Fifth International Symposium on Marine Propulsion
SMP'17, Espoo, Finland, June 2017

Development of numerical methods for marine propeller - pre-swirl stator system design and analysis

Przemysław Król[1,2], Tomasz Bugalski[1], Michał Wawrzusiszyn[1]

1 Ship Design and Research Centre (CTO), Gdansk, Poland

2 Conjoint Doctoral School at the Faculty of Mechanical Engineering, Gdansk University of Technology, Poland

ABSTRACT

The paper presents CTO's progress in pre-swirl stator and propeller system design and analysis. Whole design process is set in logical chain of successive parts. The initial stage is seeking for optimal radial distribution of stator - induced velocities. It is done by tries and errors method. The propeller with optimal radial circulation distribution is designed with lifting line algorithm for assumed induced velocity field. Radial bound circulation over the stator's blades corresponding to the velocity field that ensures highest propeller efficiency is taken as the design one.

The designed propeller is analyzed in it's design point - in non uniform velocity field, taking stator - induced velocities into account - with lifting surface program. Propeller - induced velocities in the stator's plane are also computed now. The stator's geometry is determined upon this velocity field with lifting line model.

When having propeller - stator system designed it is analyzed with viscous fluid model by RANSE approach. If it's results are satisfactory the model tests are conducted.

The design algorithm underlies to continuous development. One of most promising features is incorporating lifting surface model for determining both propeller and stator blade's pitch and camber in direct way. It allows to take their influence on each other without semi - empirical correction factors, but just with their induced velocity field.

The method is step by step described in the paper. The design example is also shown here with results of CFD viscous calculations and model tests. This research had been carried out within the framework of European Research Project INRETRO.

Keywords

Propellers, wake-improving devices, energy saving, lifting surface, RANSE

1 INTRODUCTION

Within the European Project INRETRO Nawigator XXI ship, belonging to Maritime University of Szczecin, was object of our investigations. One of our tasks was to develop procedure for designing propeller - upstream stator system and adopt it for this ship.

First step was to develop design method of the propulsion system. Lifting line algorithm was chosen as initial theory, due to its simplicity and capability of further development. After designing propeller - stator system RANSE calculations and towing tank model tests were carried out. The designed system did not meet its design parameters - required rotational speed turned out to be significantly higher, than theoretical value. However it was more efficient, than original propeller.

Results of RANSE computations and model tests became basis for algorithms evolution. They gave reference data, necessary for evaluation of our method's reliability.

2 VORTEX MODEL VALIDATION

Before attempting to elaborate own method for propeller - stator system design lifting surface software for propeller analysis was developed. Programming language C++ was chosen due to possibility of creating own classes and easiness of usage. All vortex calculations presented in this paper were conducted with this entirely in- house code.

Details of lifting surface analysis are presented in section 3.3. Only obtainable results of using it will be discussed here.

In current model it is possible to iteratively relax trailing free voritces, however separated leading edge vortex is not modeled. Due to this for the validation issue the propeller behavior in conditions not very far from the design point, was considered.

Test case for validation was DTRC4119 propeller (Koyama 1993) of symmetrical outline. The table below shows comparison between loading coefficients measured during towing tank open water model tests and resulting from lifting surface calculations:

Table 1: Representative results of lifting surface calculations

J	KT_{emp}	KT_{cal}	$10KQ_{emp}$	$10KQ_{cal}$	η_{emp}	η_{cal}
0.500	0.285	0.283	0.477	0.464	0.489	0.485
0.700	0.200	0.213	0.360	0.361	0.632	0.657
0.833	0.146	0.160	0.280	0.283	0.692	0.751
0.900	0.120	0.131	0.239	0.240	0.725	0.783
1.100	0.034	0.034	0.106	0.097	0.575	0.614

The above results are encouraging, however better agreement for highest loading, than for the design J=0.833, seems to be rather specific for this case. Experience with the software shows that accuracy level as for DTRC4119 propeller is representative for moderate skew propellers also. Upon that lifting surface software has been accepted as suitable for further development and usage for propeller - stator systems analysis.

3 DESIGN ALGORITHM

3.1 Stator bound circulation

In this paper propeller – stator system will be considered, in which the stator may be not axisymmetric, however its blades have same lengths. Initial step of design problem is determining proper stator - bound circulation. Its span wise distribution is assumed to be elliptical on each blade – thanks to this maximum bound circulation value sufficiently describes stator blade loading.

Stator blade is represented with straight bound vortex, supplemented with proper trailing vortex wake. As present theory is the initial one, any deformations of this wake are neglected – it is assumed to form flat surface, parallel to undisturbed velocity vector.

In this simple model, elliptical loading, flat wake, stator – induced velocity field changes only in magnitude, for different stator – bound circulation values. It allows to express stator – induced velocity field with dimensionless coefficients:

$$c = u \cdot \frac{L}{\Gamma_{MAX}} \tag{1}$$

Where c = dimensionless local velocity coefficient; u = local velocity magnitude (axial or tangential); L = stator blade length and Γ_{MAX} = maximum bound circulation value.

As only averaged velocity field is considered in the lifting line design algorithm, it was found useful to use averaged dimensionless coefficients:

$$C = u_{mean} \cdot \frac{L}{\Gamma_{MAX}} = \frac{1}{2\pi} \oint_{2\pi} u d\alpha \cdot \frac{L}{\Gamma_{MAX}} \tag{2}$$

Where C = dimensionless averaged velocity coefficient; u = averaged velocity magnitude (axial or tangential); L = stator blade length; Γ_{MAX} = maximum bound circulation value and α = local angular position.

Because stator free vortices deformation and viscous part of wake are neglected, stator – induced average axial velocity is zero within entire propeller disc. Therefore only tangential velocities are considered at this stage.

As all stator blades have the same length and circulation distribution shape – it is not important how total bound circulation is divided between the blades - from averaged steady state analysis point of view. There is only total bound circulation value, that has to be found at this stage. Its division between stator blades will be considered after having the propeller designed.

3.2 Propeller design

The propeller is designed by classical lifting line algorithm. The algorithm is only slightly modified, by incorporating stator – induced mean velocity field into calculations of advance angles and advance coefficients. Such approach results in propeller design with blade sections relatively wider at root sections, than it is in case of casual propeller. It is effect of stator - induced tangential velocities, which are highest at the lower radii. Special care must be taken in case of controllable pitch propellers to preserve possibility of rotating the blade around its axis. Also, in the beginning it may look like higher bound vorticity of the stator leads to higher efficiency of the propeller. It is true only as long as we consider forces acting on the propeller alone and in ideal fluid. In viscous liquid broader blade sections result in higher viscous drag of the propeller blade. Additional flaw of increasing bound vorticity of the stator is increasing its hydrodynamic drag as upstream stator thrust is negative (in essence it is drag). It leads to decrease of overall efficiency.

Preliminary propeller design is made for several stator bound circulation values. The one resulting with highest propeller – stator system efficiency – including cautions made above - is taken as a design one. Next step is the analysis of the designed propeller. The lifting surface software can be considered as the most suitable tool for this purpose. It is more accurate than lifting line model, but it is much cheaper than finite volume method realized with RANSE approach.

3.3 Propeller lifting surface analysis

Vortex lattice representation of the propeller was used for analysis task. General approach is similar as shown by "(Kerwin et al 1982)" and "(Bugalski & Szantyr 2014)". Propeller loading is modeled with vortex system. It was arranged in classical way; the set of horseshoe vortices is placed on blade's camber surface. Blade's finite thickness is modeled with set of radial source lines, whose strength is calculated by stripwise application of thin profile theory:

$$Q = ql = l \cdot \Delta t \cdot \sqrt{V_A^2 + \left(\pi D \frac{r}{R} + V_T^{stator}\right)^2} \tag{3}$$

Where Q = total source line strength; q = longitudinal source line strength; l = source line length; Δt = local chordwise thickness change; V_A = local axial velocity; D = propeller diameter; r/R = propeller local dimensionless radius and V_T^{stator} = stator induced tangential velocity.

Main part of the analysis task is determining circulation of particular vortices. It is done by solving set of linear equations:

$$\sum A_{ij}\Gamma_j = -\left(\vec{V} + \vec{\omega}\times\vec{r}_i + \vec{V}_{stator}\right)\bullet \vec{n}_i \qquad (4)$$

Where A_{ij} = influence coefficient of j-th bound vortex on i-th control point; Γ_j = j-th bound vortex circulation; V = undisturbed flow local axial velocity; ω = propeller angular velocity; r_i = radial position of i-th control point; V_{stator} = stator induced velocity and n_i = unit surface normal vector at i-th control point.

The kinematic boundary condition demands disappearing of normal velocity at the control points, placed on the lifting surface. Right hand of above equation expresses vector sum of undisturbed flow velocity with velocity field induced by the stator and by sources on the propeller's lifting surface. Averaged stator velocity field is still considered. It allows to analyze key blade only, what is common practice in VLM methods.

Important part of VLM model is geometry of free vortices trailing from the blade. Discussed analysis software allows two options for determining the geometry of the free vortices. The first one makes use of assumption that these vortices are placed on true helical surface. Its pitch angle is average of blades geometric pitch angle and kinematic advance angle. This shape is also initial assumption for second option for free vortex geometry, where they are relaxed in an iterative way. Developed iterative algorithm presents good convergence in reasonable time. Its idea is very natural: velocities induced by singularity system are calculated at the end of each free vortex segment. Then these are convected along total velocity vector. Time step is given such value that the propeller rotates by 5deg at one time step. This value is constant during the whole iteration process. Total velocity is calculated in cylindrical coordinate system; thanks to this there is no artificial radial expansion of free vortices, what happens when applied velocity vector is expressed in Cartesian coordinate system. Present algorithm neglects leading edge and tip vortices separation, but these phenomena are of less importance at design point.

For moderately loaded propellers iterative loop converges in around five steps. Rate of convergence is relative change of thrust coefficient between consecutive steps. Torque coefficient is monitored also and program's user is free to stop the calculation whenever wishes to.

Determination of the circulation distribution over the propeller blades allows performing several analyses, required for propulsion system design. First of all, pressure distribution can be calculated. It is done by computing total velocity in control points:

$$\vec{V}_{total} = \vec{V} + \vec{V}_{ind} = \vec{V}_0 + \vec{V}_{stator} + \vec{V}_{ind} \qquad (6)$$

now pressure coefficient can be obtained:

$$C_P = 1 - \left(\frac{V_{total}}{V}\right)^2 \qquad (7)$$

Integrating pressure distribution over the blade results in blade thrust and torque. They are the forces, that propeller operating in ideal fluid would experience. In real fluid there is a viscous drag also which is taken into account by usage of drag coefficient C_D. Total propeller hydrodynamic reactions are thou calculated as:

$$T = \frac{1}{2}\rho V^2 \int_S \left(\Delta C_P n_y - C_D t_y\right) dS \qquad (8)$$

and torque:

$$Q = \frac{1}{2}\rho V^2 \int_S \left[\Delta C_P\left(n_x z - n_z x\right) + C_D\left(t_x z - t_z x\right)\right] dS \qquad (9)$$

Possible effects of cavitation and flow separation are neglected at this stage.

Second important information, that VLM can provide, is propeller – induced velocity field. This will serve as input data for stator geometry design. As the propeller rotates around axis common with the stator's, averaged propeller – induced velocity field will be used for design task.

In case of pre - swirl stator, which is the subject of consideration, propeller free vortices are far from stator plane and their detailed geometry shall not contribute significantly to induced velocities calculated there. However it is recommended to iterate it, as it influences calculated circulation distribution on the propeller, what directly determines propeller – induced velocity field.

Only propeller vortex wake is iterated at this stage, because the propeller is axisymmetric. Thank to this, only key blades wake may be iterated; other blade's wakes are assumed to be the same as the key one. As the stator might be not axisymmetric, all blades wakes would have to be iterated, what was considered too much time consuming.

3.4 Stator design

Stator blades design is conducted with lifting line algorithm. Initial step is the evaluation of total velocities at particular stator blades. Velocity of "undisturbed" inflow is resulting from nonuniform velocity distribution in propeller disc – according to local radial and angular position. At this stage propeller disc velocity field was used for stator design to reduce cost of experimental part. However assumption that these two wakes to not differ markedly seems to be justified – due to small distance between propeller and stator disc.

Total velocities have to take into account stator – induced velocities also. As the stator may be not axisymmetric, stator – induced local velocities, calculated for stator plane, are used instead of averaged ones – which were used for propeller design and analysis. Due to this, axial velocities are zero no longer.

In present algorithm stators detailed geometry is determined upon method similar to one used for propellers by "(Jarzyna et al 1996)". Initial information necessary for further calculations are local values of stator bound vorticity:

$$C_L b = 2\frac{\Gamma}{V_W} \quad (10)$$

Where C_L = lift force coefficient; b = blade width; Γ = local bound circulation; V_W = local total velocity

Local cavitation number is calculated:

$$\sigma = \frac{p_A - p_v + \rho(h - l_z)g}{\frac{1}{2}\rho V_W} \quad (11)$$

Local blade thickness is initially assumed to be:

$$t = 0.02L \quad (12)$$

Local thickness to chord ratio is taken from cavitation diagram, adequate for used blade section profile. It is now possible to determine local blade width:

$$b = t\left(\frac{b}{t}\right) \quad (13)$$

What allows to directly calculate local lift force coefficient. Ideal angle of incidence is determined as:

$$\alpha_0 = 0.0245 C_L \quad (14)$$

Now local position angle of stators blade is given as:

$$\varphi = \arctan\left(\frac{V_T}{V_A}\right) + \alpha_0 \quad (15)$$

And local camber value as:

$$f = 0.0679 f \cdot C_L \quad (16)$$

Local drag coefficient is assumed to be

$$C_D = 0.008 + 1.7\alpha_0^2 \quad (17)$$

Total stator drag is calculated, after finishing design algorithm. If the whole systems efficiency, expressed as:

$$\eta = V_S \frac{T_P - T_S}{2\pi n Q} \quad (18)$$

is satisfactory, the design task is finished.

In test case of Nawigator XXI ship, blade widths determineed with above algorithm were very small, so arbitrary factor of 3.0 was introduced to give them rational values. Although, they are still rather narrow. Due to this the lifting line has been considered as sufficient approximation for stator blades and no lifting surface corrections has been introduced.

4 DESIGNED SYSTEM

The above theory was used for propeller - stator system design for Nawigator XXI ship. The assumed operation parameters for the system were as following:

- design speed: V = 12.9 knots;
- propeller shaft rotation n = 257.9 rpm;
- required thrust T = 124.0 kN ;
- propeller diameter D = 2260 mm;
- number of blades Z = 4;
- propeller shaft immersion h = 3500 mm ;
- average wake fraction coefficient w = 0.362;

Main data of the designed propeller are:

- expanded area ration EAR = 0.7592;
- mean pitch ratio P/D = 0.7500;
- skew angle SKA = 15.85 deg;

Propeller general view is given in the picture below:

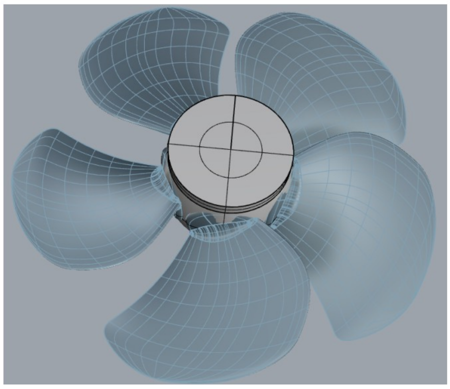

Figure 1: Propeller general view

Root sections of the designed propeller are shorter than it would result from the design algorithm, because original chord lengths would not allow the blades to rotate around their axes.

Stator blades were given same length as propeller radius, so it is $L = D/2$ = 1130 mm. Angular positions of the stator's blades were chosen upon analysis of wake field in the propeller plane (figure 8). The stator is shown in figures 2 and 3

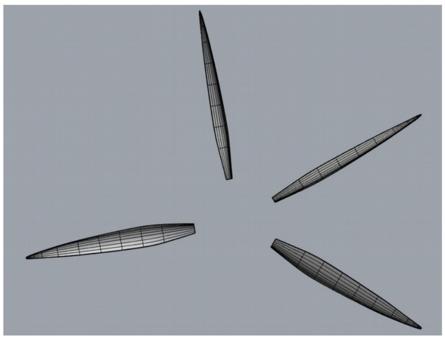

Figure 2: Stator blades front view

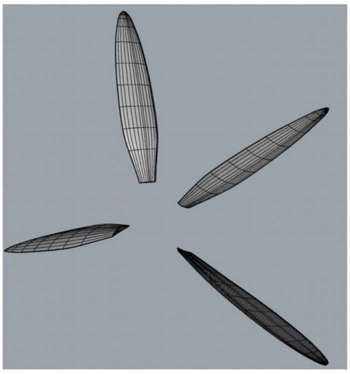

Figure 3: Stator blades general view

Model scale experiment has shown satisfactory agreement of design parameters with experimental values.

5 RANSE COMPUTATIONS

5.1 Methodology and results of CFD calculations

The computations were carried out at model scale (1:10) using RANSE method and the *Realizable K-Epsilon* turbulence model. Meshing and flow simulations were conducted with use of Star CCM+ 11.02 from CD-adapco. The inflow speed was V_M=2.099m/s. Model draught corresponded to ship design draught. code solves the RANS and continuity equations in integral form on a polyhedral mesh by means of the finite volume technique. Domain size was defined as follows [9.5L; 10.2L; 3L] [x; y; z] where L equals model length. Computations were divided into three parts described below. In the first part of the CFD a trim and sinkage values of the hull were determined. For that reason, only during this part of computations the free surface was taken into account. The grid consisted of 3.3M unstructured hexahedral cell. During these computations a symmetry of domain was used.

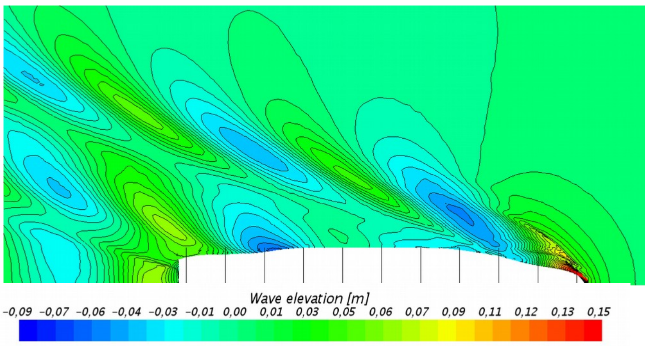

Figure 4: Free surface around Nawigator XXI, Fn = 0.285

In the second part of the CFD a velocity field in aft region was investigated. There were two sets of computations with and without pre-swirl stator. The hull was fixed (according to trim and sinkage values from first stage of computations) and without the free surface which allowed for reliable evaluation of the flow quality with significant reduction of the computational time. The grid consisted of 3.5M unstructured hexahedral cell.

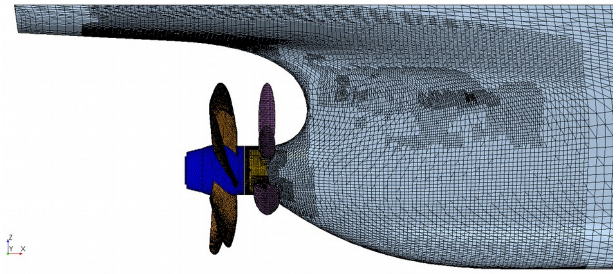

Figure 5: Meshed hull with propeller and the Pre-Swirl Stator

In Figures 6-9 below the wake fields are presented.

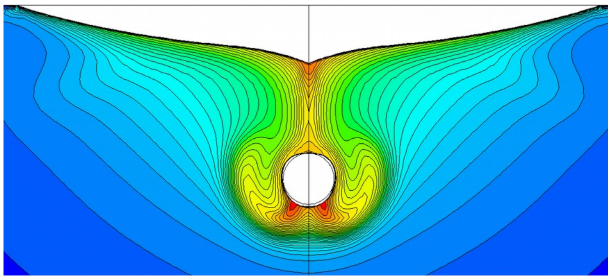

Figure 6: Stator plane without the stator

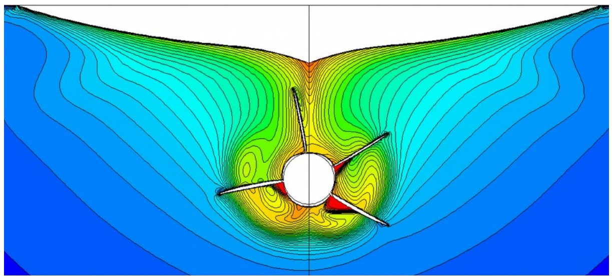

Figure 7: Stator plane

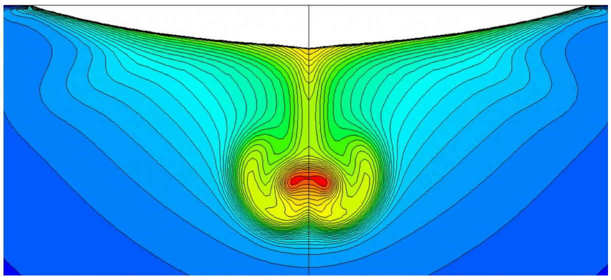

Figure 8: Propeller plane without the stator

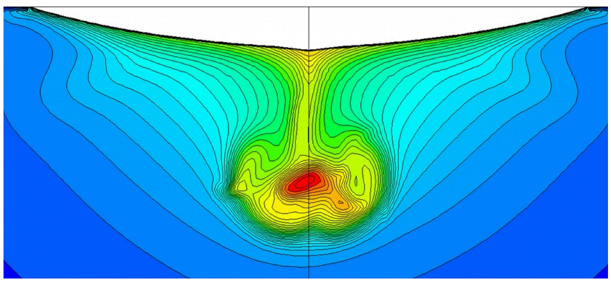

Figure 9: Propeller plane with the stator

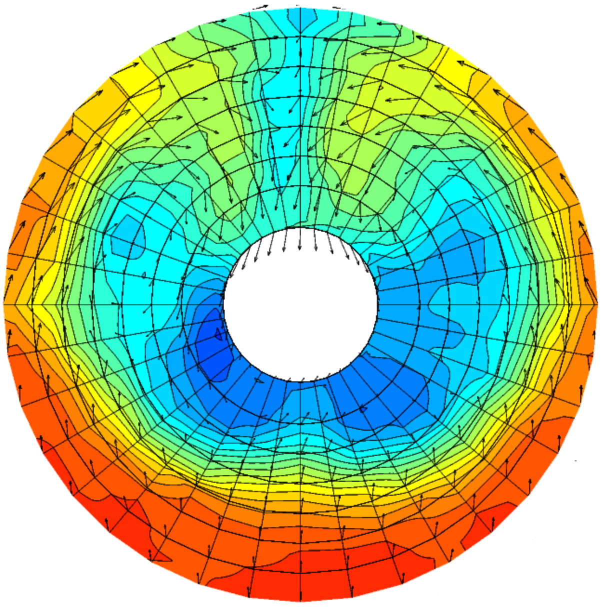

Figure 10: Wake field measured in propeller plane, with the stator present

In figure 10 there is velocity field, measured after hull model with the stator equipped. Colour scale is opposite, than in figures 6 - 9.

Table 2: Results of RANSE calculations

stator	n rps	T_P N	T_S N	Q Nm	η -
+	13.1	82.58	-1.24	2.684	0.784
-		75.30	-	2.501	0.768
+	14.0	100.76	-1.38	3.203	0.750
-		92.42	-	2.995	0.736

The efficiency η in the table above is defined by equation (18). Sign "+" in column "stator" means that the upstream stator is present in particular case nad sign "-" means that the stator is not present.

The influence of pre-swirl stator on working propeller (propeller efficiency) was analysed in the third part of CFD .The grid consisted of 1.3M unstructured polyhedral cells and 3.5M unstructured hexahedral cell, so total cell counts were 4.8M.

6 DEVELOPMENT OF VORTEX LATTICE METHOD

6.1 Main modifications of the theory

The core of the discussed design and analysis method is vortex model of propeller – stator system. It undergoes continuous modification and development. Step by step, next simplifications from basic theory are eliminated and more sophisticated models are implemented.

Main change in design module is giving up usage of dimensionless velocity coefficients. In improved method lifting line calculations are performed with VLM approach, where both stator and propeller vortex wakes geometry is determined in an iterative way. It is much more time consuming, so the simplifications of the iterative algorithm were worked out, to make it computationally cheaper, but still usable. At this stage both propeller and stator are represented with set of radial vortex lines, for sake of iterative relaxation of free vortices. Second change, which is in experimental stage, is determination of both propeller and stator blades geometry upon lifting surface model. It is based on Kerwin's approach (Kerwin et al 1988).

Analysis module has also been modified. Stator – induced velocity field is taken uniform no longer. It is determined by analysis of vortex system, representing the stator blades and their vortex wake. The kinematic boundary condition is fulfilled both on the propeller and on the stator. As the stator is not rotating - unlike the propeller - it was impossible to use velocities induced by them on each other directly, for analysis of averaged quasi steady state. Due to this circumferentially averaged velocities induced by the propeller were used for propeller influence on the stator, and circumferentially averaged velocities induced by the stator were used for stator influence on the propeller.

6.2 Cavitation test results

As stated above - iterative procedure of determining geometry of free vortices is one of the most important parts of the algorithm. There is a rich material available for propellers, but it is worse about propeller - stator systems. Due to this cavitation test was performed. It had two aims; evaluation of designed system's cavitation features and getting knowledge about deformation of stator free vortices after propeller disc. Designed system parameters were as following in tested conditions:

Table 3: Conditions of cavitation test

J	KT	10KQ	σ
0.439	0.253	0.326	2.622

Cavitation observation revealed only weak cavitating tip vortex, trailing from the propeller blade:

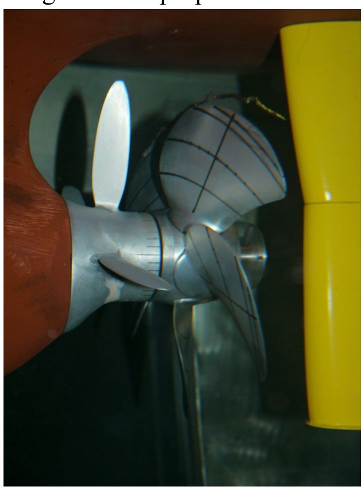

Figure 11: Propeller cavitating tip vortex

The stator turned out to be cavitation - resistant; the cavitation did not start until pressure over water surface reached value of p_a = 120mbar (σ = 1.317). Only weak cavitating tip vortex, trailing from one of the stator's blades, has incepted. It is located just above red line:

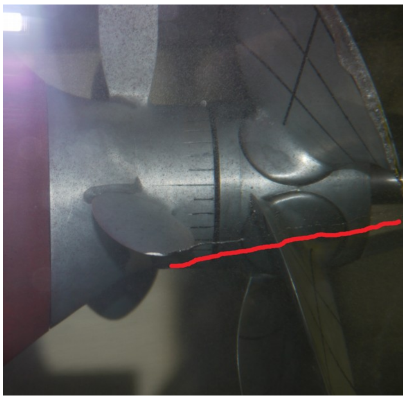

Figure 12: Forced stator cavitating tip vortex

Observation revealed that stator's free vortices more or less keep shape of straight lines. However they do not lie in plane parallel to undisturbed velocity, but are rather inclined at certain angle. Upon that we decided to give up deformation of stator's free vortices in modified version of lifting surface analysis algorithm. Only propeller's vortex wake is iteratively relaxed. Separate investigation shall be performed to determine stator's free vortex inclination angle.

7 ACKNOWLEDGEMENT

The research presented in this paper was conducted within the European Project INRETRO –ERA-NET MARTEC-2014-2017.

REFERENCES

Bugalski, T., Szantyr, J. (2014). 'Numerical Analysis of the Unsteady Propeller Performance in the Ship Wake Modified By Different Wake Improvement Devices', Polish Maritime Research.

Greeley, D., Kerwin, J., (1982). 'Numerical Methods for Propeller Design and Analysis in Steady Flow', Transactions of Society of Naval Architects & Marine Engineers **90**.

Jarzyna, H., Koronowicz, T., Szantyr, J., (1996). 'Design of Marine Propellers - Selected Problems'. Wrocław: Ossolineum.

Kerwin, J., Coney, W., Hsin, C., (1988). 'Hydrodynamic Aspects of Propeller/Stator Design', The Society of Naval Architects and Marine Engineers.

Kim, M., Chun, H., Kang, Y.(2004). 'Design and Experimental Study on a New Concept of Preswirl Stator as an Efficient Energy - Saving Device for Slow Speed Full Body Ship', SNAME Annual Meeting.

Koyama, K., (1993). 'Comparative calculations of propellers by surface panel method - workshop organized by 20th ITTC Propulsor Comitee', Papers of Ship Research Institute.

Laurens, J., Moyne, S., Deniser, F. (2012). 'A BEM method for the hydrodynamic analysis of fishing boats propulsive systems', Second Interntaional Symposium on Fishing Vessel Energy Efficiency Vigo, Spain.

Zondervan, G., Holtrop, J., Windt, J., van Terwisga, T. (2011). 'On the Design and Analysis of Pre - Swirl Stators for Single and Twin Screw Ships, Second International Symposium on Marine Propulsors, Hamburg, Germany.