VOXRTX MODEL OF IDEAL GUIDE VANE AND ITS APPLICATION TO THE REAL GUIDE VANE

Przemysław Król

1Ship Design and Research Centre (CTO), Gdansk, Poland
2Conjoint Doctoral School at the Faculty of Mechanical Engineering, Gdansk University of Technology, Poland

ABSTRACT
The paper presents systematic modelling approach to the guide vane operation. Presented models make use of vortex theory of fluid motion and ideal fluid model. Subsequent models are described, beginning with the simplest one – the vortex disc, which replaces the guide vane with bound circulation distributed uniformly over a disc. Lightly loaded lifting line model brings step towards reality by taking into account guide vanes physical nature reproduced much better by concentrated vorticity accumulated within the lifting lines. This model can however be improved by including vortex wake deformation which leads to moderately loaded lifting line model. These models are used for determination of designed guide vane operation characteristics. The most sophisticated model presented in this paper is lifting surface model, applied both to the guide vane and the screw propeller it interacts with.

Keywords
Guide Vane, Energy Saving Device, Lifting Line, Lifting Surface, Vortex Theory

1 INTRODUCTION
Guide vane is an auxiliary device applied to improve screw propeller operation. Despite their high potential of altering energetic characteristics and cavitation features of the propulsor these are not frequent solution in contemporary marine industry. One of the possible reasons is the lack of widely accepted method of designing such systems, which would give results of repeatable accuracy. In this paper author presents his attempt to elaborate theoretical base for development of such model and reference level for evaluation of designed guide vane quality.

2 GUIDE VANE VORTEX MODELS
2.1 Ideal Guide Vane – Vortex Disc
A hydrofoil of an arbitrary loading distribution may be replaced in a flow with a bound vortex of spanwise – variable circulation, which is supplemented with appropriate set of free vortices. Such structure is called “lifting line” and is well-known in foil and propeller theory. If free vortex sheet deformation is neglected this model leads to approximation of lightly-loaded foil. It allows to determine foil-forces spanwise distribution and their integral values. This model leads to well-known conclusion that foil with elliptical loading distribution has lowest possible value of induced drag at given lift value.

Above mentioned lightly loaded foil model is formally valid for an isolated foil, operating in uniform velocity field in an ideal fluid. Typical guide vane consists of not-less than three or four foils. To make the first theoretical approximation of a guide vane let us adopt the following vortex model: let there be a disc, located in guide vanes reference location, oriented normally to the ship’s velocity vector. The disc consists of continuous vortex layer of radially variable circulation, which is however constant in angular domain. It is equivalent to the guide vane consisting of infinite number of infinitely lightly loaded lifting foils of total bound circulation of:

\[ \Gamma(r) = \int \gamma(r) d\alpha \equiv 2\pi \gamma(r) \]  

where \( \Gamma(r) \) is vortex disc’s bound circulation at radial position \( r \), \( \gamma(r) \) is angular density of circulation at radial position \( r \). When comparing real guide vane characteristics with ones determined with vortex disc model, it is to be underlined that \( \Gamma(r) \) in vortex disc model – derived equations refers to total bound circulation of all guide vane’s foils. In case of three bladed guide vane, if foils bound circulations at corresponding radial position \( r \) would be e.g. \( \Gamma_1(r) \), \( \Gamma_2(r) \) and \( \Gamma_3(r) \) (three bladed guide vane), the vortex disc \( \Gamma(r) \) would be a sum of these three values.

The vortex disc is followed by cylindrical volume filled with free vortices, shedding from the disc. According to the basic laws of vortex motion, magnitude of these vortices, occurring on elementary vortex disc span \( dr \) is:

\[ d\Gamma(r) = \frac{\partial \Gamma}{\partial r} dr \]  

If radial loading distribution of the vortex disc is known/assumed, the formula (2) allows to determine intensity of the free vortices intersecting a circle of given radius, which is coaxial with the vortex disc and located behind it. Further so, using a Stokes theorem, a following formula for average guide vane – induced tangential velocity may be derived:

\[ \nu_t(r) = \frac{r \xi}{2\pi r} \]  

(3)
where $v_1(r)$ is average tangential velocity induced by an ideal guide vane at circle of a radius $r$, which is coaxial with a guide vane’s vortex disc and $f_S$ is total circulation of free vortices intersecting a circle of radius $r$. However tangential induced mean velocity field is not continuous; it has zero value before the vortex disc and full value of $v_1$ downstream from it. In the very disc plane tangential induced velocity is only half of value determined with formula (3). For clarity, tangential velocity induced at the vortex disc itself will be remarked as $v_{10}$ in further text. It is worth noticing that within described the model an induced velocity $v_1$ is independent on axial location of a circle for which it is calculated – as long as it is located behind a vortex disc and perpendicular to it, as vortex wake deformation and viscous diffusion of vorticity are neglected.

Knowing induced velocity $v_{10}$ at the vortex disc location allows to determine value of the induced drag force acting on it. Elementary ring of span $dr$ will experience elementary induced drag force, according to Joukovski’s law:

$$dD_1 = \frac{\partial \rho}{\partial r} dv_1 dr = \rho \Gamma v_{10} dr \tag{4}$$

Calculating $v_{10}$ with use of formula (3) (divided by factor of 2) and integrating equation (4) leads to following expression for total induced drag, experienced by the vortex disc:

$$D_1 = \frac{\rho}{4\pi} \int_0^R \frac{r^2(r)}{r} dr \tag{5}$$

The vortex model as described above allows to determine induced tangential velocity and the induced drag if radial distribution of bound circulation of the guide vane is known. It however turns out to be incomplete. According to well-known momentum conservation theorem, the fluid passing through a guide vane must experience a deceleration if there is a drag force to occur on a guide vane. Both vortex disc and straight line free vortices can not induce axial (negative in this case) velocities which could represent this effect. It could be done by set of vortex rings, coaxial with a vortex disc and distributed continuously behind it. We will however not attempt to determine their circulation, but rather determine axial deceleration with use of momentum conservation theorem. In order to do so we will consider elementary cylindrical flow volume, passing through a vortex disc, limited by radial positions $r$ and $r+dr$ and plane $A_0$ before the vortex disc and $A_1$ behind it. If plane $A_0$ is far enough (virtually in the infinity) from the vortex disc, it’s influence can be neglected and hence axial velocity contains no components induced by the vortex disc. The momentum flux incoming to the cylindrical volume through plane $A_0$ will be:

$$b_0 = \rho S_0 v_0^2 = 2\pi \rho r V^2 dr \tag{6}$$

where $b_0$ is momentum flux coming with the fluid through surface $S_0$ which closes elementary cylindrical volume in front of the vortex disc. By definition velocity $U_0$ is average inflow speed on the surface $S_0$ and it is equal to velocity of undisturbed flow (vessel’s velocity taken in opposite direction) $V$. As the fluid will be decelerated by the vortex disc, reference surface $S_1$ can not be taken equal to $S_0$; it will be increased, due to the expansion, resulting from mass conservation. It can be easily determined as:

$$S_1 = S_0 + \frac{b_0}{U_0} = 2\pi r V \frac{V - v_A}{V - v_A} dr \tag{7}$$

where $v_A$ is axial induced velocity at considered radius. Taking it into account momentum flux leaving cylindrical control volume will be:

$$b_1 = \rho S_1 v_1^2 = 2\pi \rho r dr V (V - v_A)^2 = 2\pi \rho r dr V (V - v_A) \tag{8}$$

The difference between momentum fluxes $b_1$ and $b_0$ shall be equal to the drag force, calculated by formula (4):

$$dD_1 = b_0 - b_1 = 2\pi \rho r dr V v_A = \rho \Gamma v_{10} dr \tag{9}$$

Rearrangement of formula (9) leads to following expression for average axial induced (negative) velocity $v_A$, representing flow deceleration induced by the guide vane:

$$v_A = \frac{r^2(r)}{8\pi r^2} \tag{10}$$

From design point of view most important feature of a guide vane is average tangential induced velocity $v_1$, which can be calculated with formula (3). As it will be shown in following paragraphs, velocity $v_1$ determined this way is in good agreement with results of numerical lifting line and lifting surface calculations. There are however considerable differences in case of the drag force coming from formula (5) and axial induced velocity from expression (10). Despite that, these can serve as a reference level for evaluation of particular guide vanes quality. The main source of deviation is replacing concentrated lifting vorticity of the guide vane foils with vorticity uniformly distributed over the disc.

### 2.2 Lightly loaded guide vane – lifting line model

The vortex disc model is a vortex representation of guide vane equivalent to infinite number of infinitely weakly loaded lifting foils. Real guide vanes however rarely have more than three, four foils. Moreover in most cases these are not spaced uniformly. Due to this calculating guide vane’s induced drag and local induced velocities requires more realistic vortex model. For an isolated lifting foil it is possible to derive analytical integral of elementary forces acting on that foil if the vortex wake is assumed to form flat surface. It is a basis from which comes a well-known conclusion that says that a foil of an elliptical bound circulation may be easily calculated by means of analytical or numerical forces integration over its span. Placing second and each next foil in its vicinity alters its
induced drag. In case of lightly loaded foils, when vortex wake deformation is neglected, this effect may be reduced to taking into account velocities induced on a bound vortex of the considered foil. It allows to treat particular foil’s drag as a linear superposition of an isolated foil’s drag and contributions of remaining foils. Drag contribution coming from adjacent foils will be dependent on their loading distribution and position with respect to the considered foil. For further analysis it is convenient to express the lifting foil induced drag as a dimensionless expression:

$$A_D = \frac{D}{\pi D^2 v^2}$$  \hspace{1cm} (11)

where $A$ is guide vane foils span. Lifting line model still calculates average axial induced velocity as zero for each radial position. It is however capable of giving non-zero local values of it, as induced by spanwise bound vortices (axially oriented free vortices do not induce axial velocities). Local values of tangential induced velocities may be calculated also. It is convenient to express both axial and tangential components of guide vane – induced velocities as dimensionless coefficients given by formula:

$$c = v \frac{\lambda}{v_0}$$  \hspace{1cm} (12)

where $\Gamma_0$ is maximum value of bound circulation over the foil’s span, $v$ is axial or tangential induced velocity, $\lambda$ is spanwise length of a lifting line. Once calculated, these coefficients may be used to determine a velocity field induced by a guide vane consisting of arbitrary number of lifting foils with arbitrary magnitudes of maximum bound circulations - as long as these may be considered "lightly loaded" and set of $c$ coefficients for applied loading distribution is known.

In further text symbols $c_A$ and $c_T$ will be used for non-dimensional $c$ coefficients representing axial and tangential components of guide vane – induced velocity. If no additional index will occur – these refers to local values of induced velocity components. Circumferentially averaged values will be remarked as $c_{A,\text{mean}}$ and $c_{T,\text{mean}}$ respectively.

2.3 Moderately loaded guide vane – lifting line model

Both vortex disc and lightly loaded lifting line models neglect deformation of guide vane’s free vortices system. It turns out to be important in case of moderately or highly loaded guide vanes, what means that they have lifting foils with dimensionless circulation $G$ exceeding value around 0.05 on a single foil:

$$G = \frac{\gamma_0}{2\pi n^2 V}$$  \hspace{1cm} (13)

Similarly as in case of lightly loaded lifting line model, the results were obtained with numerical approach. In this section only main conclusions will be pointed out. First of all, taking free vortices deformation into account allows to determine non-zero average axial velocities at particular radii. Moreover, in region of lifting lines root/tip positions these are positive. It results from free vortex sheet roll – up which leads to local acceleration of fluid. Rolled vortex tube induces strong fluid acceleration within it, slowing down the flow in their outer region. This phenomenon was not predicted by vortex disc and lightly loaded lifting line models.

2.4 Guide vane and propeller operating in nonuniform inflow – lifting surface

All models described above have significant flaw: the guide vane foils are replaced with vortex disc or lifting lines with known/assumed circulation distribution, operating in uniform velocity field, with no other object in the flow taken into account. Due to above mentioned simplifications, these models can serve as an auxiliary tools at the design stage, however are useless when it comes to analysis of an existing system. Therefore more advanced lifting surface model was elaborated for analysis task. It is applied for verification of designed geometry on later stages of the design process. Theoretical basis for the lifting surface model can be easily found in the literature, so it won’t be repeated here.

In this model both guide vane foils and screw propeller blades are replaced with vortex grids. The guide vane is fixed while the propeller rotates and hence circumferentially averaged induced velocities of each other are taken into account. At the beginning the boundary condition is satisfied on the guide vane foils. Having their circulation distribution determined, mean velocities induced by the guide vane at the propeller disc are determined. Then the boundary condition is satisfied on the propeller blades and in turn – mean velocities induced by the propeller at the guide vane location are calculated. It enables to determine new circulation distribution on the guide vane what allows to determine new circulation distribution on the propeller etc. This loop is repeated until convergence, which is normally achieved very quickly – in up to 4 runs.

When having converged circulation distribution both on the propeller and the guide vane, their vortex wakes geometry may be determined by a relaxation algorithm, which basis is described in (Król, Tesch 2018a). The initial assumption for the guide vane vortex wake is a flat surface, following undisturbed flow direction. In case of a propeller it is helical surface with radially variable pitch. The pitch angle at each radius is calculated by means of formula:

$$\beta_i = \tan^{-1} \left( \frac{V(1-w_{ER}) + u_A - v_A}{2\pi n r - u_T + v_T} \right)$$  \hspace{1cm} (14)

where $w_{ER}$ is effective wake fraction at corresponding radius, $u$ is propeller-induced velocity in a propeller disc, $v$ is guide vane – induced velocity in a propeller disc (circumferentially averaged value) and $n$ is propeller rate of revolution.

2.5 Calculations

The case adopted for calculations is guide vane ST002 interacting with propeller CP753. This system was designed and tested in model scale in Ship Design and Research Centre CTO Gdańsk. It was already a subject of some numerical simulations described in (Król, Tesch 2018b). The guide vane ST002 consists of three foils of
span (measured from the propeller shaft axis) equal to \( A = 1.30 \text{m} \), mean angle of attack \( \alpha_{\text{mean}} = 18.91 \text{deg} \) and mean blade width ratio \( b_{\text{mean}}/A = 0.174 \). Angular positions of the foils are 0, 30 and 60 deg. The propeller CP753 is five-bladed propeller of diameter equal to \( D = 2.26 \text{m} \), expanded blade area ratio \( A_{E}/A_0 = 0.759 \) and design pitch ratio \( P_0/D = 0.828 \). Axial distance between the propeller and the guide vane discs is equal to \( 1.0 A = 1.30 \text{m} \).

**Figure 1:** Propeller model CP753 and guide vane model ST002 prepared for self-propulsion test (scale 1:10)

The model scale experiment was conducted to determine propeller and guide vane operation in self-propulsion test conditions. Numerical simulations were conducted as following: in the first step lifting surface model calculations were performed to determine propeller and guide vane forces, induced velocity field and – what is crucial for subsequent computations – circulation distribution. In the next steps lifting surface – determined guide vane circulation distribution is applied for lifting line and vortex disc calculations. This approach allows to evaluate adopted models influence on obtained results. Similarly as the experiments, the calculations were conducted for model scale at scale ratio 1:10.

In Figure 2 guide vane foil bound circulation distribution, made non-dimensional similarly as in equation (13), calculated with lifting surface model in self-propulsion test conditions (nonuniform velocity field, operating propeller present) is given. Self-propulsion test model scale conditions are given there also: hull model speed, propeller rate of revolution and measured thrust force value. For comparison propeller thrust force value calculated with lifting surface model is presented.

**Figure 2:** Guide vane bound circulation distribution (single foil) calculated with lifting surface model at corresponding self-propulsion test conditions

This circulation distribution is an average between the guide vane foils. However calculated differences are so small that can be considered lower than numerical accuracy and hence mean value was used for further analyses for use by other vortex representations.

Subsequent vortex models were used to determine the guide vane’s drag. The results are given in Table 1 in form of non-dimensional coefficient, defined with formula (11):

<table>
<thead>
<tr>
<th>Case</th>
<th>VD</th>
<th>LL</th>
<th>ML</th>
<th>LS</th>
<th>LS+D</th>
<th>EXP</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_{D} \times 10^{-2} )</td>
<td>0.66</td>
<td>3.87</td>
<td>3.89</td>
<td>3.55</td>
<td>7.68</td>
<td>7.23</td>
</tr>
</tbody>
</table>

where: VD – vortex disc, LL – lightly loaded lifting line, ML – moderately loaded lifting line, LS – lifting surface, LS+D – lifting surface with viscous drag included, EXP – experimental value. Experimental drag value was approximated as a difference between propeller thrust values measured during self-propulsion test with and without the guide vane. Value “LS+D” was calculated by addition of a drag calculated by Johnson formula at each guide vane lifting surface panel (Jarzyna et. al 1996):

\[
C_D = 0.008 + 1.7 \alpha^2
\]  

(15)

Where \( \alpha \) is blade section angle of attack, determined as one between local total velocity vector and guide vane foil section chord.

Results of numerical determination of guide vane – induced velocities are given in Figures 3 – 11. All calculations were conducted in the model scale, at the propeller disc position which is located \( 1.0 A = 0.130 \text{m} \) downstream from the guide vane’s position. Angular position of the guide vane foils are 0, 30 and 60 deg. Increasing angle corresponds to the right-handed propeller direction of revolution. Induced velocities – both circumferentially averaged values and local ones, were made non-dimensional and are presented in form of \( c \) coefficients, defined by equation (12).
In Figure 3 averaged tangential component of guide vane – induced velocity is given in the propeller disc axial position – as deduced by subsequent vortex models.

Figure 3: Mean induced tangential velocity coefficient $c_{T,\text{mean}}$ deduced by subsequent vortex models (1.0 Λ downstream from the guide vane axial position)

In Figure 4 averaged axial component of guide vane – induced velocity is given in the propeller disc axial position – as deduced by subsequent vortex models.

Figure 4: Mean induced axial velocity coefficient $c_{A,\text{mean}}$ deduced by subsequent vortex models (1.0 Λ downstream from the guide vane axial position)

Mean axial induced velocity calculated with lightly loaded lifting line model is zero everywhere downstream from the guide vane. Differences between results of vortex disc model and ones including vortex wake deformation (moderately loaded lifting line and lifting surface) are significant. However mean values, over the propeller disc, of $c$ coefficient are quite close: -0.002 for vortex disc and -0.006, both for moderately loaded lifting line and lifting surface, what can be considered zero, within numerical accuracy.

In Figure 5 mean axial induced velocity coefficient, as deduced by vortex disc model, is given.

Figure 5: Mean induced axial velocity coefficient $c_{A,\text{mean}}$ deduced by vortex disc model

In Figures 6 – 11 local values of induced velocity components are presented in form on non-dimensional coefficients. For clarity these are given only for selected radial positions. As stated previously, guide vane foils angular positions are 0, 30 and 60°.

In Figures 6 – 8 axial induced velocity coefficients are given.

Figure 6: Local induced axial velocity coefficient $c_A$ (lightly loaded lifting line, 1.0 Λ downstream from the guide vane axial position)

Figure 7: Local induced axial velocity coefficient $c_A$ (moderately loaded lifting line, 1.0 Λ downstream from the guide vane axial position)
Induced velocity peaks observed in Figure 7 for radial positions 0.3 and 0.4 result mutually from vorticity concentration on the root region and numerical reasons. In Figure 8 curves from Figure 7 are repeated however with changed scale to better present results in angular vicinity of the guide vane foils. Results for radial positions 0.3 and 0.4 are omitted to provide better clarity.

Figure 8: Local induced axial velocity coefficient $c_A$ (moderately loaded lifting line, 1.0 Λ downstream from the guide vane axial position, foils vortex wake region)

Character of induced axial velocity is notably different in case of lightly and moderately loaded lifting line models. One deduced by lightly loaded lifting line is symmetrical with respect to the middle foils position, with deceleration area concentrated around 90deg position. Local values of induced velocity are very low. In case of moderately loaded lifting line still there is deceleration in similar region however the velocity field in symmetrical no longer. Moreover local spots of accelerated flow are seen around guide vane foil tips positions (radial position 1.0). Besides abovementioned regions axial induced velocity is small, as absolute values of local $c_A$ coefficients hardly exceed level of 0.3 – except radial positions 0.3 and 0.4

In Figures 9 – 11 tangential induced velocities are given.

Figure 9: Local induced tangential velocity coefficient $c_T$ (lightly loaded lifting line, 1.0 Λ downstream from the guide vane axial position)

Character of induced tangential velocity is similar both for lightly and moderately loaded lifting line models for most of angular positions. Differences are located mostly in angular vicinity of guide vane foils. Velocity peak deduced by moderately loaded lifting line for radial position 0.4 is probably mostly of numerical nature. In Figure 11 curves from Figure 10 are repeated however with changed scale to better present results in angular vicinity of the guide vane foils. Results for radial positions 0.3 and 0.4 are omitted to provide better clarity.

Figure 10: Local induced tangential velocity coefficient $c_T$ (moderately loaded lifting line, 1.0 Λ downstream from the guide vane axial position)

Induced tangential velocity fields deduced by both lightly and moderately loaded lifting line models are not in significant difference. Unlike axial velocity field, the tangential one is more concentrated in angular positions of guide vane foils. Below and above foils root and tip respectively, negative values are observed, in radial vicinity of tip and root positions. Due to vortex roll up in moderately loaded lifting line model, there are some differences in root region, where the vorticity of all foils is concentrated.

Figure 11: Local induced tangential velocity coefficient $c_T$ (moderately loaded lifting line, 1.0 Λ downstream from the guide vane axial position, foils vortex wake region)
3 CONCLUSIONS

Upon presented comparison of experiment and numerical results following conclusions may be drawn:

- Circumferentially averaged value of guide – vane induced tangential velocity may be successfully determined by all of presented vortex models, including the simplest one – vortex disc;
- Local values of guide vane induced velocities should be determined by a model including vortex wake deformation into account, as neglecting its deformation leads to loss of local effects (local acceleration at guide vanes foil root and tip positions). Both moderately loaded lifting line and lifting surface may be used in this purpose.
- Induced drag given by the vortex disc model is significantly lower than one determined by lifting line and lifting surface. It may be treated as limiting reference value for real guide quality evaluation.
- Lifting line model including guide vane vortex wake deformation can be used to produce reliable initial evaluation of designed guide vanes induced drag.

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REFERENCES


