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Simulation of progressive flooding in a damaged ship

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Summary. This paper presents an overview of time-domain simulation of progressive flooding in a damaged ship. The principles of the applied pressure-correction method are presented in detail. In addition, some validation results from dedicated model tests are shown. Finally, several practical examples, including statutory calculations of cross-flooding and accumulation of water on deck, are briefly discussed.

Key words: ship stability, progressive flooding, time-domain simulation

Introduction

Progressive flooding to undamaged compartments can result in the capsizing or sinking, even if the ship would have survived the flooding of the damaged compartments. During the intermediate phases large heeling angle or waves can cause flooding to the bulkhead deck and further down to the undamaged compartments through the trunks and staircases. Furthermore, progressive flooding typically includes also leaking and collapsing of non-watertight structures, such as closed doors. Thus the chain of flooded compartments can be long. Time-domain flooding simulation provides a tool for analyzing such critical damage cases and allows better design of subdivision and counter-flooding devices.

Flooding simulation consists of the two main problems: the calculation of flooding inside the ship and the evaluation of the ship motions. Naturally, these are coupled since the floodwater affects the motions and the flooding rates depend on the motions. This paper concentrates on the first issue, i.e. how to solve the distribution of floodwater inside the ship at each time step. Based on this, the corresponding floating position of the ship can be solved.

An implicit method, based on the pressure-correction technique has proven to be an efficient approach for this problem. Its iterative nature ensures numerical stability and accuracy also in very complex flooding cases. This paper describes the principles of this method along with some validation results and practical applications in ship design. The simulation method can deal with air compression inside the flooded rooms, but for the cause of simplicity, the equations are derived only for water flows.

Simulation method

Principles

The problem of progressive flooding in a complex system of rooms and openings in a damaged ship is very similar to the problem of pipe system, presented in Patankar (1980) and Siikonen (2001). The method, described by Siikonen, has been further developed and enhanced to include also air compression and airflows. The details are presented in Ruponen (2007). A brief overview is given in the following. The method is implemented in the NAPA software, utilizing the 3D ship model of the compartments and openings.

The ship model is considered as an unstructured and staggered grid (Figure 1). Each modelled room is used as a single computational cell. However, the flux (water flow) through a cell face is possible only if there is an opening that connects the rooms (cells). The method is based on pressures, and thus the volume of water is presented as a water height from a common reference level. The volumes of water are calculated after each time step from the converged water heights by taking into account the heel and trim angles. The initial values for each iteration round are marked with an asterisk (*) and corrections with an apostrophe (′).

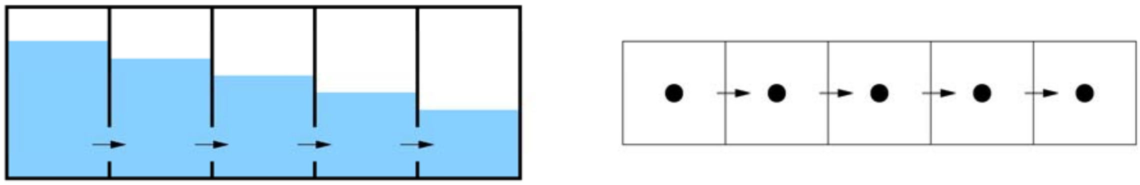

Figure 1. Staggered grid in flooding simulation

Governing equations

At each time step the conservation of mass must be satisfied in each flooded room. The equation of continuity for water is:

$$\int_{\Omega} \frac{\partial \rho}{\partial t} d\Omega + \int_{S} \rho \mathbf{v} \cdot d\mathbf{S} = 0 \tag{1}$$

where ρ is density, **v** is the velocity vector and S is the surface that bounds the control volume Ω. For water flow the density is constant, resulting in:

$$\rho \int_{S} \mathbf{v} \cdot d\mathbf{S} = 0 \tag{2}$$

The mass balance for water, i.e. the residual of the equation of continuity, in the room i can be expressed as:

$$\Delta \dot{m}_{w,i} = \rho S_{fs,i} \frac{dH_{w,i}}{dt} + \rho \sum_{k} Q_{w,k} \tag{3}$$

where S_{fs} is the area of free surface in the compartment (assumed to be constant during the time step), H_w is the water height and Q_w is the volumetric water flow through an opening in the compartment. The index k refers to an opening in the room i.

The velocities in the openings are calculated by applying Bernoulli's equation for a streamline from point A that is in the middle of a flooded room to point B in the opening:

$$\int_A^B \frac{dp}{\rho} + \frac{1}{2}\left(u_B^2 - u_A^2\right) + g\left(h_B - h_A\right) = 0 \tag{4}$$

where p is air pressure, u is flow velocity, g is acceleration due to gravity and h is height from the reference level. The equation applies for inviscid and irrotational flow. For water flow the density is constant and the equation (4) reduces to:

$$p_B - p_A + \frac{1}{2}\rho\left(u_B^2 - u_A^2\right) + \rho g\left(h_B - h_A\right) = 0 \tag{5}$$

It is assumed that the flow velocity is negligible in the center of the room ($u_A = 0$). The pressure losses in the openings are taken into account by applying semi-empirical discharge coefficients (C_d). Consequently, the mass flow through an opening k is:

$$\dot{m}_{w,k} = \rho Q_{w,k} \approx \rho C_{d,k} A_k u_k \tag{6}$$

where $C_{d,k}$ is the discharge coefficient, A_k is the area of the opening and u_k is velocity. Basically equation (6) applies only to very small openings. The implementations of tall openings and subsequent modifications to the pressure-correction equation have been presented in Ruponen (2007).

Bernoulli's equation for water flow through the opening k that connects the compartments i and j (positive flow from i to j) can be written in a form of a pressure loss, Ruponen (2007):

$$\frac{1}{2} K_k' \dot{m}_{w,k} \left|\dot{m}_{w,k}\right| = \left(P_i - P_j\right)_k \tag{7}$$

where the absolute value is used to define the direction of the flow. The dimensional pressure loss coefficient is defined as:

$$K_k' = \frac{1}{\rho C_{d,k}^2 A_k^2} \tag{8}$$

The effective pressure difference for an opening k that connects the compartments i and j is:

$$\left(P_i - P_j\right)_k = \rho g\left[\max\left(H_{w,i} - H_{o,k}, 0\right) - \max\left(H_{w,j} - H_{o,k}, 0\right)\right] \tag{9}$$

where H_w is the height of the water level and H_o is the height of the opening, measured from the same horizontal reference level. The water level has no effect on the flow if it is below the opening.

It is also possible to deal with openings that can be formed when non-watertight structures (e.g. closed doors or down-flooding hatches) collapse under the pressure of the floodwater.

Pressure-correction equation

The linearization of Bernoulli's equation (7) results in:

$$K'_{w,k}\left|\dot{m}^*_{w,k}\right|\dot{m}'_{w,k} = P'_i - P'_j \tag{10}$$

Consequently, by using equations (3) and (9) and the following notation:

$$F(i,k) = \max\left[\text{sign}\left(H_{w,i} - H_{o,k}\right),0\right] \tag{11}$$

the pressure-correction equation can be derived, Ruponen (2006a) and (2007):

$$\sum_k \frac{F(i,k)\cdot H'_{w,i} - F(j,k)\cdot H'_{w,j}}{K'_{w,k}\rho\left|Q^*_{w,k}\right|} + \underline{\underline{C_{\Delta t}\frac{\rho S_{fs,i}}{\Delta t}H'_{w,i}}} = -\Delta\dot{m}^*_{w,i} \tag{12}$$

where Δt is time step (constant) and the mass balance is:

$$\Delta\dot{m}^*_{w,i} = \rho\sum_k Q^*_{w,k} + \underline{\underline{\rho S_{fs,i}\dot{H}^*_{w,i}}} \tag{13}$$

The coefficient $C_{\Delta t}$ depends on the applied difference formula for the time derivative *dH/dt*. Usually a three time level method of the second order is used ($C_{\Delta t}$ = 1.5). The underlined terms in equations (11) and (12) are zero for a room that is filled up with water.

The water heights in the flooded rooms are updated by adding the solved corrections to the initial values:

$$H_{w,i} = H^*_{w,i} + \alpha H'_{w,i} \tag{14}$$

These results are then used as initial values for the next iteration round. Some under-relaxation ($\alpha < 1$) is usually needed. The iteration is continued until all mass balances are small enough. In a matrix form the equation (13) is:

$$\mathbf{A} \bullet \mathbf{H}'_{\mathbf{w}} = -\mathbf{\Delta\dot{m}_w} \tag{15}$$

Obviously, the coefficient matrix **A** is often very large and sparse, especially if the number of flooded rooms is large. Thus, application of a proper sparse matrix storage system will ensure the best possible performance. Also, it should be noted that since the method is iterative, it is not necessary to solve the pressure-corrections with high accuracy. Indeed, iterative methods for solution of a system of linear equations have proven to be superior. The bi-conjugate gradient stabilized method (Bi-CGSTAB), van der Vorst (1992), was successfully used in this study.

The pressure-correction algorithm for one time step is presented in Figure 2. After the iteration has converged, the volumes corresponding to the water heights are solved. Based on this distribution of added weight of floodwater the new floating position of the ship is solved.

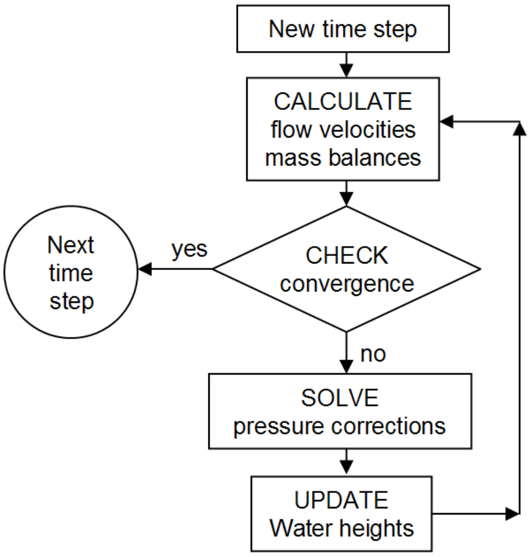

Figure 2. Flow chart for one time step

The same pressure-correction approach can also be applied to air compression in flooded rooms with restricted ventilation level. The air flows in openings and pipes are calculated by using Bernoulli's equation for compressible fluid. The whole flooding process is assumed to be isothermal. A detailed description is given in Ruponen (2006a) and (2007).

Validation

The simulation method has been validated by comparing calculated results to the measurements of various flooding cases in model of a box-shaped barge. The model tests are described in Ruponen (2006b) and a detailed analysis of the validation work is presented in Ruponen (2007).

The model and some examples of the validation results are shown in Figures 3 and 4, respectively. The applied discharge coefficients for the openings were determined experimentally by draining water through the openings. The results clearly indicate that if the input data is correct, the results of the simulation correspond very well with the measurements in the model tests.

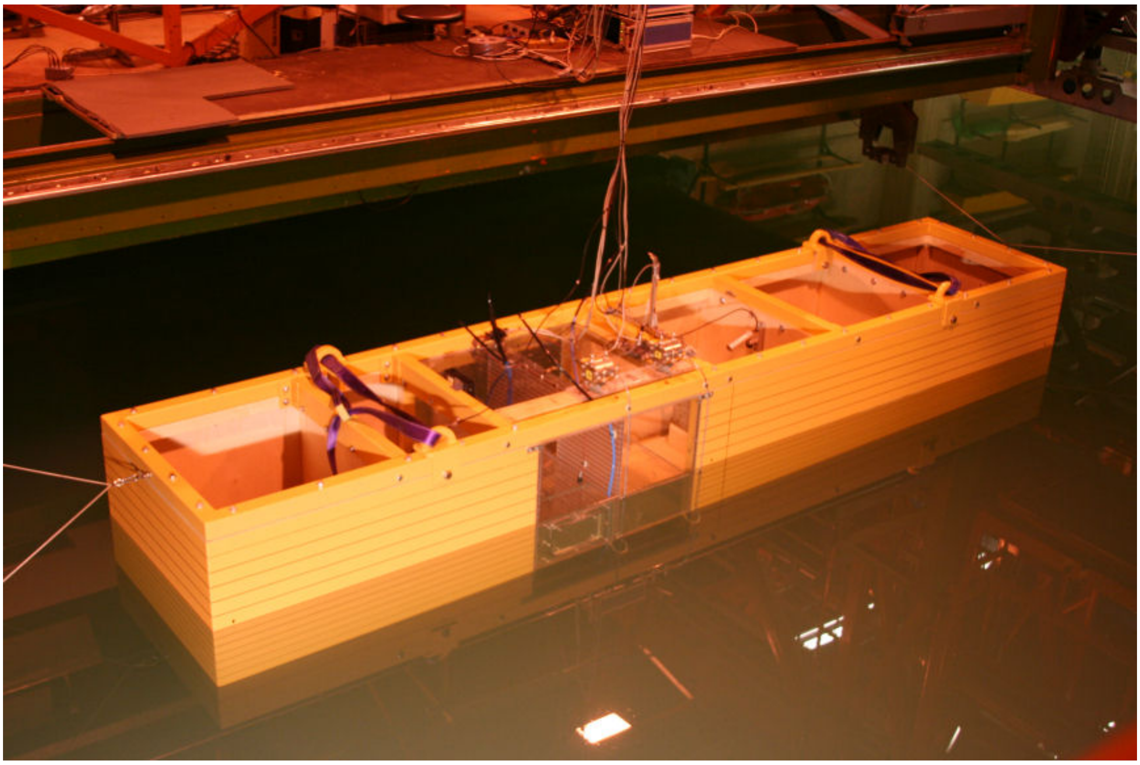

Figure 3. Model of the box-shaped barge

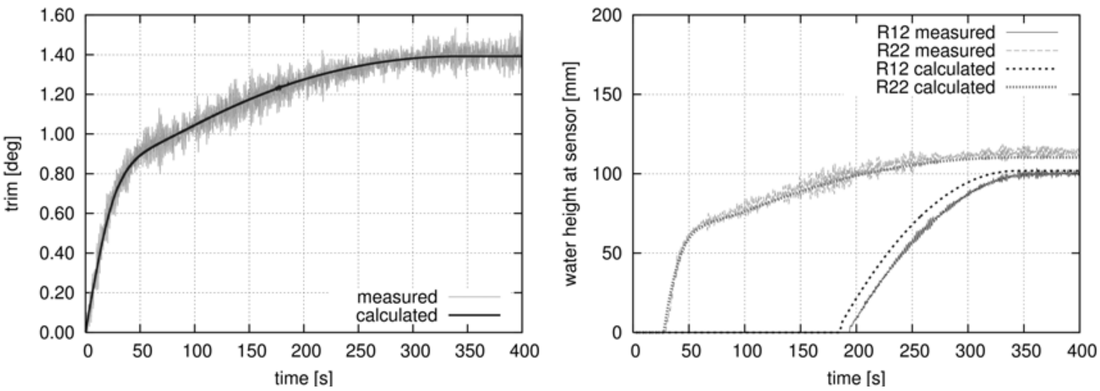

Figure 4. Examples of validation: trim angle and water levels in flooded compartments.

Applications

Cross-flooding

In order to avoid asymmetric damage cases that could result in large heeling angles, cross-flooding between the damaged tank and the equalizing tank is usually arranged through a pipe or a duct. The situation is illustrated in Figure 5. It is assumed that the damage side is flooded instantly (dark shaded areas). The regulations set requirements for the time that is needed to equalize the flooding. There is simplified method for this but time-domain flooding simulation provides a more realistic approach since the real geometry of the flooded rooms and the changes in the floating position are calculated at each time step.

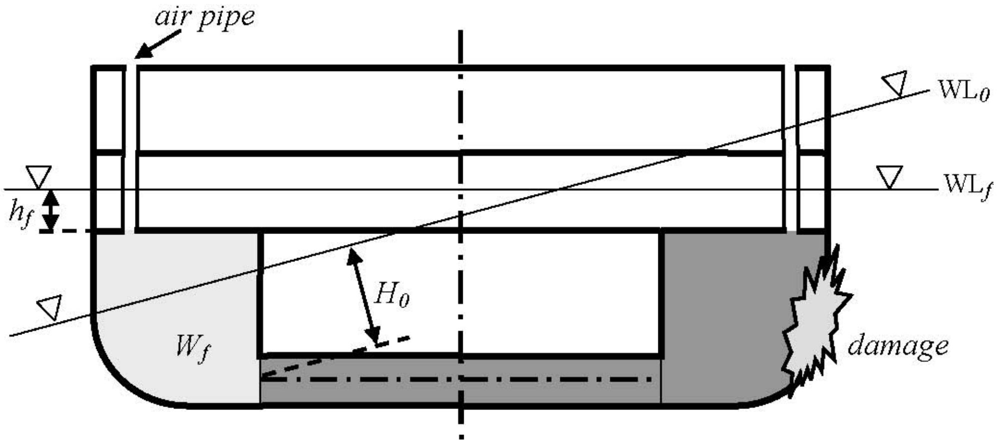

Figure 5. Definitions for cross-flooding; the initial condition is marked with subscript *0* and the final condition with *f*

In order to fill the equalizing tank with water the air must be vented through an air pipe. Large ventilation arrangements are not feasible due to the restrictions in the design of the upper decks (see Figure 5). The major benefit of the pressure-correction method for flooding simulation is the possibility to solve also air compression in tanks and air flows in the ventilation pipes, thus providing a powerful tool for optimising the cross-flooding and air pipe arrangements. A more detailed description and analysis of the results for a case study are presented in Ruponen and Routi (2007).

Progressive flooding

Flooding simulation can also be used to assess time-to-flood or time-to-sink for progressive flooding in a complex system of rooms and openings. Such studies can concentrate on a certain part of the ship, e.g. van't Veer et al. (2004) and Ruponen (2007), but also the whole ship can be modelled so that any arbitrary damage case can be simulated. The latter one can also be implemented in the decision support system onboard the ship. In that case the model cannot be very detailed since the simulation must be fast. An example of very detailed modelling of four watertight compartments on one deck of a passenger ship is presented in Figure 6.

The results are dependent on the applied input data for pressure losses in the openings (discharge coefficients) and critical pressure heads for leaking and collapsing of closed non-watertight openings. This problem was pointed out by van't Veer et al. (2004). Currently, there is both experimental and numerical research, aiming at more reliable assessment of these parameters. The accuracy of time-to-flood calculation can only be as reliable as the applied input data.

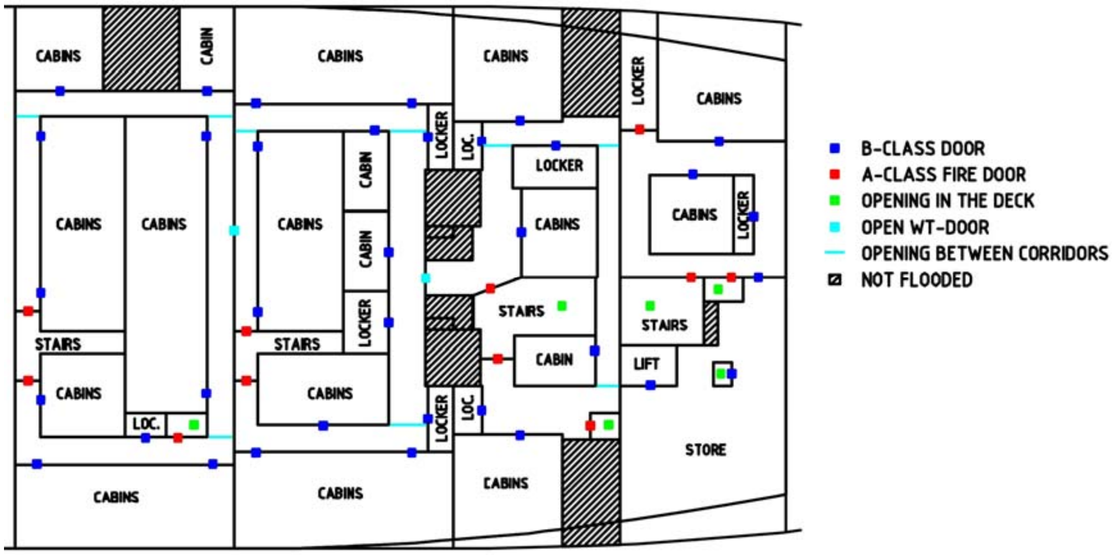

Figure 6. General arrangement of the flooded compartments

Accumulation of water on deck

The tragic accidents of the *Herald of Free Enterprise* in 1987 and the *Estonia* in 1994 show how significant the flooding of the vehicle deck can be. Time-domain simulation is a practical tool for assessing this phenomenon.

The sea level is used as a boundary condition for the flooding problem. Thus the wave elevation can also be taken into account. This is described in detail in Ruponen (2009). One practical application for this feature is the accumulation of water on the vehicle deck of a ro-ro passenger ship after collision damage. Dynamic roll motion with linear damping is solved with a simplified approach that the wave excitation forces are ignored. The other degrees-of-freedom are considered to be quasi-stationary.

The case study ship is presented in Figure 7. The results for heeling angle in two different wave realizations of the same wave spectrum are shown in Figure 8. High waves at a critical moment result in rapid capsize while in the other case the ship survives the relatively large transient heeling. A more comprehensive description of the simulation of accumulation of water on the vehicle deck of a damaged passenger/ro-ro ship is presented in Metsä and Ruponen (2009). The results were also found to be in good correlation with the simple calculation method of the so-called "Stockholm Agreement".

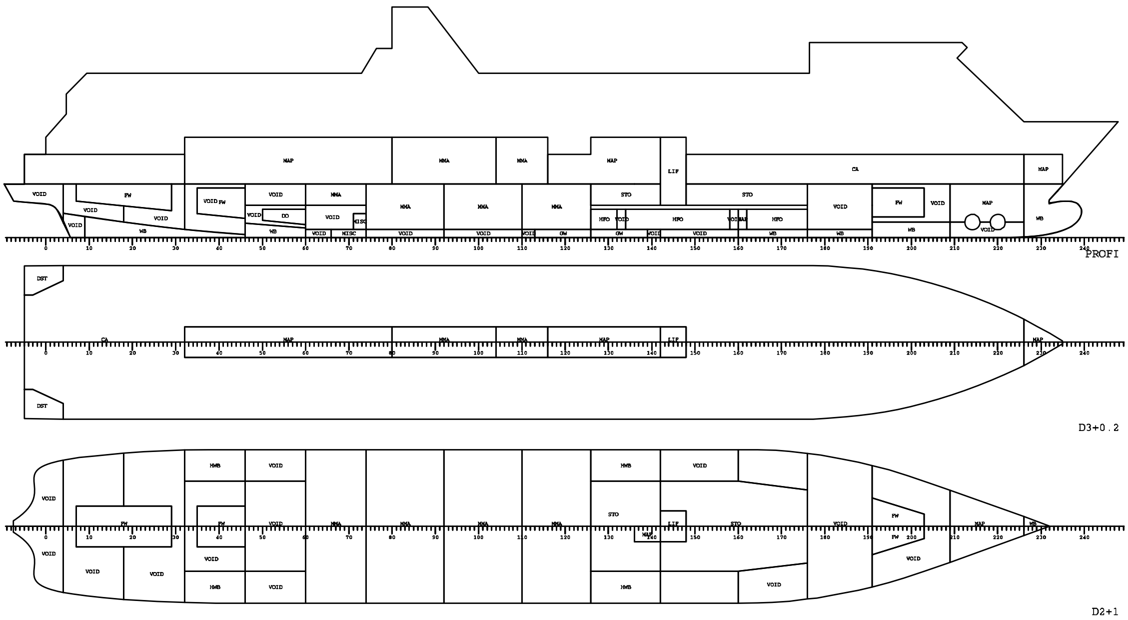

Figure 7. General arrangement of the studied passenger/ro-ro ship

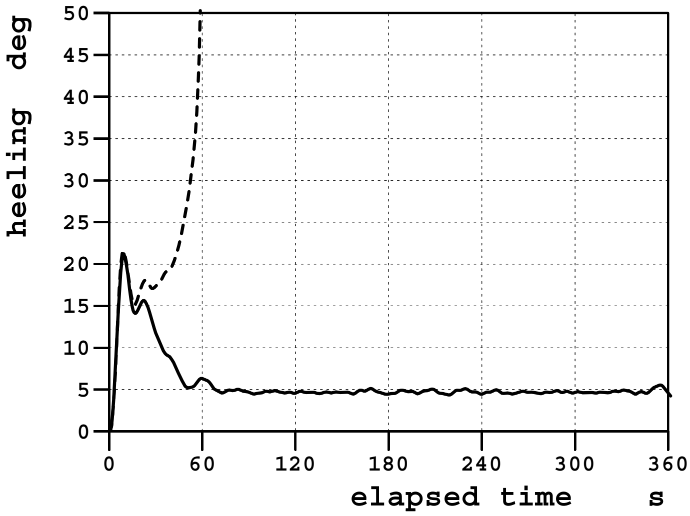

Figure 8. Example of roll motion in two different wave realizations

Conclusions

A time-domain flooding simulation has many applications in ship design. It can be used as an alternative method for the calculation of cross-flooding time in asymmetric damage cases. With calculation of dynamic roll motion and irregular waves, the simulation tool can also be used for assessing the accumulation of water on the vehicle deck of a damaged ro-ro vessel.

The major benefit of the pressure-correction method for flooding simulation is the capability to solve complex progressive flooding cases with a relatively long time step. This can be used in the design of the ship in order to ensure that the ships stays afloat long enough for orderly evacuation and abandonment even in the most severe damage cases. In addition, the simulation can be used onboard the damaged ship for a rough estimation of the available time for evacuation. In this case the calculation is based on the water level measurements inside the flooded compartments.

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