RANS Based Analysis of Roll Damping Moments at Bilge Keels

Florian Kluwe (kluwe@tu-harburg.de), Daniel Schmode, Gerhard Jensen

Introduction

The simulation of ship motions in seaways gets increasing relevance for the evaluation of ship safety. Usually the hydrodynamic forces are calculated with potential flow methods. The damping forces of the roll motion, in particular those of the bilge keels can be considered only by empirical methods. These are based on experiments and estimations, for example obtained by using plates in transverse flow. In this paper various results of instationary flow calculations by means of RANS-simulations are presented for different bilge keel configurations. Using these results regression formulas for the damping work can be determined. Subsequently the nonlinear damping coefficients can be gained.

Model

In order to find results, which are not influenced by a specific hullform, a simple cylindrical hull section was used for the parameter studies. Using such a form furthermore omits all interactions between the forces at the bilgekeel and the forces on the main hull. Additionally a parallel midship section was used to investigate the influence of different bilge radii on the damping forces. Another practical advantage of these simple models is that they are easy and quickly to variate.

All numerical models have full scale size. The length of the computational domain is 60 meters. The Radius of the cylindrical cross section is 13 meters, whereas the outer boundary of the computational grid extends to a radius of 53 meters. This gives a 40-meter water layer above the hull surface. No free surface is considered in the simulation, assuming that the bilge keels are always sufficiently submerged.

Figure 1: Perspective view of the model with cylindrical cross section
Therefore the water surface is treated as symmetry plane. Also symmetry can be found at the ship’s centre plane. For the models with a cylindrical cross section these two symmetry planes are identical, which reduces the computational domain to a quarter of the full model. Figure 1 shows the numerical grid of such a variation. For the ship-like cross sections one half of the full model has to be calculated, because the four symmetry planes differ from each other. Therefore only the water plane is used as a symmetry-boundary. Figure 2 shows such a numerical grid for a hull section with a 4m-bilge-radius.

![Finite Volume grid of hull section with 4m bilge radius](image)

The hull sections described above are fitted with various different bilge keels. Three main types of bilge keels are investigated (Figure 3): One type consists of a continuous bilge keel throughout the whole domain. In this case no leading and trailing edges exist within the model. The second type is a continuous bilge keel, which starts and ends within the boundaries of the computational domain. The third type consists of two consecutively placed bilge keels. This type is used to investigate the effects of a gaps between bilge keels on the roll damping, because this is a common and widely used construction.

Within these three main types the length, height and gap width of the bilge keels are systematically varied. The calculations for the different bilge keels are repeated with various roll periods and roll amplitudes.

![The three main types of bilge keels investigated](image)
A block-structured grid with refinement towards the hull surface is used. The highest grid resolution is concentrated around the bilge keels, because it is important to capture the flow in this area as detailed as possible in order to get satisfying results for the calculated forces. The overall number of cells is limited by the computation time needed, as a large number of variations has to be investigated for the parameter studies.

The rotational axis is fixed amidships in the waterplane level and oriented along the global x-axis. The roll motion of the ship (rotation around x-axis) is implemented by using body forces, which lead to a periodic acceleration of the water in the computational domain.

All borders of the numerical grid must be treated with boundary conditions, which have to be specified. Figure 5 shows which boundary conditions are applied to the model borders. If the ship moves with forward speed the forward and backward ends of the hull section are modeled as Inlet, respectively Outlet -boundaries. Otherwise Symmetry Planes are used on each end. The hull surface and the bilge keels are covered with a Noslip Wall -boundary, which considers that there is no flow through the surface. Additionally this boundary type captures the friction between wall and fluid (no tangential velocity on the surface). The outer border is modeled with a Slip Wall. Due to the roll motion of the model and the resulting circular flow, the water surface and the midship plane are connected as Cyclic Couples with each other.

Turbulence is modeled by a standard $\kappa$-$\epsilon$-model. Due to the limited number of cells, the velocity distribution within the boundary layer near to the hull surface is modeled with a wall function. In order to consider the influence of the foreship, which is not included in the numerical grid, a logarithmic velocity profile, representing the foreship’s boundary layer, is introduced at the inlet boundary.

![Figure 4: Boundary Conditions](image)

**Error Estimation**

Three main types of errors are found:

- **The model error**: This category contains all parts of the error occurring during the modelling process. This contains the introduction of artificial borders like the outer boundary wall, or the idealisation of the hull as parallel midship. Also using a fixed rotational axis instead of a instantaneous centre of rotation is part of the model error. This type of error can not be estimated by mathematical methods.
• The Discretisation Error:

This error occurs if a continuous region, like in this case the water around the ship is divided into discrete volumes. The variables then have to be approximated on the surface of these control volumes. To estimate the discretisation error the Richardson Extrapolation is used. For this method the solution must be known on three systematically refined grids. Then it is possible to extrapolate a grid independent solution. The same method is used to approximate the discretisation error in the time domain.

![Discretisation Error](image)

Figure 5: Development of the Discretisation Error on refined grids

• The Iteration Residuals:

The Equation System resulting after modelling and discretisation has to be solved iterative. The difference between the exact solution of the discrete equation system and the result delivered after a certain number of iterations is called the residual. The solution is called converged if the calculated values do not change anymore, even if the iteration residual is further reduced. This part of the error is easy to control via the convergence criterion.

Parameter Identification and Regression Model

As in this parameter study a lot of different variations have to be compared, it is necessary to have a single value as measurement for the roll damping of each version. The damping work is used for this as an integral value. To obtain the damping work the moments are integrated over a half period. The moments obtained from the simulation contain velocity and acceleration dependent parts. Only the velocity dependent share is relevant for the roll damping. Due to the changing signage the acceleration dependent share of the moment disappears during the integration. Figure 6 shows a time-plot of the momentum (red) and its acceleration and speed dependent shares (blue). These blue curves are the two first order elements of the fourier series of the momentum.

Period and amplitude are the two characterising values for an oscillating motion, they determine the rotational velocity of the body. These two closely connected parameters are investigated together. Using the calculation results, a nonlinear regression based on the least squares method delivers the following formula for the damping work:
Figure 6: Velocity and acceleration dependent shares of the moment produced by the bilge keels

\[ J = c \cdot \frac{\dot{\phi}^2.45}{T^{1.9b}} \]  \hspace{1cm} (1)

All values in this paper have been made dimensionless with the ship’s breadth \( B \), the gravity \( g \) and the density of the water \( \rho \). The correlation coefficient \( c \) is dependent on the bilge keel geometry. In Figure 7 the dots represent the results of the simulation. The plane is obtained from the regression formula (1).

Figure 7: Damping Work in dependency of Amplitude and Period

Figure 8: Scatter plot: Simulation results vs. Regression values

The scatter plot (Figure 8) shows a good correlation between simulation results and values obtained with the regression formula. The average error is about 4 %, whereas the calculation
results for small amplitudes and periods are met worse than in the medium and upper range. Besides the kinematic factors amplitude and period the forces produced by a bilge keel are influenced by its geometry. First of all the geometry is described by the main parameters length and height. The results obtained from the RANS simulations approximately show a linear relationship between length and damping work (see Figure 9). Different lengths with and without forward speed are tested. The gradient is approximately the same for both cases, but the bilge keel with a forward speed component produces a larger damping work than without.

![Figure 9: Damping Work in dependency of the bilge keel length](image)

As for the length, the dependence of the damping work on the height is expected to be linear as well. This proves to be correct for moderate heights, but for large bilge keels an increasing drag coefficient can be observed. Therefore a potential regression function is applied to consider the bilge keel height in the overall regression model:

\[ J_{Sk} = c \cdot h_{Sk}^{1.5} \]  \hspace{1cm} (2)

\( c \) again is the correlation coefficient.

Furthermore the relationships between the damping work on the one hand and the bilge radius, the distance to the rotational axis and the forward speed on the other hand are investigated by regression analysis.

All the relationships are composed to one regression formula containing all relevant parameters. With this formula (Equation 3) it is possible to approximate the damping work for any given parameter configuration within a certain range of values.

\[ J = \left( c_1 + c_2 \cdot v^{1.5} \right) \cdot \left[ \left( \frac{v^{2.45}}{T^{1.90}} \right) \cdot lh^{1.5} \cdot \frac{r^{2.59}}{r_B} \right] \]  \hspace{1cm} (3)

The influence of forward speed is considered as additive term, because it must not be zero for the cases without forward speed. \( r \) is the distance between the bilge keel and the roll axis. \( r_B \)
Figure 10: Damping Work obtained with RANS simulation compared with empirical methods represents the dependency between the damping work and the bilge radius. The other factors consider the geometric dependences and finally the relationship between amplitude and period, which have been discussed above. All parameters must be put into the formula dimensionless. The damping work then is $J = \bar{J} \cdot \rho g B^4$.

Figure 10 compares the results from the RANS simulations with those calculated with the regression formula. The error between the regression formula and the RANS results averages 10%. The deviation from the ideal 45-degrees-line may increase significantly for other hull forms. The model yet has not been validated with other hull forms than those described above.

Blume [1] uses a method for the consideration of the damping forces produced by the bilge keels, which was originally developed by G.E. Gadd [2]. It is based on test series with oscillating plates. Figure 11 shows the results obtained from Gadd’s method compared with the results of the new regression model. Gadd’s method predicts a smaller roll damping than the RANS simulations for small $\hat{\varphi}$-values. Consequently it predicts larger roll damping for large $\hat{\varphi}$-values.
Figure 11: Comparison of Regression Model with Results obtained by G.E. Gadd [2]

References


