ABSTRACT

Nowadays higher demands are made on the vibration level of modern ships, especially passenger ships. As limiting values of vibration are part of the building contract, it is important for the building shipyard to receive soon substantial predictions. In order to execute corresponding calculations by means of structural analysis programs (FEM), it is necessary to know as clearly as possible the forces which excite the structures. The propeller induced pressure pulses have turned out to be a main source of excitation. These pressure pulses are generated by the hydrodynamic flow around the propeller and are propagated by the water to the aftbody.

This paper is based on an existing vortex-lattice method [9][12] and develops a prediction procedure by which it is possible to make a substantial prediction of the pressure pulses during the early design stage. Therefore the numerical characteristics and the numerical stability of the chosen method were examined in a first step. In a second step the influence of the wake was investigated.

The difficulty was that the necessary wake for calculation does not exist, because in a model testing tank (Fig.2) only the nominal model wake is measured. So it is necessary to carry out corrections, because the effective full scale wake is needed for the calculation. To handle this problem two procedures were examined within the scope of this paper. Firstly a method of Yazaki was applied to adjust the distribution of isotachyls of the wake to the conditions under full scale. Secondly a method was developed and implemented to calculate the contraction effect of the propeller on the wake. These two approaches have been used to evaluate the influence of the propeller on the nominal wake in order to get a conversion from the nominal to the effective wake.

To evaluate the method a data set of 21 propellers was examined. For these propellers measurements have been done by model-testing establishments. For most of the propellers both the cavitating and the non-cavitating part of pressure pulses have been measured. On the basis of this data set, it was investigated, what kind of correction method produces the best results of calculation. Further a statistical correlation method was developed in order to calibrate the calculation results by the existing empirical data.

1. INTRODUCTION

Today classification societies define rules for vibration levels. Therefore, a shipowner has clear guidelines for the shipyard. To handle these guidelines the building contract defines clear positions in the shipbody, where vibration and noise measurements have to be carried out before accepting the newbuilding. If the defined vibration level is not reached during the trial trip, the shipyard has to mend these problems.

To mend vibration problems in this state of the project, mean normally to lose much money. Firstly, it is
difficult and expensive to do changes to an existing ship and secondly it means often a delay for the delivery and therefore an additional contract penalty. Beside problems with the comfort, in some cases safety problems can result from not reaching the defined vibration levels. An example is a premature fatigue of safety relevant components like a lubricating oil pipe due to the vibration level.

To handle these problems, two things are necessary. Firstly, the steel structure has to be optimized for a minimal vibration level and secondly the exciting forces have to be minimized. The main sources for such forces are:

- the main engine
- the propeller and rudder

In special cases there are sometimes also other sources as cavitation effects on appendices. The exciting forces of the engine are normally known because they are given by the engine maker. Because engines are normally standard products, there is already information from a test bench. The exciting forces resulting from the propeller are more complicated, because a propeller is a unique component and no duplicate part. Therefore, it is impossible to get real measurements about exciting forces, unless the propeller has been installed under the aftbody of the ship. Only model testing and numerical simulations are possibilities to get information about a propeller design.

The propeller induces mainly two types of vibrations to the structure. Firstly, there is a mechanical interaction between stern gear and the steel structure and secondly the propeller induces periodical pressure pulses. These pressure pulses are resulting from hydrodynamic effects of the flow around the propeller blades. They are propagated through the water to the aftbody of the ship, where they excite the steel structure.

These types of exiting forces are nowadays difficult to calculate, because the physical phenomena’s are extremely sophisticated. Primary cavitation effects on the blades are difficult to handle with a reliable degree of accuracy. Overall, propeller induced pressure pulses can be divided in three parts:

### The non-cavitating part

This part results from the displacement effects of the propeller blades and the free circulations based on potential theory. In an homogenous flow the pressure pulses mostly consist of frequencies of first order (this mean to multiply propeller revolution by the number of blades). If the propeller is in a wake, there are moreover pressure pulses of higher orders, because the blades are working with a different load depending on the angle within the wake.

With modern propeller designs the non-cavitating part can be even the main part of the pressure pulses. This effect can be observed particularly by ships with flat aftbodys where a relevant excitation of the structure is generated by an areal distribution of overpressure and low pressure.

### The cavitating part

Resulting from low pressure, there are areas with cavitation voluminous on the propeller blades. Relating to the position within the wake these voluminous are fluctuating. On the bases of improvements in quality of numerical calculations, nowadays it is possible to predict the dimension of cavitation areas with quite a good quality. This allows an optimization of propeller designs for little cavitation areas. Ten years ago propeller induced pressure pulse were around 8-10 kPa for the first order. Today there are high skew propeller with only 1-1.5 kPa. These propellers contain around 1 kPa only for the non-cavitating part of the pressure pulses. This means that the partitioning of cavitating and non-cavitating parts are totally different in contrast to the past.

### The tip vortex

The tip vortex results from flow around the blade tip based on overpressure and low pressure of the opposite side of a blade. Because the thickness varies with the blade angle the tip vortex induces pressure pulses with higher harmonics. In a worst case there is a bursting of the tip vortex, which means a wideband of noise. Such a problem should be avoid in any case. Regrettably, these days it is not possible to predict the tip vortex with a useful accuracy. Therefore, the only way to handle this problem during the propeller design is to reduce the load of the blade near the tip.

All these effects are part of the total pressure pulses which are exciting the aftbody. A prediction has to generate results with a sufficient accuracy. This means that a following structure analysis is able to calculate the vibrations within the steel structure. The goal of this study is to get a method to predict the propeller induced pressure pulses during the early design. Such a method is necessary to do optimizations before model testing, because they are expensive and time-consuming and therefore not useful during the early design stage. Moreover, model testing can be used in a more specific way, if a numerical optimization has been done before.

Model testing is problematic, too, because of scale effects. Even under good conditions, it is difficult to get measurements with a lower dispersion of values as 0.3 kPa. To take an example there are bubbles and gerns of cavitation which are inducing stochastic effects to the measurement. The big differences in the Reynolds-Number between model testing and full-scale is a further difficulty for the prognoses. Based on technical reasons, it is impossible to get the same Reynolds-Number both in model testing and in full-scale. But the wake of a ship is mainly an effect of the boundary-layer. So the wake in model testing is different from full-scale. This is a problem in the same way for model testing as for numerical simulation. In particular it is very important, which wake is used for calculation. The main task of the study was to investigate which wake is needed and how
to generate it. Because the distribution of isotachyls has a direct influence to the generated pressure pulses, this distribution has to be filed in the calculation tool. Without useful input-data the best numerical method is unable to calculate information of useful quality.

But beside a physical optimization, a correlation with a database of measurements is still necessary for both model testing and numerical simulation. A second task is to implement a correlation strategy for a numerical method in the same way as it is common in model testing.

This study uses a method from Streckwall [12][13]. This method implements a numerical model based on a vortex-lattice method [6][11] to describe the 3D-geometrie of the propeller blades by a grid of vortices as shown in Fig. 3. The model allows to calculate the pressure distribution on the blades. The pitch of the free vortices downstream of the propeller is calculated by a lifting-line method [5][17]. This allows to configure the arrangement of the free vortices. Further a model for calculation of cavitation is included [3][8].

This tool is the basis for this study. Theoretical, tools with a more detailed physical module could be used, too[1][4][14]. Perhaps RANSE-solver could be used in the same way for generating numerical values for a prognosis of propeller induced pressure pulses. But this has not been done because of the time critical requirements during the early design stage. This process needs tools, which allow to evaluate design changes very quickly. Lately, at the next day the calculation has to be finished. Otherwise, the information can not be used, because the design process can not wait any longer. For a optimization task, a more quicker calculation is needed. If a design engineer wants to optimize a propeller design or the wake, a result of a calculation is needed lately after a few minutes. A longer calculation time would be eliminate the possibility of evaluating enough design variants.

This study has been focused on the question of the workflow for the design engineer. The engineer wants a tool, which can be used in a reliable way. As descript, the effort of executing such a prognosis is a hard criteria for the early design stage. Further, the quality of resulting data has to be clear. A prognosis, which returns often very exact information and sometimes absolutely wrong information is useless. A minimal demand is that the prognosis tool returns information about the reliability of the prognosis. Therefore, a main task of this study is to evaluate the quality of the used prognosis tool. This has been done in comparison with a set of measured data. It was possible to use the information of twenty-one propeller designs, which have been analyzed mostly in the HYCAT of the HSVA. Afterwards a correlation has been done between the calculated results and the measurements.

2. NUMERICAL EVALUATION OF THE USED VORTEX-LATTICE METHOD

The used vortex-lattice method needs different kinds of input data. In a first step the robustness of the used tool has been evaluated. This means, not the physical correctness was within the main focus but the ability of the tool to return reliable and repeatable values. Therefore some studies of parameter have been done. The influence of grid fineness has been investigated in the same way as the robustness against little parameter variations.

Especially the last point could be handled in an easy way. Studies in variation of x-, y- and z-position of the propeller have result in very robust values of calculated pressure pulses. In the same way variations of the inflow velocity have not result in unexpected information.

Another investigation has been done in the influence of the rudder and in the influence of wakes with a different degree of homogeneity. The results of these investigations can be read in [2].

A more interesting thing is the influence of the grid used for the calculation. The investigation in grid fineness is of great importance. From the view of computational effort it is preferable to use a coarse grid. But if a grid is too coarse, the results of the calculation are useless. For example, if a pressure peak is definitely smaller than the panel, the mathematical model would spread out the pressure peak over the whole panel, with a result hard to analyze.

On the other side a fine grid has problems, too. Firstly, the performance of the calculation is worse. Especially in the early design this is a very important characteristic. Additionally, a fine grid is problematic for a potential theory model. Because this model is based on the method of solving the Laplace equation, the problem has to be describe with rotation free streamlines. In contrast to methods based on viscose models, the potential theory cannot handle physical effects like turbulences. This characteristic implies, that an explicit separation of streamlines like at a square stern has to be modeled with special panels. Otherwise, it is impossible to get a solution for the Laplace equation.

A detailed description of handling grids for the calculation of pressure pulses is given in [2]. To summary the results, it can be said, that it is important for a prognosis to run more than one calculation. The grid is a very important input data. A variation in density can help to analyse, whether a calculation result is useful or not. Sometimes there are numerical problems, resulting in useless calculations. But a comparison of calculation
results, with little grid variations help to decide whether a calculation is useful or not. The results of a little set of calculations can generate information for a reliable prognosis. Grids in the range of 200 to 1000 panels have to be proved as useful.

2.1. Modelling of wake

After investigation in numerical robustness of the used software-tool, it was investigated, which physical effects are triggering the pressure pulses. To do this a partitioning has been done in simulations with and without cavitation. This is useful, because in modern propeller designs the non-cavitating part of the pressure pulses is already a significant one. In further investigations the cavitation part was in the main focus. But in modern propeller designs the cavitation has been reduced very much. Therefore, the non-cavitating part has become more important.

The wake has been investigated, too. By doing a pressure pulses calculation, a difficulty is within the fact, that the needed wake is not available. A calculation for full scale needs a full scale wake. But a wake is normally measured by Froude’s method of model testing. This procedure has two consequences. Firstly, the wake is a wake with much more smaller Reynolds-Number. Therefore, the influence of the boundary-layer is significantly stronger as in full scale. Further, measurements in the cavitation tank are done again by another Reynolds-Number. In this case there is no longer the same Froude-Number. Because a pressure pulse prognosis does not need the same formation of waves as in full scale, a bigger Reynolds-Number can be used. This allows to get a more similar wave as in full scale. If changes of the speed number of advance are measured, though the thrust coefficient is constant, the assumption is, that this difference results from a change of the efficient wake number. The same procedure has been used for the calculation. To evaluate the measurements with a numerical simulation, the thrust coefficient within the simulation has been set to the same as in the measurement. As a result of this assumption, this study is discussing, in which way the wake must be corrected to get a wake more similar to the one of the experiment. A second point is, that only the nominal wake can be measured. The effective wake is impossible to measure, because even if a measurement would be done with an active propeller, only the resulting wake with propeller-induced velocities would be measured. Either the nominal wake \( \bar{v}_{n,mod} \) can be measured, or, if a model with active propeller would be used, the resulting velocity \( \bar{v}_{n,off} + \bar{v}_{rad} \) is measurable. The effective wake is a pure theoretical value with no representation in reality. But a simulation would need this wake to model the physical correct. Now these both effects will be analysed.

2.2. Influence of Reynolds-Number

For this study it was possible to use a method tested by the HSVA in practice. This method bases on an empirical procedure developed by Yazaki, which only needs the wake number of model scale and the main dimensions of full scale:

\[
\frac{1 - w_{FS}}{1 - w_{MS}} = f\left(w_{mod,ell}, L_{pp}, B, T\right) \tag{2}
\]

An interesting feature of this method is, that the function does not include the scale factor. A reason is that in spite of very different main dimensions and serves speeds the Reynolds-Number is similar in contrast to a Reynolds-Number of a model test. This function has been developed to translate a global wake number from model to full scale. Now, this function has been used to translate a total wake. This has been done by translating each local wake number of the nominal model scale wake (Fig.4).

By this procedure the wake of Fig.5 has been generated. Fig.5 shows in relation to Fig.4 a clearly more homogeneous flow. The isotachyls of the model scale wake are clearly more near as in the full scale wake. This behaviour is in consistency with the physical effect of a stronger boundary layer influence.

The effects within the cavitation tunnel has to be somewhere in the middle. But these both wakes allow to get an upper and downer border of the behaviour within
the cavitation tunnel. This will be discussed more detailed later.

2.3. Generating an effective wake

In a second step a model should be developed for generating an effective wake based on a nominal wake. This means, not the propeller induced velocities are important but the qualitative changes to the wake. A main influence of the propeller to the wake is a contraction of the flow resulting from the continuous equation. This effect is shown in Fig.6/7. Streamlines are roped in the propeller area, whose are outside by a nominal wake. Therefore, flow near of the hub becomes less influential on the simulation. On the other hand, flow outside of the propeller area is now inside and will take effect on the calculation results. Depending on the wake, the effect can be positive or negative for the wake.

The contraction of flow has been handled by the use of a lifting line method [7] in a previous step. This method has been used to calculate a radial distribution of induced velocity, like Fig.8. Although the lifting line method is based on a homogenous flow, it is quite useful for this purpose. Because the contraction of the flow is based on the thrust of the propeller, the contraction can be handled as an averaged effect of the propeller area. As long as the same thrust is used, the contraction should be the same by the use of a homogenous flow or an effective wake. This procedure allows to calculate with low effort a function, which represent an over the angle averaged value of induced velocity.

Now it is possible to calculate the contraction between two radii of the wake by use of the continuous equation. Therefore, the average mass flows through the area $A_i$ between $r_i$ and $r_{i-1}$. As a simplification, only the axial component of the flows has been used.

$$
\dot{m}_i = \rho \cdot \frac{1}{A_i} \cdot \int_{A_i} \vec{v}_x(r, \varphi) \cdot d\vec{A}
$$

(3)

In the case of a working propeller a new mass flow is active. Resulting from the induced velocities the fluid is flowing with a higher speed. But because the induced velocity has been already calculated by the use of a lifting line method, it is possible to calculate an average mass flow of the effective wake. In the same way as in equation (3) only the axial component has been used.

$$
\dot{m}_i' = \rho \cdot \frac{1}{A_i} \cdot \int_{\varphi=0}^{2\pi} \int_{r=r_{i-1}}^{r_i} \left( v_x(r, \varphi) + v_{ind,x}(r) \right) \cdot r \cdot dr \cdot d\varphi
$$

(4)

A combination of equation (3) and (4) with the continuous equation, results in the following term:

$$
\dot{m}_i' \cdot \pi \left( r_i^2 - r_{i-1}^2 \right) = \dot{m}_j \cdot \pi \left( r_j^2 - r_{j-1}^2 \right)
$$

(5)

This equation allows to calculate new radii of the contracted flow. Each contracted radii is defined by:

$$
\frac{r_j^2 - r_{j-1}^2}{m_i} + \frac{r_i'^2 - r_{i-1}'^2}{m_i'}
$$

(6)

This recursive function allows to calculate the contraction effect of the propeller in a previous step. The generated wake can be now interpreted as an effective wake, which can be used as an input wake for the pressure pulse calculation.

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Fig.6 Streamlines without propeller
Fig.7 Streamlines with propeller influence
Fig.8 Distribution of induced velocity
Fig.9 Nominal and effective wake by a single-screw vessel
Because of the recursive characteristic, a termination for the first radii is necessary. This will be done with:

$$r_0' = r_0$$  \( (7) \)

This assignment is correct, because the innermost radii is the hub of propeller. Clearly, there is no contraction possible and consequently the hub radii of the nominal wake is equal to the hub radii of the effective wake.

The Fig.9 shows an example for the use of this method. These examples explain, in which way the contraction of the wake affects the wake of a single-screw vessel. The shown wake has most of the low inflow velocity near the hub. A contraction resulting from the propeller has the effect of a reduction of this area. Instead of this, higher inflow velocity from outside is roped within the propeller area. Therefore the effective wake number becomes less. The using of this wake for a simulation has the consequence, that in case of the nominal wake the ship velocity has to be set to 23.9 kn to get the correct kT value. By an use of the effective wake this velocity has to be reduced to 23.0 kn. In a model test a velocity of 22.5 kn has been measured. This means, the effect of the wake correction changes the behaviour of simulation in the correct way.

3. SIMULATION RESULTS

Now there are two methods available to correct the nominal model wake. These correction methods have been used for their own and in combination on the measured nominal model wake. In this way, four different types of simulation have been generated for all of the propellers of the database. These calculations have been done for the non-cavitating and for the cavitating case. With this procedure it has been investigated, what kind of quality are able to be generated by modelling physical effects with models of low numerical effort. In spite of these numerical corrections there are still differences between measurement and simulation. That is why a correlation has been used to minimize the averaged error level. Some functions have been investigated [2], but a simple quadratic polynomial has been proved of value:

$$P_{\text{corr}} = f(P_{\text{Sim}}) = a_1 \cdot P_{\text{Sim}} + a_2 \cdot P_{\text{Sim}}^2$$  \( (8) \)

The coefficients $a_1$ and $a_2$ have been calculated by a minimization of the quadratic error.

3.1. Non-cavitating results

In Fig.10 are shown the results of non-cavitating simulations. The blue bar visualizes the measurement of the cavitation tank. It is obvious that the calculations are consequently to low. Especially the Reynolds-Correction with Yazaki results too low pressure pulses. This behaviour is not surprising. The Yazaki-correction has changed the wake in direction of full scale. This correction has lowered the gradients of isotachyls, which consequently results in lower pressure pulses. This behaviour is known and is according with reality. But because a simulation with a model scale wake already results in too less pressure pulses, a correction to full scale has to generate a higher error level. It is important to realize, that especially the measurement of the non-cavitating part includes some physical problems. The
procedure in the cavitating tunnel is to add to the pressure so long until no cavitating is anymore to see. But a residual invisible cavitation could be still there. Such an error would influence the measurement in direction of too high pressure pulses. Because of all these uncertainties a correlation has been used to reduce the error-level. The different calculation methods have result in error-levels, shown in Fig.11. This figure shows, that the Yazaki-correction does not improve the calculation. In contrast to the full scale correction, the correction to an effective wake results in a lower error-level. This means the assumptions about the effective wake should be correct. After a correlation this tendency is no longer very distinct (nominal wake: Error=0.11; effective wake: Error=0.10). This little difference does not allow to conclude a real lower error level. But by the use of the effective wake, it is possible to reduce the part of statistically correlation by the use of a physical model. Seen from an engineers point of view this is the better way.

3.2. Cavitating results

In the same way as by the non-cavitating part, the calculations have been done for the cavitating part. The results have been compared to measurements, too. These calculations result in total different conclusions. In contrast to the non-cavitating simulations, the calculated pressure pulses have a tendency for too great values (Fig.12). But now the full-scale correction with Yazaki effects the prognosis in much better way. Because of the tendency to calculate the pressure pulses too big, the full scale wake with smoother isotachyls generates better results.

It is feasible, that calculations with cavitation acts in an other way as without cavitation. Cavitation is very sensible about variations to the wake and the KT value. Therefore, a bad wake means a deterioration of pressure pulses in two ways. Firstly, a bad wake generates directly higher pressure pulses, and secondly the cavitating volumes increase, which means higher pressure pulses too. In contrast to the non-cavitating case, the displacement effect of the propeller is not constant.

As explained the nominal model wake generates clearly too high pressure pulses. But this result can be used as a worst case prognosis. The engineer can be nearly sure, that a propeller design does not have more pressure pulses as the calculation result based on the nominal model wake. Sometimes the result is unrealistic too high, but in this case the engineer knows, that the prognosis is not useful and will not be misled. Therefore, the prognosis will not seduce the design engineer to bad decisions. In contrast to this a prognosis, based on a Yazaki-corrected full scale wake, will generate a prognosis with a clearly lower error level. Fig.15 shows this behaviour. But a tendency to calculate the pressure pulses too low is still within the prognosis, as Fig.13 shows. A correlation can minimize this error further (Fig.14).

A usability of the effective wake correction cannot be deduced from these calculations. Without a full scale correction the prognosis has a high error level anyway. But the use of a full-scale effective wake does not reach the quality of the nominal full-scale wake. After a correlation the difference is not any longer great, but with the same argument as in the non-cavitating case, this study uses the nominal full-scale wake, because there is a smaller part of the statistical correlation.
4. CONCLUSION

In the previous chapters it has been investigated, in which way the pressure pulses prognosis can be done individual for the cavitating and non-cavitating part. These information can be used for a prognosis of propeller induced pressure pulses. An engineer can generate reliable informations during the early design. A useful prognosis has to generate two pieces of information:

1. A worst case prognosis should guarantee, that the engineer does not make wrong decisions, because problems are hidden by a prognosis too well.
2. The prognosis should generate a value for the pressure pulses with an error level as little as possible.

The first item is easy to realize. As in the previous chapter described, a calculation with caviation and based on the nominal model-scale wake without a correlation returns such a worst case prognosis. Fig.12 visualizes the calculation with nominal model-scale wake over the measured pressure pulses.

The second item, the minimization of differences between prognosis and measurement can be done in a first step by the use of a prognosis based on the nominal full-scale wake (Fig.13). This diagram shows that the prognosis has a tendency for too low pressure pulses. The real measured value is mostly within this bandwidth of these two calculations. This information can be used as a bases for design decisions. The engineer can get a feeling for quality of the propeller performance. A calibrating of the calculation with the nominal full-scale wake optimizes the value of pressure pulses within this bandwidth, as Fig.14 shows. With this strategy it is possible to get a set of reliable information about a propeller design before model testing.

The study has shown, that the use of a vortex-lattice method is practical for the prognosis of pressure pulses. Such a numerical method is a tool easy to use with a high performance. Results can be produced fast enough, to use such a tool during the early design.

Anyway, there are two difficulties. First, the grid generation can influence the calculation results in a dominat way. Therefore it is necessary to validate results by the use of a few similar but not equal grids. This procedure allows to validate whether a result is stable or not. Second, a calculation with caviation has a significantly worse quality as a calculation without cavitation. Furthermore, the quality of the used wake has a great influence to the calculation result. It is possible to define a bandwidth by the use of a nominal model-scale wake and a nominal full-scale wake. This bandwidth will be decrease, if the quality of a propeller design increase. So a design engineer has a practical tool to evaluate a propeller design during the early design.

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