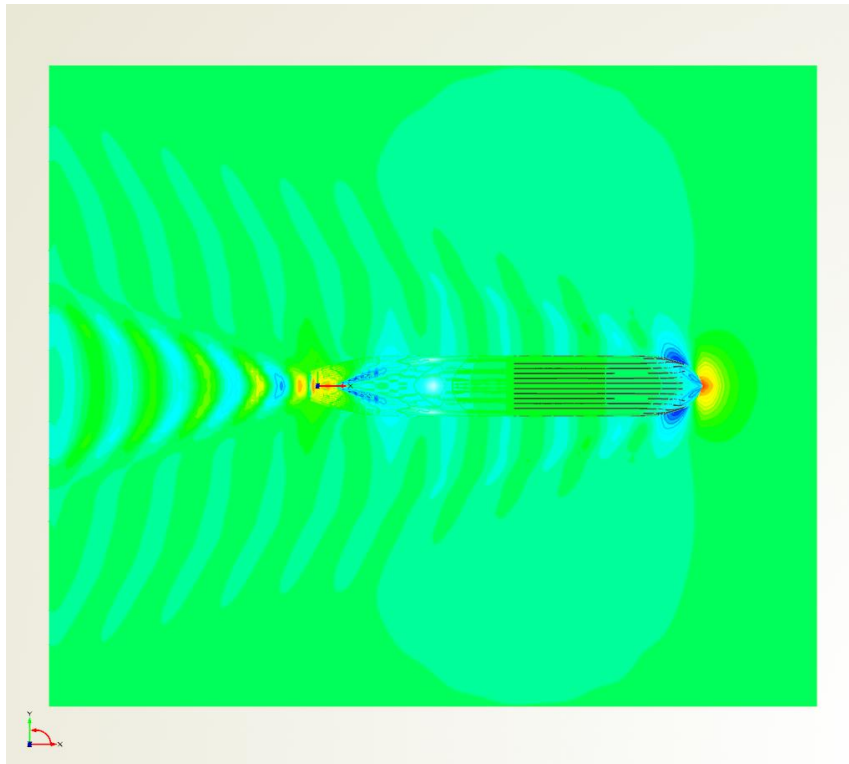**Ballast T=9.74**   V=12knots
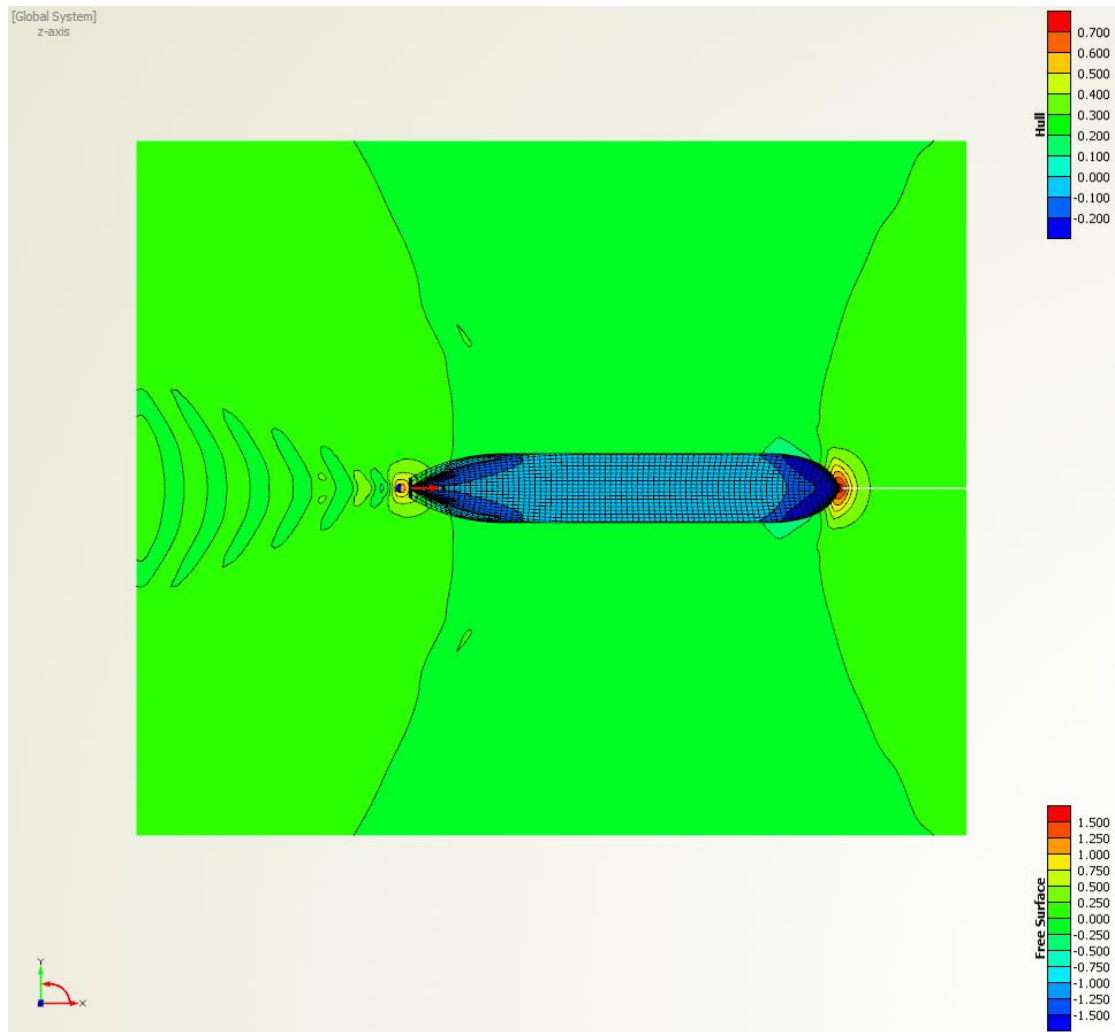
V=13knots

V=14knots

V=15 knots

V=16knots

V=17knots

Viscous FLD T=16,52m and design speed V=15knots

Viscous Ballast T=9,74m and design speed V=15knots