ROMAI J., **4**, 1(2008), 215–224

DESIGN SENSITIVITY ANALYSIS AND SHIP STERN HYDRODYNAMIC FLOW FIELD IMPROVEMENT

Horaţiu Tănăsescu, Nasta Tănăsescu

ICEPRONAV Galaţi, Univ. "Dunărea de Jos" Galaţi

Abstract The paper draws attention and briefly focuses on ship hulls stern flows in the light of two original ideas (concepts) in ship hydrodynamics, belonging to the author: 1. a new stern hydrodynamic concept (NSHC), with radial crenelated-corrugated sections (Tănăsescu's stern shape); 2. using of an inverse piezo-electric effect [(electric current→high-frequency power generator→piezoelectric driver made of certain ceramic material, which induces an elliptical vibratory movement (high frequency over 20 kHz), into the elastic side plates (15 mm thickness) in the streamlines direction (of the external flowing water)], able to reduce the total forward resistance.

Keywords: ship hydrodynamics.

2000 MSC: 76D55.

Introduction. A naval architect, a ship owner, or a simple passenger, in looking over the stern of a ship and the turbulent tossing above the propeller race, instinctively realizes that most of this upheaval is an wasted effort. The irregular nature of the currents which flow into the propeller disc imposes to this propulsion device to take such a complex water flow and make so much out of it in the way of useful thrust, inducing the idea that the turmoil surging out of the propeller disc can be converted into useful power that increases the ship velocity. To this aim it is necessary a profound knowledge of the basic phenomena and fundamental principles governing the motion of water and the causes for the particular behavior of a ship and its propulsion devices.

Theoretical aspects. In real conditions, a propeller is fitted behind the ships (models) hull stern, working in a non-uniform water stream, which has been disturbed by the ship hull during its forward motion. The ship moving hull carries with it a volume of surrounding water forming a region, known under the name of boundary layer, across which there is a steep change in velocity, the propeller being placed behind the ship hull stern, in the ship body trail. As a consequence, the velocity (even considering its average value) of water particles relative to the propeller disk is no longer (neither in magnitude nor in direction) equal to the velocity of advance of the propeller relative to still water. This trail, where there is a difference between the ship speed and the speed of the water particles relative to the ship is also termed wake. The wake is a zone poorly investigated theoretically (analytically), due to very complex, aleatory flow character within it. In ship propeller theory, a distinctive importance is given only to the incipient part of the trail (wake), located immediately in the front of the propeller disk plane. The movement in this zone is called wake movement or simply wake. The wake movement can be investigated either in the presence or in the absence of the propeller, bearing the name of the effective wake or the nominal wake, respectively. However, the wake movement of interest is only that from the plane where the propeller follows to be situated. The flow average velocity from that plane is termed wake speed V_W, and, in general, it is smaller than the ship speed V_S, relative to the infinite upstream water. If the water is moving in the same direction as the ship, the wake is said to be positive. Then

$$Wake = V_S - V_W.$$

In order to non-dimensionalize this relation, we can use as characteristic speed either V_W or V_S, leading to two wake factors

-Froude wake factor= $w_F = (V_s - V_W)/V_W$;
-Taylor wake factor= $w = (V_s - V_W)/V_S$.

Besides, this general effect of the ship hull, there exist local perturbations due to the shaft, shaft bossings or shaft brackets and other appendages. These effects combined lead to the so-called relative rotative efficiency (RRE), defined by

$RRE = \eta_R =$ efficiency of propeller behind the ship hull/ efficiency of propeller in open water (at speed V_W).

Always, but especially in present circumstances, for a better functioning it is necessary a propeller cavitation reducing, overall propulsive efficiency and stability improving. As already mentioned, the dynamics of a cavitating propeller depends on the system environment in which it is operating, the flow field within a propeller mounting behind a ship hull is very different from that one in an open water test or in a section of a cavitation tunnel. Thus, a propeller that is very efficient in open water can not be suited for a certain kind of stern shape architecture. For this reason, *the wake distribution in the propeller disk plane represents a key element for designing a ship hull stern form.* A uniform wake distribution from an immediately upstream propeller parallel plane disk can diminish the propeller cavitation (having as an indirect consequence on the noise and vibration level induced on board and in the hull stern structure, lowering) and increases the propulsive efficiency (and so, obtaining the minimum energy consumption). Therefore, to obtain a good nominal wake distribution is an important objective of naval architects. In addition, the global - directional hydrodynamic stability improving by using a special kind of stern having more appropriate architecture, can not be but favorable.

The state of the art in the field. The present-day tendency in maritime transportation industry is represented by designing and building of bigger, faster, more energy-efficient and stable ships but simultaneously having stricter noise and vibration levels for stern hull structure. A modern ships hull lines are designed to minimize the forward resistance, to reduce the propeller cavitation, to improve the propulsion performance and to increase the global hydrodynamic stability. Since the apparition of the first ships, the naval architects tried to improve the existing hull forms. As a general recently accepted opinion, the ships of the future will be designed and built only on the basis of some *new devised concepts.* It is well known that the stern flow problem is very complex. However, the ship hull stern flows have received much attention these last years, in particular with respect to their modeling and design principles. The most recently known industrial achievements focused on flow improvement in the stern region, which consist in symmetrically flattening of the stern lateral surfaces towards the central plane. This concept has resulted in a huge amount of inconveniences almost in all practical applications to real ships (unsuitable placing of equipments, lack of necessary spaces for inspections, repairs etc.). For a long time, the authors thought how to redesign the two systems - hydroframe system and propulsion system - very important (critical) for a ship, so that the hydroframe may meet the propulsion and the propulsion may meet the hydroframe in an optimal way.

Scientific research objectives: - total forward resistance reduction, propulsive efficiency increasing;
- propeller cavitation reduction (for level of noise and vibration induced on board and in the stern structure decreasing);
- development of a numerical parameterized model;
- design sensitivity analysis of fields generated;
- optimizations;
- original concepts and ideas validation;
- new methodologies establishing.

Project description, results obtained, future prospects. Having in view the presented ideas, within the contract no. 208, CEEX, I have proposed (intuitively, based on experience), a new stern hydrodynamic concept of streamline tube type, (having quasi-cylindrical increasing sections), which starts from front propeller disk and stretches until hull cylindrical region (fig. 1). In devising this new design concept, the author referred (as a supplementary basic background) to two existing theories:

- *the streamline tube theory* (the water particles axial velocities distribution at entrance in the propeller disk can be configured favorably - homogenized - by comprising the radial crenelated - corrugated stern sections in a stream tube that also comprises the propeller disk);

- *the Bernoulli effect* (increasing of water particles axial velocities in the regions within which the water pressure is decreased).

Taking into account the streamline tube theory and the Bernoulli effect, we can estimate that *the 3D spectrum* of flow generated around and outside a classical stern hull having practiced transversal crenellated-corrugated stern sections can be substantially improved by an architectural optimization in the direction of axial velocities from a propulsion propeller immediate front plane uniformization (fig.2).

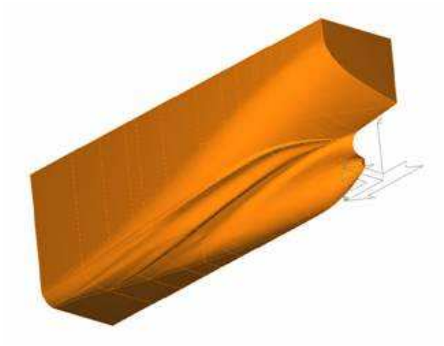

Fig. 1. The new stern hydrodynamic concept.

The directions of the crenelated-corrugated sections teeth crests and troughs longitudinal curved lines, will be those of the stern natural streamlines (which can be established experimentally in a flow visualization test) for vortices turning up avoiding and for a minimum forward resistance obtaining.

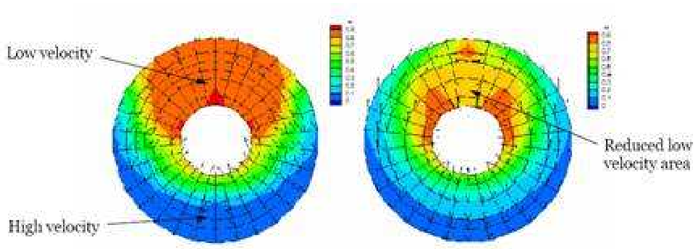

Fig. 2. Comparison between experimental wake obtained for the model with initial stern shape design (left) and for the model with modified stern shape according to our design (right).

Finally, the most important, until now, proved result, is the reducing of propeller cavitation (working in the simulated nominal wake of the hull using the new stern hydrodynamic concept with radial crenellated - corrugated sections, Tănăsescu's stern shape), practically to zero (fig.3).

Unfortunately, this cavitation decreasing (lack of cavitation) is associated with a total forward resistance (of the ship) increasing (approximately 4-5%)

Fig. 3. Simulated nominal wake testing, in 850x850 mm section of the cavitation tunnel at 25 rps rotative speed (it can be remarked lack of cavitation).

due to initiation and movement of some multiple increased vortices (fig. 4), resulted from the separation (although a low one - fig. 5) of the boundary layer (destruction of an important part of fluid mechanical energy, pressure decreasing downwards the ship stern body etc).

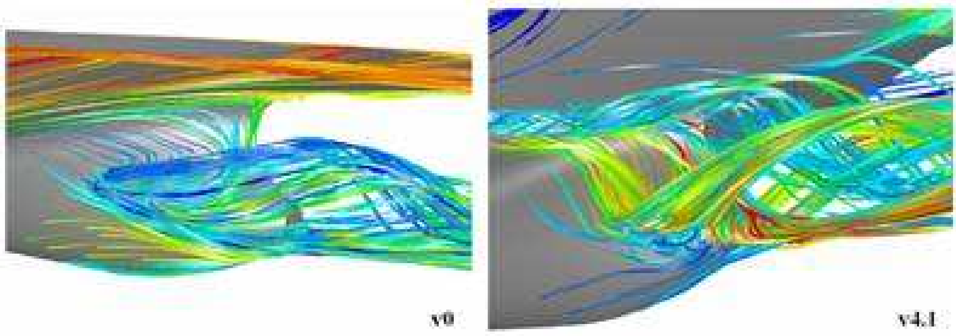

Fig. 4. Vortex initiation and separation - FLUENT 6.3. (left - the model with initial stern shape design - simple vortex; right - the model with modified stern shape according to our new concept design - multiple vortices).

Therefore, it would be necessary a much more reduction or even complete separation and multiple vortices phenomena (within the turbulent boundary layer) avoiding. *In this respect I thought that I should try to use the inverse piezoelectric effect (electric current → high-frequency generator → piezoelectric driver made of certain ceramic material - fig. 6), which induces an elliptical*

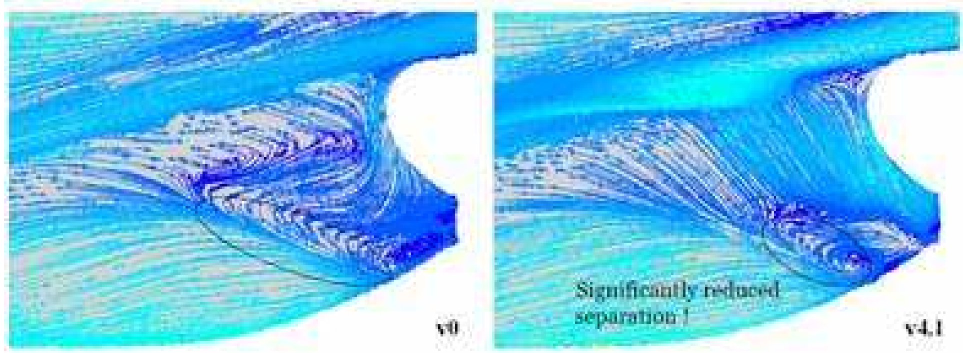

Fig. 5. Limit streamlines on stern surface - FLUENT 6.3. (left -the model with initial stern shape design; right - the model with modified stern shape according to our new concept design).

vibratory movement (high frequency over 20 kHz), into the elastic side plates (15 mm thickness) in the streamlines direction (of the external flowing water).

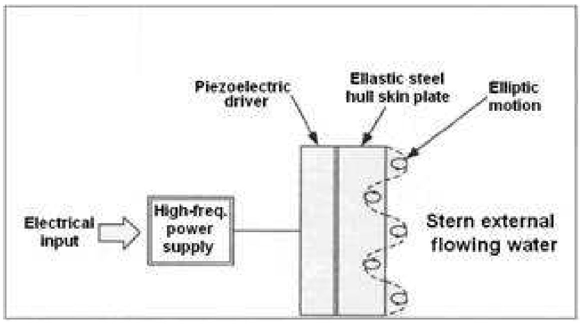

Fig. 6. Principle scheme of an ultrasonic vibrator.

Piezoelectricity is the ability of crystals and certain ceramic materials to generate a voltage in response to an applied mechanical stress. Piezoelectric effect was discovered by Pierre and Jacques Curie in 1880.

The basic principle would be the following: certain piezoelectric ceramic materials can be used to convert electrical energy into mechanical energy in the form of vibrations of an elastic body (ship hull stern plates), whose surface points perform an linear elliptic motion (in the streamlines direction of the external flowing water), with an ultrasonic frequency over 20 kHz.

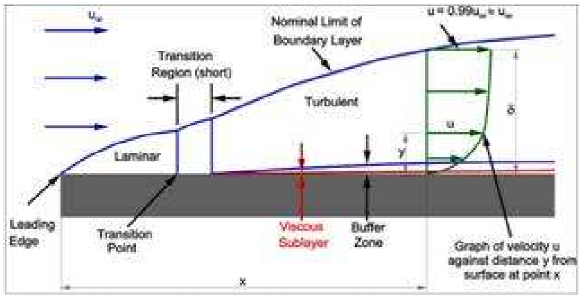

Fig. 7. Boundary-layer flow regions.

Water particles (from within the ship hull stern turbulent boundary layer - fig. 7), are pressed against vibrating steel plates reducing the interface (hull - water), skin friction drag. It is hoped that such a combination of devices can reduce ship forward resistance due to hull skin-water friction reduction by controlling the inside turbulent boundary layer flow characteristics.

In addition, as a continuation and a completion of the researches accomplished in this CEEX contract, author considers of interest the realization of:

- *a parameterized geometrical model* streamline tube type, (including the effects of new stern design having quasi-cylindrical increasing radial crenelated-corrugated sections on inside propeller flow);

- *a design sensitivity analysis* of the new stern fields generated.

In these cases different geometries (as necessary form, width and depth, along hull distances, for flow separation avoiding), should be studied theoretically, numerically and experimentally.

Design sensitivity analysis consists in determining derivatives of a system response with respect to its design parameters x_i. In the context of design optimization (of the new hydrodynamic stern concept proposed), the response is expressed in terms of objective and constraint functions and, accordingly, the overall aim of design sensitivity analysis is to find the gradients of these functions. However, since any such problem function depends explicitly on the dependent variables Φ of the considered problem, sensitivity formulations in essence aim at the calculation of the derivatives $\delta\Phi/\delta x_i$. In other words, the changes in the flowfield Φ following from a given change in design must be predicted. After the determination of these flowfield sensitivities, it is a matter of a straightforward calculus to compute the design sensitivities of any problem function

$$\nabla f = \frac{df}{dx_i} = \underbrace{\frac{\partial f}{\partial x_i} + \frac{\partial f}{\partial \gamma}\left[\frac{\partial \gamma}{\partial x_i}\right]}_{grid\, sensitivity} + \underbrace{\frac{\partial f}{\partial \phi}\left[\frac{\partial \phi}{\partial x_i}\right]}_{flow\, sensitivity},$$

$i = 1, ..., n_{dv}$, where: dv are the design variables;
$f(x_i)$ - problem function (typically identical to objective and constraints function);
x_i - design parameters;
$\gamma(x_i)$ - geometrical quantities;
$\Phi(x_i)$ - vector containing unknown flow variables (velocity, static pressure, possibly turbulence modeling quantities), determined by the governing equations. Obviously, both geometry and flow are implicitly controlled by the design parameters through hull stern surface parametrization, mesh generation and flow analysis.

Interdisciplinary research. The main disciplines involved into the present project are: mathematical physics (partial differential and integral equations); applied physics; technical physics; materials physics; modeling and simulation; hydraulics and fluid mechanics; naval hydrodynamics.

References

[1] G. K. Batchelor, *An introduction to fluid dynamics*, Cambridge University Press, 1991.

[2] C. A. J. Fletcher, *Computational techniques for fluid dynamics*, Springer, Berlin, 1991.

[3] FLUENT 6.3, *User's Manual*, Fluent Incorporated, Lebanon, NH, 2006.

[4] J. P. Ghose, R. P. Gokarn, *Basic ship propulsion*, Applied Publishers, Pvt. Ltd., New Delhi, 2004.

[5] S. K. Godunov, V. S. Reabenki, *Finite difference computing schemes*, Bucharest, 1977.

[6] H. Lamb, *Hydrodynamics*, Cambridge University Press, 1952.

[7] J. N. Newman, *Marine hydrodynamics*, Massachusetts Institute of Technology, 1982.

[8] W. H. Press, S. A. Teukolsky, W. T. Vetterling, B. P. Flannerly, *Numerical recipes in Fortran - The art of scientific computing*, Cambridge University Press, 1992.

[9] K. J. Rawson, E. C. Tupper, *Basic ship theory*, Longman, London, 1995.

[10] M. G. Salvadori, M. L. Baron, *Numerical methods in engineering*, Bucharest, 1972.

[11] H. E. Saunders, *Hydrodynamics in ship design*, The Society of Naval Architects and Marine Engineers, New York, 1957.

[12] N. Tănăsescu, *Numerical methods in MATLAB*, MatrixRom, Bucharest, 2002.

[13] H. C. Tănăsescu, Al. A. Vasilescu, *Fluid mechanics, Course for engineers*, University of Galaţi, 2000.

[14] H. C. Tănăsescu, *Numerical analysis, Course for master of science engineers*, University of Galaţi, 2001.

[15] H. C. Tănăsescu, *Contributions concerning surface ships forward resistance studied by numerical simulation*, PhD thesis, University of Galati, 1998.

[16] Al. A. Vasilescu, *Hydromechanics course*, University of Galaţi, 1962.