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WING BODY JUNCTIONS IN SHIP HYDRODYNAMICS

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ABSTRACT

Starting with the 1st of January 2013, all ships greater than 400 gross tons have to comply with design or operational energy efficiency index, in order to reduce the greenhouse emissions. From the naval architect’s point of view, the emission reduction measures can be hydrodynamic, structural, technological and operational. The hydrodynamic measures, which are the first that can be taken into consideration in order to reduce the EEDI, are materialized through the optimization of the hull. The Naval Architect may interfere on the bulbous bow, hydrodynamic shoulders, bulb stern, transom or appendages, the drag being then modified by reducing the wave, viscous pressure or frictional resistance components. Another way to improve the hydrodynamics of a ship is the use of Energy Saving Devices (ESD). These are appendages, mounted on the ship hull, developed to improve the flow near the propeller, which operate in the non-uniform wake field of the ship. The flow mechanism around ESDs comes down to wing-body juncture flow problems and, due to their application to the ship appendage flow, they have recently received much attention in ship hydrodynamics. Despite its simple geometric configuration, the wing-body junction flow is a very complicate flow due to the so-called horseshoe vortex system determined by the adverse pressure gradient induced by the presence of the obstacle and the three-dimensional boundary layer separations around the junction. The horseshoe vortex flow affects the drag, lift and causes a persistent lack of uniformity in the wake and is also considered as one source of the noises, vibration and unsteady inflow for the propeller.

Keywords: Ship energy efficiency, wing-body junction, juncture flow, energy saving devices

1. INTRODUCTION

In recent years, interest in global warming has increased markedly, and topics such as energy efficiency, environmental pollution, or reducing greenhouse gas emissions are topical. International efforts to reduce the impact of climate change began in 1992, in Rio, where more than 150 governments signed a framework agreement for sustainable development. In 1997 the Kyoto Protocol was adopted, by which the signatory states, 37 industrialized states and the European Community, pledged that, by 2012, they would reduce the level of greenhouse gases by 5.2% on average, as compared to 1990. Due to the international character, naval transport could not be explicitly dealt with in the Kyoto Protocol, Appendix 1. In contrast, public and political pressure on greenhouse gas emissions from naval transport has been shifted to the International Maritime Organization (IMO). According to the "Second IMO GHG Study 2009", "the most comprehensive and authoritative estimation of the greenhouse gases in the naval domain", in 2007, the shipping of goods produced approximately 1046 million tonnes of gas emissions, representing approx. 3.3% of global emissions, of which 870 million tons of carbon dioxide (CO2), 2.7% globally. Performing calculations on various scenarios of gas emissions, IMO found that, in the absence of concrete environmental policies, by 2050, the level of CO2 emissions will increase by 150-200% compared to the level of 2007. Thus, starting with January 1 2013, the Energy Efficiency Design Index (EEDI) and the Operational Efficiency Index (EEOI) became mandatory for all ships over 400 tonnes (MPEC 62, 2011). According to the IMO resolution, these indices are specific to each type of ship and should be lowered by 2025, up to 30% in report to the reference level. In fact, these indices represent the ratio between the total CO_2 emissions from the ship and the transport capacity, speed and parameters related to the operating conditions of the ship.

2. EMISSION REDUCTION MEASURES

Ships in operation are less susceptible to major design changes, and are based rather on retrofitting of the engine room or using energy-saving devices. For new projects, the mission of naval architects to increase energy efficiency is becoming more difficult, because the new ships already incorporate the latest developments and innovations in the field existing on the market at that time. According to Ungureanu et al. (2013), the measures that a naval architect can take to reduce the energy efficiency design index are divided into four distinct categories:

- operational measures;
- technological measures;
- structural measures;
- hydrodynamic measures.

Operational measures refer to how the ship is operated and includes measures such as reducing service speed, optimizing the ballast and trim, cleaning the body of the ship and the propeller, maintaining the propulsion machine as well as optimizing the navigation route and programming in ports. These measures involve modest investments in hardware and software products. The most important measure in this category is speed reduction due to power dependence to the third power of speed. However, speed reduction, as main measure used, cannot be applied to perishable goods and it affects the time of delivery of the goods as well as the operating costs and implicitly the profit of the shipowner. Therefore, any reduction in cruise speed must somehow balance the costs of operating the goods with the owner's profit.

The technological measures aim to reduce the power on board by improving the energy efficiency of the engines, main and auxiliary, by using alternative fuels or by implementing alternative energy production systems. In general, these measures require consistent financial investments to achieve substantial reductions in greenhouse gas emissions. The main pollutant on board the ship is the main engine (or main engines). The required power and engine size (s) depend on the ship resistance and the efficiency of the propulsion system. The main classic propulsion engine is the two-stroke fuel-oil engine. Two-stroke engines are slow, economical but oversized and highly polluting. The efficiency of the propulsion systems is higher if the diameter of the propeller is larger. This determines, most of the times, that the ship is designed "around" the propulsion system and not vice versa. Also, shaft lines can have considerable dimensions influencing the efficient use of spaces in the stern area. One way to increase the efficiency of the ship is to replace the classic propulsion system with diesel-electric systems. The classic engine-shaft-propulsion system is replaced by diesel-generators or batteries and electric thrusters. Even if these diesel-generators are optimized to operate at certain speeds and loads, they do not solve the problem of environmental pollution. According to

AEA Energy & Environment (2008), the propeller consumes only approx. 43% of the energy of the used hydrocarbons, the rest being lost by exhaust gases, 27%, and heat, 30%. Knowing this, an important step in reducing engine emissions aboard the ship is the use of dual fuel, diesel / LNG, or LNG-only engines. According to a study carried out by the Norwegian classification society, Det Norske Veritas (2010), the use of natural gas leads to a 20% decrease in CO2 emissions. Also, emissions of sulfur oxides (SOx) and particles in the atmosphere are eliminated and nitrogen oxide (NOx) emissions are reduced. In contrast, there are two drawbacks in adopting these systems. One is the cost of the investment, at present being with 10-20% more expensive than the classic ones, and the other is the refueling infrastructure, which limits the autonomy of the ship.

Another direction for improving efficiency is the use of alternative energy production systems such as:

- heat recovery systems evacuated through the exhaust (MAN, 2012);
- systems of solid sails with photovoltaic panels, which use the wind and solar energy at the same time (Sommer, 2013);
- the use of parachutes for the exploitation of air currents (Ockels et al., 2006; Naaijen et al., 2007; Erhard et al., 2012);
- the use of wind turbines on board the ship for the production of electricity (Sommer, 2013);

Structural measures contribute to the decrease of the EEDI by increasing the ship's transport capacity. This is possible either by optimizing the ship's strength structure or by using high-alloy steels that lead to a decrease in the thickness of the plates used and thus of the lightship. Thus, at the same displacement of the ship and at a smaller lightship, the carrying capacity increases.

Hydrodynamic measures are the most important measures that can be taken in the design phase. These measures are achieved by optimizing the size and shape of the ship or designing propellers adapted to the ship's wake. The main purpose is to reduce the ship resistance and to increase the efficiency of the propulsion system, which ultimately leads to the reduction of the power located on board the ship. Given that the hull form of a ship is far from being perfect, from a hydrodynamical point of view, being the result of a compromise between the main dimensions imposed by the size of the locks, the depth of the channel, the depth of in the port, tax levels, the transport capacity (deadweight, volume), the equipment of the ship (cars, deck installations, hull installations), hydrostatic performance and, last but not not least, of the hydrodynamic performances of the ship, the so-called flow control devices or devices Energy Saving Devices (ESD) are increasingly used in order to improve flow around the ship. Without being considered as corrections of possible hull design errors, these devices are appendices mounted on the hull of the ship, usually at the stern of the ship, close to the propeller. They have the role of uniformizing the flow field in the propeller disc, mounted in front of of the propeller, or to recover the energy lost through the tangential velocity component of the propeller, in which case it is mounted aft of the propeller. Carlton (2007) makes a complex description of all control devices. The most popular flow control devices include the upstream and downstream propeller networks, the Schneekluth nozzle (www.schneekluth.com), DSME prestator, (Daewoo Shipbuilding & Marine Engineering, 2008), the Mewis nozzle, the Grim device (de Jong, 2011); the swirl system.

The idea of using devices in the stern of the ship is not new. Although the first reference in the literature belongs to Van Lammeren in 1949, the first commercial device appears only in 1980 and belongs to the Mitsui shipyard, the integrated Mitsui nozzle.

Although it was not well known how the Mitsui system helped reducing fuel consumption on board the ship, the global oil crisis has led to the success of these types of devices. Neglected after the stabilization of the oil price, these energy saving devices return due to the unstable oil market, due to conflicts in the Middle East, on the one hand, and due to the introduction of energy efficiency indices, on the other. Thus, a possible decrease of even 5% of the on board power makes these devices very attractive to shipowners.

3. WING-BODY JUNCTION FLOW

In ballast navigation, the profiles can come out of the water penetrating the free surface. The free surface flow around blunt bodies manifests with breaking waves, cavitation, phenomena that can lead to an increase in the ship resistance. Thus, in the global economy of the ship resistance, such appendices can additionally increase the ship resistance, on the one hand, but at the same time they can disrupt the flow at the ship stern leading to unevenness in the flow field in the vicinity of the propeller, contrary to the main purpose of using these devices.

The free surface flow around hydrofoils is a hydrodynamic problem with an apparently simple geometric configuration but with a complicated flow topology due to the presence of the obstacle, the interaction between the boundary layer and the free surface, turbulence, wave breaking, cavitation, surface tension effects, water and air. As the appendices become more and more used and with increasing dimensions, the general understanding of the flow around the appendages and wing body junction is a topical issue for naval hydrodynamics

When the flow encounters a body mounted on a flat or curved solid surface, separation occurs in front of it due to the blocking effect. As a result of this, the fluid develops vortical structures, called horseshoe vortex, the current being one with a completely three-dimensional character, complicated by the interactions between the boundary layer and the thus generated vortical structures. The horseshoe vortex is generated by the combination of two effects: the skewing and the stretching of the transverse component of the vorticity present in the turbulent boundary layer of the current, bypassing the obstacle, on the one hand, and the development of the turbulent structures in the vicinity of the leading edge, vertically, due to the high pressure gradient generated by the geometry of the strut, on the other. The distribution of the average vorticity tends toward an elliptical shape, and the component along the current of the vorticity, except for the surface of the appendix, is fed by the term cross-sectional compression (cross-sectional skewing).

The name of horseshoe vortex comes from the shape of the vortical structures around the cylinders, and not from itself, since it has no classical tornado structure. Horseshoe vortex was experimentally captured by smoke insertion by Baker (1979) around a flat-plate cylinder junction flow, and by Dickinson (1987) around a wing-body junction flow.

The flow around the wing-body junctions is influenced by the following factors:

- Shape of the strut nose

Mehta (1984) and Rood (1984) pointed out that the dimensions of the horseshoe vortex as well as the energy consumed by it increase with the radius of the strut nose. Fleming et al. (1991) introduce the bluntness factor as a parameter to correlate the geometry of the nose with the development of the vortical structures.

- Reynolds number

Fleming et al. (1993) compared the experimental results available for the Rood junction at various Reynolds numbers and relative heights of the boundary layer and propose the Momentum Deficit Factor-MDF. This parameter correlates the effects of the adverse pressure gradient on the flow along the junction. If the MDF value increases the velocity fluctuations in the direction of the current decreases, the secondary flow profile becomes elliptical, the vortical structures approach the junction, and the vorticity and helicity increase when the height of the boundary layer and the reference velocity are dimensioned. Another comparative study was carried out by Roach and Turner (1985) based on the foil drag. For Reynolds numbers larger than $4x10^5$, they observed an increase of the drag due to the junction related to dynamic pressure of the undisturbed flow. Moreover, they concluded that neither the relative height of the boundary layer nor the shape of the profile section have such a large influence on the foil drag. Ungureanu and Lungu (2009a) studied the influence of the Reynolds number on the flow around the junction between a NACA 0012 profile inclined upstream, downstream and laterally mounted on a flat, concave and convex plate. The studies were conducted at 10^6, $5x10^6$ and 10^7 Reynolds numbers, showing a decrease in the drag coefficient on average by 30% from 10^6 to , $5x10^6$, and only 2% from $5x10^6$ to 10^7. Also, the increase of the dynamic pressure in the proximity of the leading edge leads to a decrease of the vortex development area as well as a closer proximity to the surface of the appendice.

- Froude number

Ungureanu and Lungu (2010) numerically investigated the free surface flow around a symmetrical profile NACA 0012 of infinite span at Froude numbers 0.16, 0.32 and 0.48. At small Froude numbers, 0.16 and 0.32 the classic Kelvin wave system is observed, while at Froude 0.48, the flow is manifested by breaking both, leading edge and trailing edge waves, as a result of the blocking phenomenon and the boundary layer detachments.

- Angle of attack (aoa)

If for the junction between a cylinder and the flat plate, the angle of attack is irrelevant, in the aero-hydrodynamic profiles the surface of attack of the profile increases with the angle of attack. Shizawa et al. (1996) studied the influence of the aoa on a constant section profile and with semicircular nose. The study showed that if the aoa increases more than 15 degrees, turbulent kinetic energy and tangential stresses increase on the suction face. The area of vortices development remained constant with respect to the base plate, instead on the profile surfacete vortices move on the pressure face towards the area of the maximum thickness.

- Inclination angle

Ahmed and Khan (1995) studied the effect of inclination in the plane of symmetry of the leading edge from -45 degrees to 45 degrees for the Rood junction, without angle of attack. For the downstream angles, the separation lines move toward the profile, while the vortices moves downstream. When inclining upstream, the flow is manifested in the opposite direction of the inclination downstream. For a NACA 0015 profile inclined upwards by 20 degrees at various angles of attack, Bernstein and Hamid (1995) observed, based on the pressure distribution, a slight decrease in profile lift as the pressure component of the drag increases. Ungureanu and Lungu (2009a, b) numerically investigated the influence of the inclination in three directions of a symmetrical profile NACA 0012 with unlimited span, in the symmetry plane upstream and downstream and normal on the symmetry plane. Studies have shown that in the case of inclining the normal profile on the plane of symmetry, the drag coefficients increase with the angle. In the case of the inclination of the upstream and downstream profile, keeping the geometric symmetry and the flow, a decrease in the the drag coefficients was observed.

- Curvature of the base plate

Ungureanu and Lungu (2009 a, b) carry out numerical studies on the influence of the curvature of the base plate on the drag coefficients. The necessity of the study consists in the fact that the surfaces of the ship in the aft area on which the flow control devices are mounted are complicated surfaces with double curvature. Numerical investigations performed on different discretization grids, C-H (2009a) and O-H (2009b), showed a significant influence of the curvature of the plate on the resistance to advancement in all cases of inclination of the upstream, downstream and lateral profiles. Thus, the decrease in the radius of curvature in both concave / convex situations leads to the increase in the drag coefficients.

- Free surface

Due to the large density difference between water and air, the flow around a profile that wraps the free surface can be assimilated to the flow of a profile mounted on a plate. As long as the Froude numbers are small , below 0.1, and the deformation of the free surface is negligible, the flow topology is identical to that on a solid plate. The complexity of the junction at the level of the free surface increases with the Froude number, when the elevation of the surface becomes consistent, due to the freedom of movement on all three Cartesian directions of the water particles on the free surface. The flow topology becomes much more complex when the wave breaking phenomenon that interacts with the horseshoe vortex, also called the vortices necklace. Metcalf et al. (2006) experimentally investigate the interactions between the free surface and the boundary layer on a hydrodynamic profile, NACA 0024, at three Froude numbers (0.19, 0.37 and 0.55) associated with three different flow regimes: steady, with reattachement and no reattachement. At low Froude number a calm flow and Kelvin wave system is observed, while for medium Froude numbers, the flow manifests with the phenomenon of breaking the wave, but the streamlines are reattaching the profile, however, maintaining the Kelvin wave profile, while at large Froude number, the current is no longer attached to the hydrofoil, the first wave crest has a considerable height, the energy consumed at breaking the wave is high and the Kelvin wave system is no longer visible.

Ungureanu (2011) tested in the towing tank a NACA 0012 profile, investigating the evolution of the free surface in respect to Froude number (0.32, 0.40, 0.48, 0.56, 0.64). In this study, it is observed that, at relatively small Froude numbers, the wave on the surface of the profile shows two heights, and at large Froude numbers the bow wave manifests with the breaking wave phenomenon. Due to the increase in the wavelength, the second wave height on the profile migrates to the trailing edge. At high Froude numbers, the wave generated by the trailing edge becomes prominent, taking the form of a whale tail, with height closer to that of the leading edge.

4. CONCLUDING REMARKS

The flow around the junctions between a body and the appendages is a simple geometry with a complicated flow and can be controlled by a judicious design of the geometries of the component elements, so that the regime of pressure fluctuations, induced vibrations and energy consumption can be controlled from the outside. The flow control around the junctions has practical relevance and because it can significantly influence the lift and the drag, the stability characteristics through the control of the topology and the intensity of the vortical structures or it can lead to sources of noise or structural vibrations.

In the physical world that surrounds us we find the flow around the junction with trees and buildings with the ground, at the feet of bridges built in rivers, turbomachines or wing-fuselage coupling to an airplane. In naval hydrodynamics, in addition to ESD, the junctions are also encountered as skegs, rudders, shaft struts, bilge keels or stabilizing wings. The sailing yachts have below the keel a very large skeg, which plays the role of counterweight during navigation, providing the lifting force to stabilizes the transverse inclination and also counteracts the lateral drift induced by the action of the wind. The skeg form junctions at the connection with the ship's shell and at the tip, at the connection with the float. Also the junctions have an important role for submarines because they can become sources of noise or vibrations, things to avoid especially during military tactical missions, for the hydrofoil boats where the lifting force may decrease due to the turbulence generated by the junction between the hydrofoil and the struts, for SWATH (Small Water Area Twin Hull) vessels where the junction between the vertical part of the hull and the floating bodies is in the vicinity of the free surface, and the influence between junction and the free surface can influence the operation of the thrusters.

The horseshoe vortex flow affects the drag, lift and causes a persistent lack of uniformity in the wake and is also considered as one source of the noises, vibration and unsteady inflow for the propeller. So, one of the most challenging problems related to the juncture flow is to find a proper geometry to minimize the drag, to reduce the intensity of the horseshoe vortex for a more uniform inflow for the propeller.

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