Sideways launching process of a ship using the Arbitrary-Lagrangian-Eulerian approach

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1 Introduction

The launching process of ships is always a critical event during its construction. Especially a sideways launching process can be challenging. Besides high loads on the ship's hull structure at the impact with the water surface, the stability has to be checked carefully to prevent capsizing of the ship. The resulting maximum heeling angle is one of the most critical parameters during such a launching process. If the maximum heeling angle gets too high, the ship can capsize or higher openings (e.g. ventilations) can come in contact with the water resulting in flooding of compartments. Therefore, the movement of the ship and the loads at impact with the water surface have to be assessed as accurately as possible during the design of a ship, if a sideways launching process is planned.
In the past two decades, simulation techniques utilizing fluid-structure interaction (FSI) were continuously advanced to a point, where even complex systems with sophisticated simulation models can be simulated in a feasible timeframe. However, for simulating such a sideways launching process different complex phenomena are to be covered by a suitable FSI-approach. The non-linear response of the ship (complete stability range) is relevant. A free 6-DOF movement of the ship with according equation of motions including added masses and hydrodynamic damping is given. Further, free water surfaces with spray have to be considered. Regarding the ship's hull structure the resulting dynamic loads at the impact of the ship hull with the water surface are important. High stresses at highly loaded areas must be captured correctly for assessing the response of the hull.
Within this paper, the sideways launching process of a special purpose ship is investigated using the Arbitrary-Lagrangian-Eulerian (ALE) approach in LS-DYNA®. The focus lies on the verification of the ALE-approach for this intended use case and the different underlying phenomena. After presenting the material models, a verification based on slamming experiments as well as analytical approaches.
Furthermore, a parametric study regarding the different relevant parameters and settings of the card **`*CONSTRAINED_LAGRANGE_IN_SOLID`** is carried out. Different settings of the FSI-algorithm are varied and the influence regarding the results (movement as wells as loads at impact) are evaluated based on box structure.
Finally, model tests of a sideways launching process have been carried out at a ship model test facility. Besides the movement of the ship, the pressure at different points of the ship hull was measured especially for verification purposes of the ALE-approach. The simulation results are compared and discussed.

2 Material models

Using the ALE-approach the media surrounding the ship's hull structure are modelled with equation of states (EOS). Air is modelled according to the ideal gas law. For this purpose the following EOS is used, which is also known as the gamma-law EOS [1]:

$$p = (1+\mu)\cdot(\kappa-1)\cdot E_i \quad \text{[Pa]} \tag{1}$$

In equation (1) the pressure p is described as a function of the internal energy E_i of the gas. The expression κ is the specific heat ratio of the gas. The term μ in equation (1) is defined as follows:

$$\mu = \frac{\rho}{\rho_0} - 1 \quad \text{[-]} \tag{2}$$

The expression ρ / ρ_0 in equation (2) is the ratio of the current density ρ to the reference density ρ_0. Using the gamma-law EOS it is possible, to describe isentropic processes. Compression and expansion of air can be covered using this EOS, which are needed to account for the free surface of the water. The gamma-law EOS is modelled in LS-DYNA® by using ***MAT_NULL** together with a general polynomial EOS (***EOS_LINEAR_POLYNOMIAL**), which is defined as follows [2]:

$$p = C_0 + C_1 \cdot \mu + C_2 \cdot \mu^2 + C_3 \cdot \mu^3 + (C_4 + C_5 \cdot \mu + C_6 \cdot \mu^2) \cdot E_i \quad \text{[Pa]} \tag{3}$$

An ideal gas according to gamma-law EOS can be modelled by setting the constants C_i in equation (3) as follows [2]:

$$C_0 = C_1 = C_2 = C_3 = C_6 = 0 \quad \text{[-]} \tag{4}$$

$$C_4 = C_5 = \kappa - 1 \quad \text{[-]} \tag{5}$$

The material parameters of air used for ***MAT_NULL** as well as the gamma-law EOS (***EOS_LINEAR_POLYNOMIAL**) are given in Table 1:.
The water is modelled using the Mie-Grüneisen EOS (***EOS_GRUNEISEN**) together with ***MAT_NULL** in LS-DYNA®. The Mie-Grüneisen EOS has been originally derived for calculating shock waves in solids at high pressures and is used often for the assessment of seismologic phenomena [3]. Due to the high bulk modulus of water, it is possible to use the Mie-Grüneisen EOS to describe fluids like water under impact loads. Examples for this approach are given by Steinberg [4], Shin et al. [5], Hamashima et al. [6] among others. The authors of this paper have been successfully utilizing this EOS to describe water in the context of simulating underwater explosions for the design of naval ships using the ALE-approach in LS-DYNA® [7]. The Mie-Grüneisen EOS can be formulated as follows [2]:

$$p = \frac{\rho_0 \cdot c_0^2 \cdot \mu}{(1 - S_{MG} \cdot \mu)^2} \cdot \left(1 - \frac{\Gamma \cdot \mu}{2}\right) + \Gamma \cdot E_i \quad \text{[Pa]} \tag{6}$$

In EOS (6) the term c_0 is the speed of sound at a reference state, Γ is the so-called Grüneisen parameter or Grüneisen gamma and S_{MG} is a material coefficient. EOS (6) is only valid for compression. To account for expansion and tension waves, a second EOS has to be introduced. For this purpose, the following EOS can be used [2, 3]:

$$p = \rho_0 \cdot c_0^2 \cdot \mu + \Gamma \cdot \mathrm{E_i} \quad \text{[Pa]} \tag{7}$$

The material coefficients for the Mie-Grüneisen EOS (7) used for water in this paper are obtained from [6]. These values are given in Table 2:. These values have been slightly modified to account for conditions during experiments / model tests (e.g. adequate density). In addition, to account for cavitation of the water a pressure cutoff p_{cutoff} is defined in ***MAT_NULL** at the value of the vapor pressure of water for 20°C. Therefore, the water is allowed to cavitate numerically.

term	unit	value	reference
ρ_0	[kg/m³]	1.20	[1]
κ	[-]	1.40	[1]

Table 1: Material parameters used for air ***(*MAT_NULL + *EOS_LINEAR_POLYNOMIAL)***

term	unit	value	reference
ρ_0	[kg/m³]	998	[6]
p_{cutoff}	[Pa]	2337	[1]
c_0	[m/s]	1480	[6]
S_{MG}	[-]	1.79	[6]
Γ	[-]	1.65	[6]

Table 2: Material parameters used for water ***(*MAT_NULL + *EOS_GRUNEISEN)***

All material models for the structures investigated within this paper are modelled with according elastic material models (***MAT_ELASTIC**). Non-linearities or plastic material behavior are not of interest during the different verifications within this paper.

3 Verification of underlying physical phenomena

For the simulation of the sideways launching process two main aspects are important: the stability / motion of the ship and the resulting loads on the ship's hull structure. Especially the loads at contact with the water surface are to be checked carefully. Therefore, relevant physical phenomena of these two aspects are investigated in advance before simulating the sideways launching process with the ALE-approach.

3.1 Loads on ship's hull structure

During the sideways launching process of a ship two different kind of load mechanism will act upon the ship's hull structure:
1. pressure peak / impact loads at first contact of the ship's hull with the water surface
2. deceleration of the ship due to resistance forces resulting from the water

The fist load mechanism – pressure peaks at impact with the water surface – is comparable to impact loads, when a ship's bow is hitting the water during rough seas. This process is called slamming in naval architecture. In literature a lot of research regarding this topic can be found. In the past decades a lot of experiments / model test were carried out, where different aspects of this topic have been investigated in detail.
Due to the similarity and good availability of sufficient data, a verification of the impact loads during the sideways launching process will be carried out based on slamming experiments. For this purpose the experiments conducted by Javaherian et al. [8] are used. In contrast to many other slamming experiments, Javaherian et al. [8] used a wedge with flexible bottom plating constructed with aluminum. The flexible bottom plating does resemble a typical ship structure (plate-stiffener construction) more realistically than a rigid wedge. Details regarding the wedge can be found in Table 3:.
During slamming experiments conducted by Javaherian et al. [8] the following data were measured among others, which are used for verification purposes within this paper:
- mean vertical velocity of the wedge
- deformation of the bottom plating
- pressure resulting on the bottom plating at seven different positions

Details regarding the conducted experiments as well as the measurement equipment used can be obtained from [8]. A FE-model in LS-DYNA® is set up in order to simulate the conducted slamming experiments. The FE-model is shown be seen in Fig.1: a). A quarter model of the wedge is used taking advantage of the symmetric nature of this problem. The wedge is modelled with shell elements with ELFORM=2 (Belytschko-Tsay element formulation). The surrounding media of the wedge (air and water) are modelled using 3D-ALE elements with ELFORM=11 (1 point ALE multi-material element). An average element length of 10mm is chosen for shell elements as well as for the ALE-elements. The simulation starts right before the impact of the wedge with the water surface. The velocity at impact according to Table 3: is set using ***INITIAL_VELOCITY_GENERATION**.
The resulting pressure using the ALE-approach is read out using the function ***DATABASE_TRACER_GENERATE**. At each position of the pressure sensors as used by Javaherian et al. [8] tracer points are generated in 0.5ms intervals (20kHz) following the trajectory of the wedge. The coupling between the wedge and the water is done by ***CONSTRAINED_LAGRANGE_IN_SOLID**. The settings used for this card are given in Table 4:.
In Fig.1: b) to d) the resulting pressure-time signals using the ALE-approach are compared to experimental results by Javaherian et al. [8] for three different points as indicated in Fig.1: a). Due to the fluctuating nature of the pressure time-signals, the curves resulting from the ALE-approach as plotted in Fig.1: b) to d) are lowpass-filtered using a cutoff frequency of 400Hz.
As Fig.1: b) to d) shows, the pressure-time signals resulting from the ALE-approach show good agreement with the experimental results by Javaherian et al. [8]. The biggest peak resulting at the initial contact (Point P1; see Fig.1: b)) can be covered well using the ALE-approach. The loads resulting at the points P4 and P7, who will be in contact later with the water, are a bit more smoothed than the experimental results by Javaherian et al. [8].

parameter	unit	Value
length	[mm]	635.0
width	[mm]	572.7
height	[mm]	408.9
weight	[kg]	40.6
deadrise angle	[°]	20.0
thickness of bottom plating	[mm]	3.17
drop height	[mm]	254.0
velocity at impact	[m/s]	2.23

Table 3: Parameters of the wedge investigated by Javaherian et al. [8]

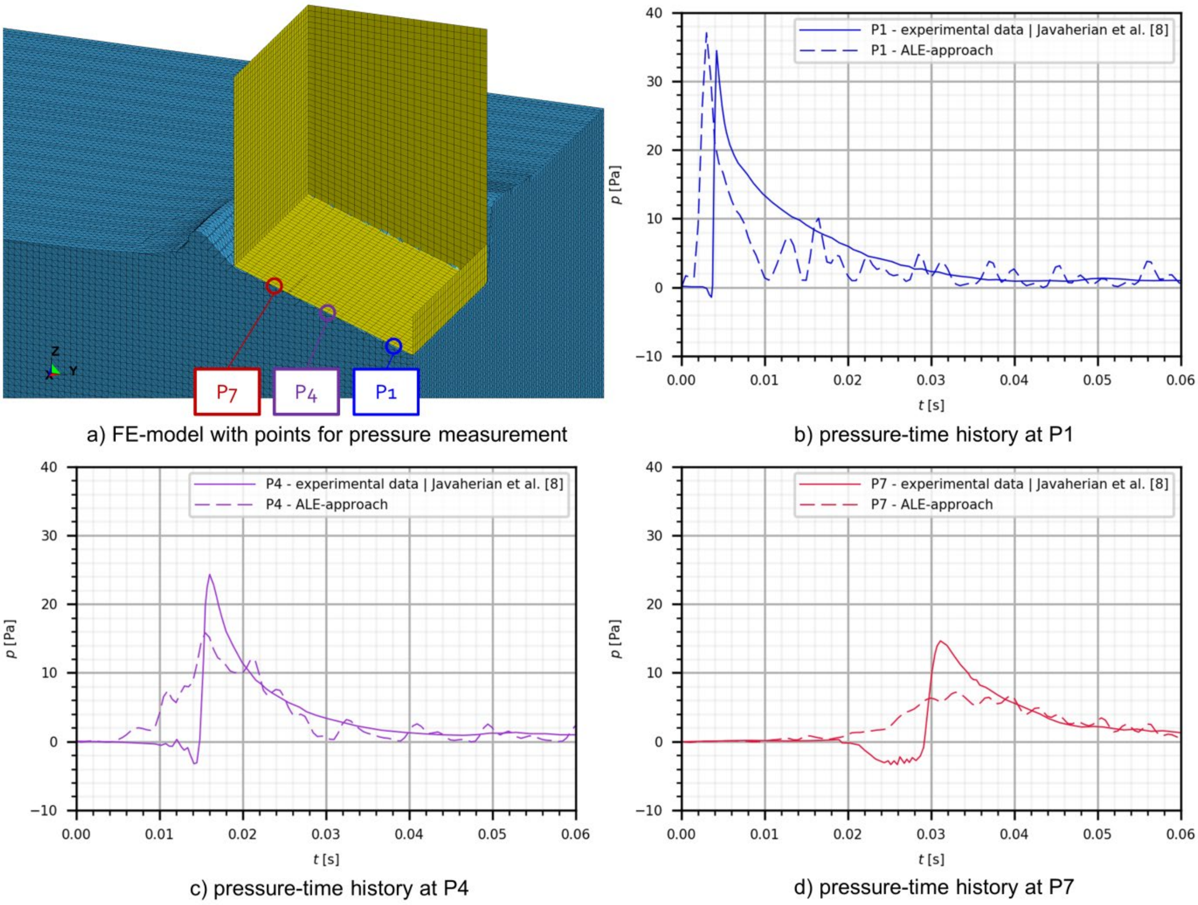
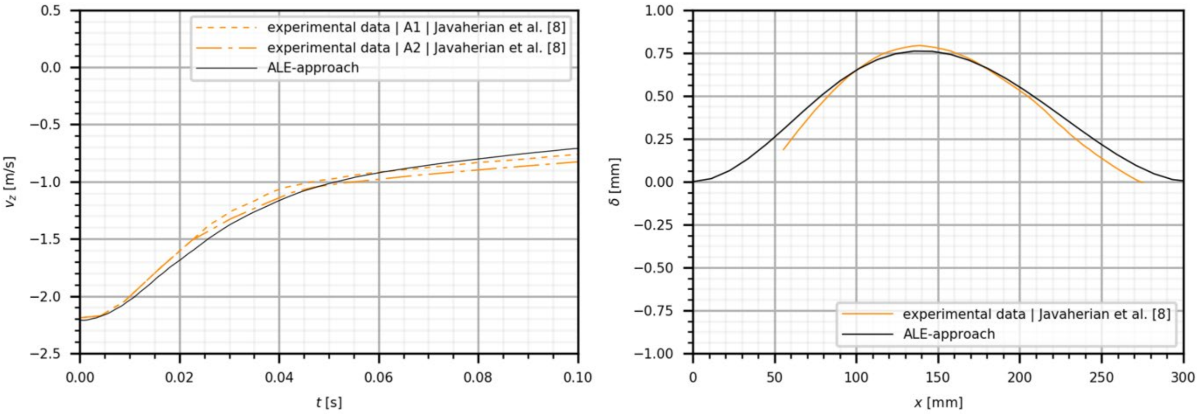


Fig.1: Pressure-time histories of slamming experiments conducted by Javaherian et al. [8]

However, if the impulse (integration of pressure-time signal) is compared, the results for P4 and P7 do match quite well. Therefore, comparable loads for the first load mechanism (pressure peaks / impulses at impact with water surfaces) between experimental results by Javaherian et al. [8] and the ALE-approach can be observed.

The second load mechanism is loads resulting from the deceleration of the ship's hull structure due to resistance forces from the water. These loads can be verified by the experiments conducted by Javaherian et al. [8], too. For this purpose the kinematics of the wedge is investigated. In Fig.2: a) the vertical velocity of the wedge during its immersion is shown. As Fig.2: a) indicates the results of the ALE-approach show very good agreement with the experimental results. The same is true for the resulting deformation of the bottom plating of the wedge, as illustrated in Fig.2: b). The deformation resulting from the loads transferred via **`*CONSTRAINED_LAGRANGE_IN_SOLID`** does fit very well to the experimental results obtained with optical measurement systems.



a) vertical velocity of wedge b) deformation of bottom plating of wedge at t=17ms

Fig.2: Kinematics of a wedge during slamming experiments conducted by Javaherian et al. [8]

3.2 Ship motion

For assessing the movement of the ship during the sideways launching process correctly, two main aspects are to be covered by the ALE-approach:

- external loads acting upon the ship's hull structure (see section 3.1)
- the ship's inertia including the inertia effects of the surrounding water

For assessing the ship motion correctly using the ALE-approach, the influence of the surrounding water on the dynamic behavior of the ship has to be covered. The inertia forces resulting on a submerged structure can be described using the approach of added masses. Added masses are virtual masses, which account for the forces acting upon a submerged structure, if the structure is moved through the surrounding water. The total inertia forces $F_{submerged}$ acting upon such a submerged structure can be calculated as follows:

$$F_{submerged} = (m_{structure} + m_{added}) \cdot a \quad [\text{N}] \tag{8}$$

The term $m_{structure}$ in equation (8) is the mass of the body, whereas a is the acceleration acting upon the submerged body. The added mass m_{added} around a cylinder can be calculated analytically based on assumptions of the potential flow theory. One example for such an analytical solution is given e.g. by Wendel [9].

For ship-like contours one common approach is using so-called Lewis-frames as describe e.g. by Korotkin [10]. Lewis used the method of conformal mapping, where different geometries resembling the contour of ship frames are mapped onto a unit circle by choosing appropriate mapping functions. According to Korotkin [10] the added mass m_{added} of a different ship frames can be calculated by using this approach as follows:

$$m_{added} = 2 \cdot \rho_{fluid} \cdot \frac{1}{\pi} \cdot T_{frame} \cdot k_{Lewis} \quad [\text{kg}] \tag{9}$$

The term T_{frame} in equation (9) is the draught of the corresponding ship frame. The coefficient k_{Lewis} is depending on the shape described by the parameter β, the draught T_{frame} as well as the breadth B_{frame} of the corresponding Lewis-frame. Values of k_{Lewis} for Lewis-frames with different values of β and B_{frame} / $2T_{frame}$ can be found in [10]. The added masses according to equation (9) are valid for the horizontal movement of the frame section. For the sideways launching movement this added mass is relevant for the sliding of the ship's hull into the water.

The approach based on Lewis-frames to verify, if added masses can be covered using the ALE-approach. For this purpose four different frame geometries are investigated, which are representative for the different cross sections of ship hull (aft ship, amidships and fore ship). The different geometries are plotted in Fig.3:.

For all frames the breadth B_{frame} = 2m and the draught T_{frame} = 1m resulting in an aspect ratio B_{frame} / $2T_{frame}$ = 1. The frames are modelled in LS-DYNA® – in accordance to theory of Lewis-frames – in a 2D-plane. For this purpose 2D-ALE elements with ELFORM = 13 (plane strain element formulation) are used. An element size of 40x40mm is chosen. A domain size of 10x10m is chosen for the ALE-elements. The frame contours are modelled as hollow bodies using beam elements with ELFORM = 7 (2D plane strain shell elements) with an average element size of 40mm, too. This element size would roughly correspond to an element size of about 300x300mm to 400x400m if scaled up to the ship hull investigated in section 5 of this paper. The inside of the frame contour is filled with air, whereas the outside consists of water. The corresponding fluid domain is generated using ***INITIAL_VOLUME_FRACTION_GEOMETRY**. By modelling a hollow body, $m_{structure} << m_{added}$ is ensured during simulations.

The coupling of the ALE-elements and the structure of the ship frames is again done by ***CONSTRAINED_LAGRANGE_IN_SOLID**. The settings used for this card are given in Table 4:. Via ***BOUNDARY_PRESCRIBED_MOTION_SET** a defined movement of the frame structure is applied as a time-acceleration-function. The reaction forces needed for the given movement are read out using ***DATABASE_BNDOUT**.

A comparison between the resulting reaction forces with the ALE-approach and the analytical solution using equation (8) and (9) is given in Fig.3:. As Fig.3: shows, it is possible to account for added masses around a ship's hull using the ALE-approach. Only minor differences between the analytical solution and the results of the ALE-approach can be observed. For all investigated frame contours, the ALE-approach does slightly overestimate the added masses compared to Lewis-frames. A difference of about 10% can be observed. However, these minor discrepancies should not alter the ship motion during the sideways launching process significantly.

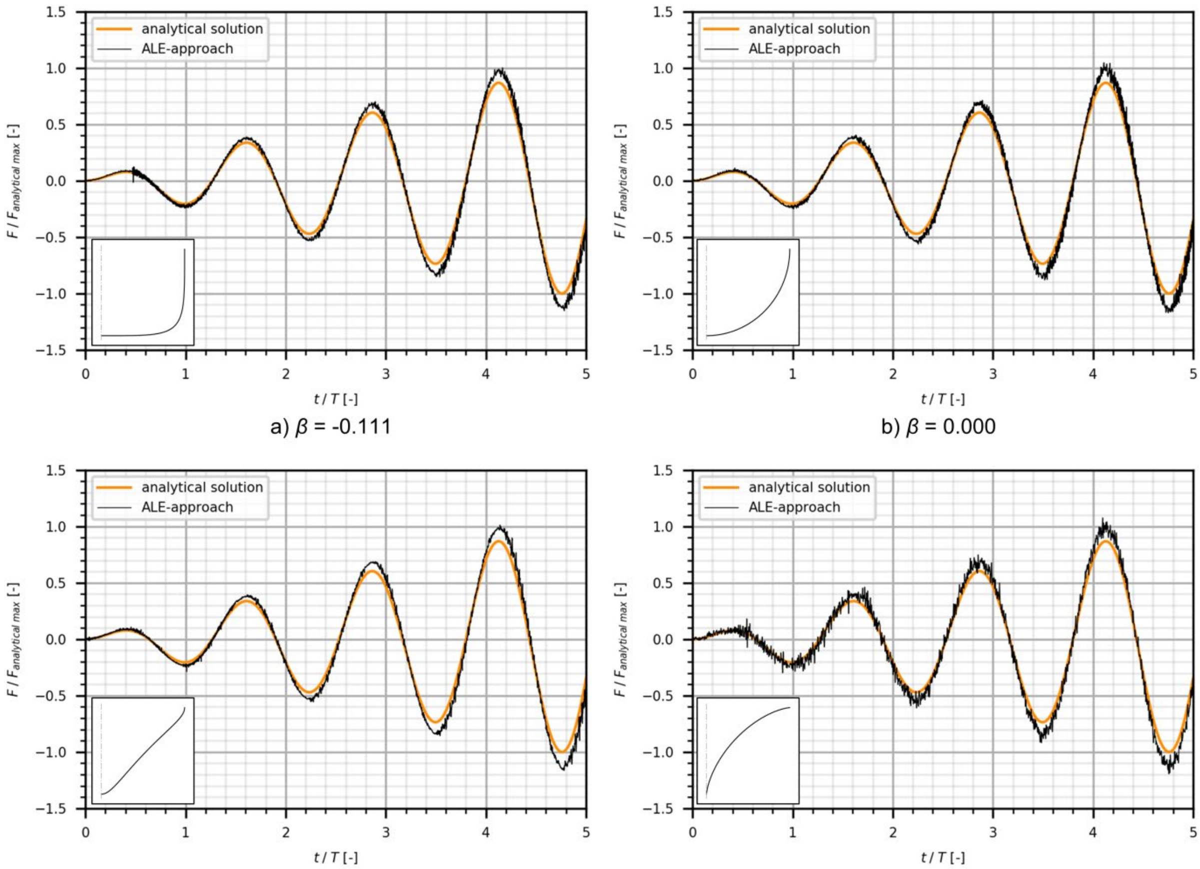


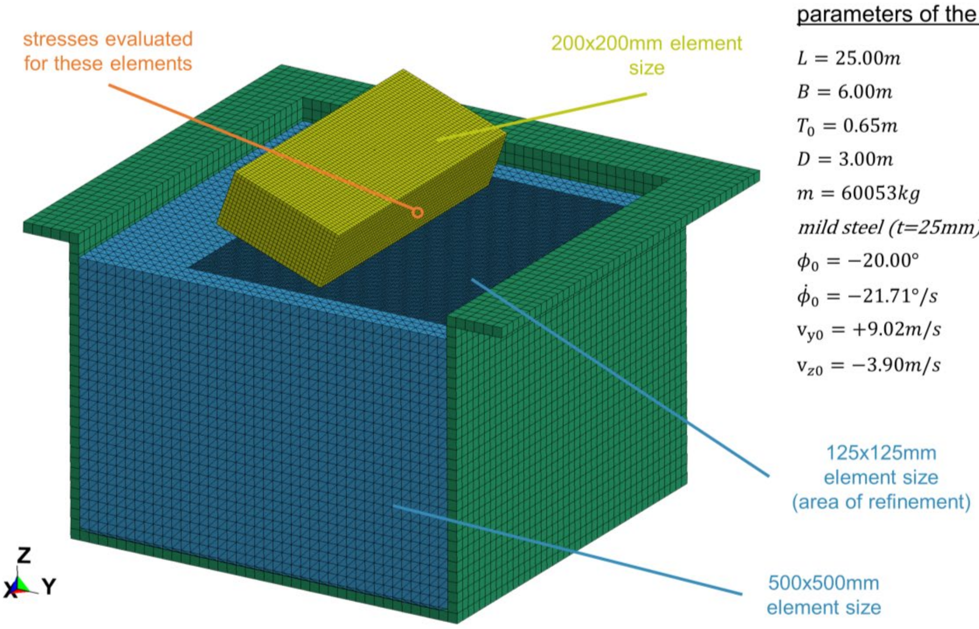
Fig.3: Added masses of different Lewis-frame geometries

4 Investigation of relevant parameters for the ALE-approach

After successfully verifying the underlying relevant physical phenomena in section 3 of this paper, a closer look is taken on the influence of different settings and regarding relevant results for the use case of a sideways launching process. Due to the size of the simulation model as presented in section 5.1 of this paper, a parametric study regarding different settings relevant for the ALE-approach is not feasible. Therefore, a smaller FE-model is set up resembling the conditions given at a sideways launching process. This FE-model is shown in Fig.4:. This model consists of a box structure and a small fluid domain resembling a dock of a shipyard. The ALE-domain has a size of 22.50m x 25.00m x 19.00m. The box structure is modelled with shell elements with ELFORM=2 (Belytschko-Tsay element formulation). The surrounding media of the wedge (air and water) are modelled using 3D-ALE elements with ELFORM=11 (1 point ALE multi-material element). The element sizes are given in Fig.4:. The coupling of the ALE-elements and box structure as well as the pier (green part in Fig.4:) is again done by **`*CONSTRAINED_LAGRANGE_IN_SOLID`**. More details – including the chosen initial conditions – are given in Fig.4:.
Different settings are varied and the influence on the motion of the box structure as well as the resulting loads inside the box structure is assessed. The following parameters are investigated:

- **`*CONSTRAINED_LAGRANGE_IN_SOLID`**
  - DIREC: direction of coupling (1: tension and compression | 2: compression only)
  - PFAC: scaling factor of stiffness for coupling algorithm
  - DAMP: scaling factor for damping forces of coupling algorithm
  - NQUAD: number of coupling points across each coupled Lagrangian element
- **`*DAMPING_PART_MASS`**
  - variation of scaling factor SF
- element size of ALE-elements
  - element size is controlled by NLVL inside **`*CONTROL_REFINE_ALE`**
- ALE advection method by METH in **`*CONTROL_ALE`** (1: Donor cell with Half Index Shift (HIS) | 2: Van Leer with HIS, second order accurate)
- Number of cycles between ALE advection by NADV in **`*CONTROL_ALE`**

Details regarding all these parameters con be found in the LS-DYNA Theory Manual [2]. Each of these parameters is varied one at time starting from the "baseline". The settings for the baseline are derived based on experience with the simulation of underwater explosion for the design of naval ships [7].
During the sideways launching of a ship, different aspects of the ship motion are of interest.



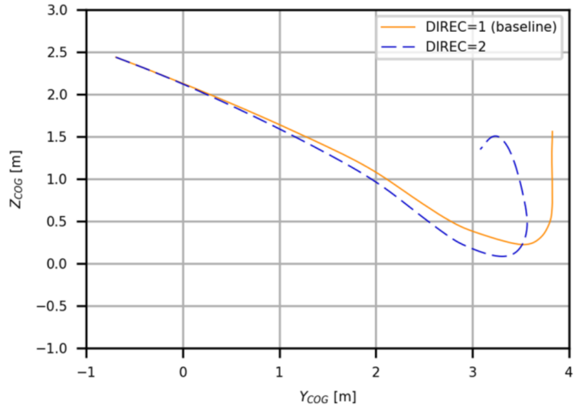
parameters of the box structure:

$L = 25.00m$
$B = 6.00m$
$T_0 = 0.65m$
$D = 3.00m$
$m = 60053kg$
mild steel (t=25mm)
$\phi_0 = -20.00°$
$\dot{\phi}_0 = -21.71°/s$
$v_{y0} = +9.02m/s$
$v_{z0} = -3.90m/s$

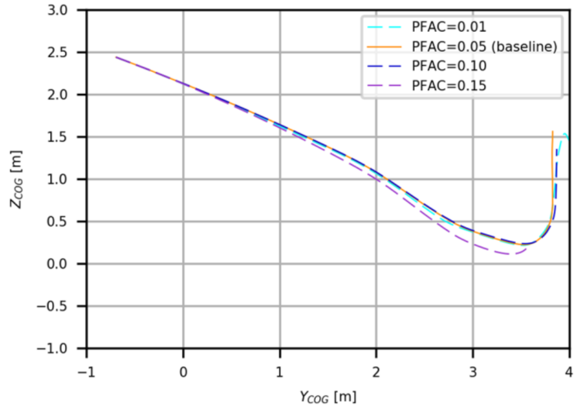
Fig.4: FE-model of a box structure impacting the water surface used for investigation of relevant parameters for ALE-approach

In case of this parametric study, the following different aspects of the motion relevant for a sideways launching process are checked:
- trajectory of the box structure (center of gravity = reference point)
- maximum heeling angle $\varphi_{X\,max}$
- time at which the maximum heeling angle $\varphi_{X\,max}$ occurs $T(\varphi=\varphi_{X\,max})$
- time needed of box structure to upright itself $T(\varphi=0)$
- point of / position at deepest immersion of the box structure

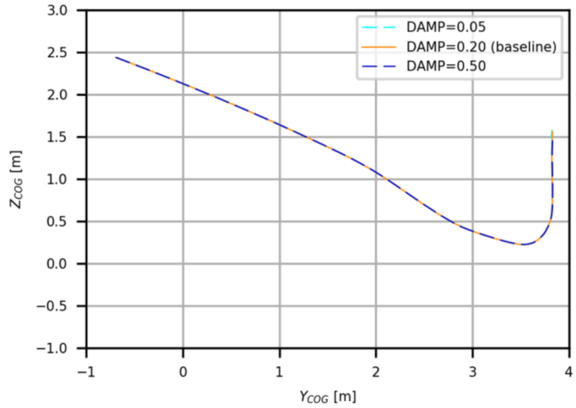
To keep the content of this paper at a feasible level, only the two most important aspects of the box structures motion are presented and discussed within this paper: the trajectory and the maximum heeling angle. In case of sideways launching process, the maximum heeling angle is the most important parameter. If the heeling angle gets too high, the ship may not be able to upright itself and will capsize. Or openings in higher decks (e.g. for ventilation) could come in contact with water resulting in flooded compartments of the ship. Both are worst cases to be avoided during the sideways launching process. The trajectory for each variation simulated is shown in Fig.5:, the heeling angle as function of time is plotted in Fig.6:. In addition, the maximum heeling angle $\varphi_{X\,max}$ is compared in Fig.7: as a bar chart for each variation.
Regarding the box structures motion, the different parameters can influence the behavior in two different ways. On one hand, the fluid can be made stiffer. This can be seen in case of a coarser element size of the ALE-elements (NLVL=1) or a higher factor for the stiffness inside the coupling algorithm (PFAC=0.15). The box structure is decelerated more quickly and does not travel as far in a transverse direction. In addition, this deceleration will increase the maximum heeling of the box structure due to higher resistance of the fluid.
On the other hand, the fluid can be made less stiff resulting in a more dynamic behavior of the box structure. This can be done by setting DIREC=2 (compression only) in ***CONSTRAINED_LAGRANGE_IN_SOLID**. The box structure is not decelerated as fast and will immerse deeper (compare Fig.5: a)). The heeling is higher too, but in contrast to the stiffer fluid the box structure will upright itself more quickly and dynamically (compare Fig.6: a).
Besides the above mentioned cases, other parameters do not significantly influence the motion of the box structure. This is especially true for the maximum heeling angle, as Fig.8: proofs.
Besides the motion of the box structure, the influence of the investigated parameters on the resulting loads on the box structure is checked. For this purpose the resulting pressure is checked at different positions of the box structure as well as the resulting equivalent von-Mises stresses of chosen elements (see Fig.4:). The resulting stresses inside the center of the side plating of the box structure are shown in Fig.7:. Due to the fluctuating nature of the resulting pressure-time signal a comparison is quite difficult. No clear conclusions could be obtained by this approach. Therefore, only the resulting stresses are presented and discussed within this paper.
As Fig.7: indicates, the direction of coupling DIREC as well the mesh size of the ALE-elements (NLVL) are the most relevant parameters for the resulting stresses inside the box structure. DIREC=2 does result in slightly higher stress levels, while simultaneously showing a smoother signal with less fluctuations underlying the hypothesis of a less stiff fluid (compare Fig.7: a)). As Fig.7: c) shows, the mesh size of the ALE-elements is extremely important if stresses inside a structure are of interest. Using NLVL=1 (coarser ALE-mesh than baseline) the fluctuations of the stresses are extremely high. The resulting stresses a completely different than all other variations. Therefore, a sufficient minimum element size is needed if stresses are of interest / to be evaluated. When using a finer ALE-mesh (NLVL=3) than the baseline, the stresses are smoother and seem to be filtered. If the frequency of the fluctuations are compared, it can be seen that the frequency of NLVL=3 is about 2x the frequency of NLVL=2. The frequency of fluctuations seems to be in correlation with the encounter frequency between the Lagrangian-elements of the box structure and ALE-elements. This could indicate that the fluctuations as seen in Fig.7: could be numerically induced by the contact algorithm and are not of any physical interest. More investigations regarding this phenomenon seem advisable.
All other parameter do not majorly influence the stresses observed in the side plating of the box structure. Only the fluctuations are altered slightly by the different parameters. The stress levels on a global scale are not influenced.
As these investigations are showing, the parameters with the most influence regarding the use case of sideways launching of a ship are the element size of the ALE-elements as well as the direction of coupling (DIREC in ***CONSTRAINED_LAGRANGE_IN_SOLID**). The influence of other parameters is negligible emphasizing the robustness of the ALE-approach.



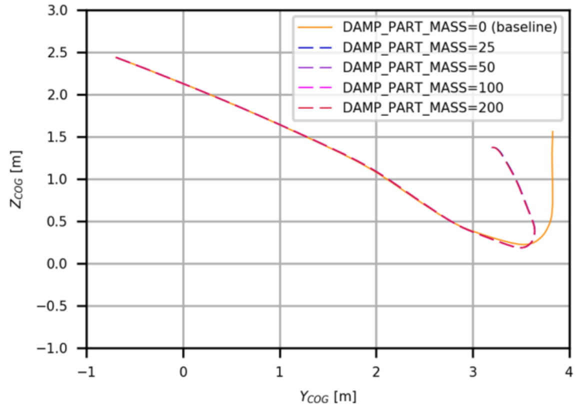
a) DIREC



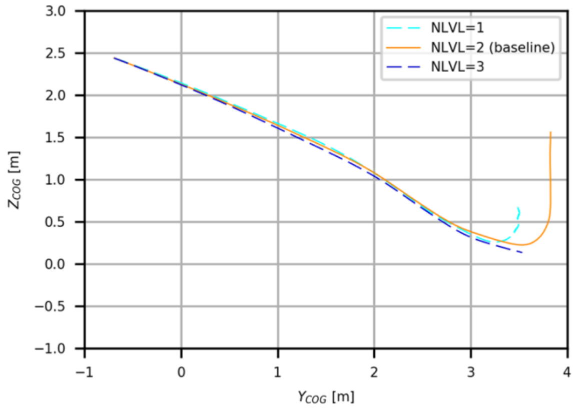
b) PFAC



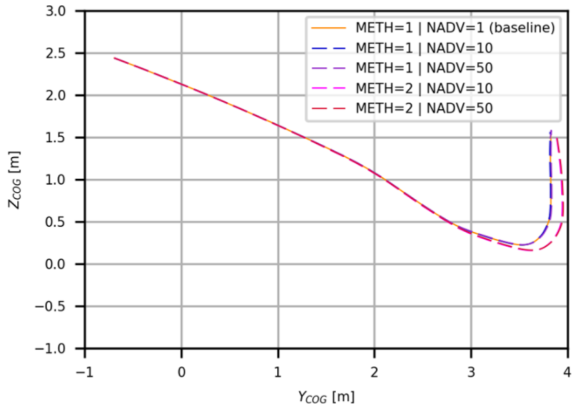
c) DAMP



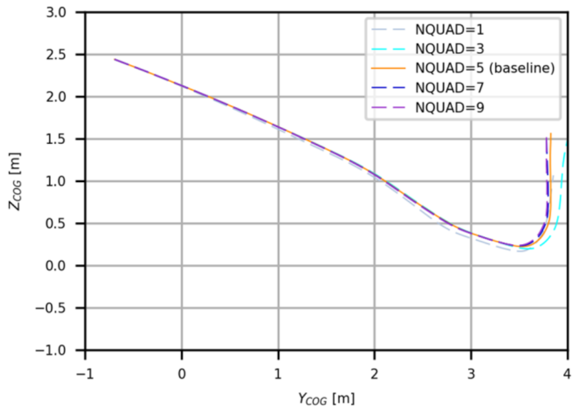
d) *DAMPING_PART_MASS



e) NLVL (mesh size)



f) ALE advection method



g) NQUAD

Fig.5: Influence of different parameters on the trajectory of the box structure

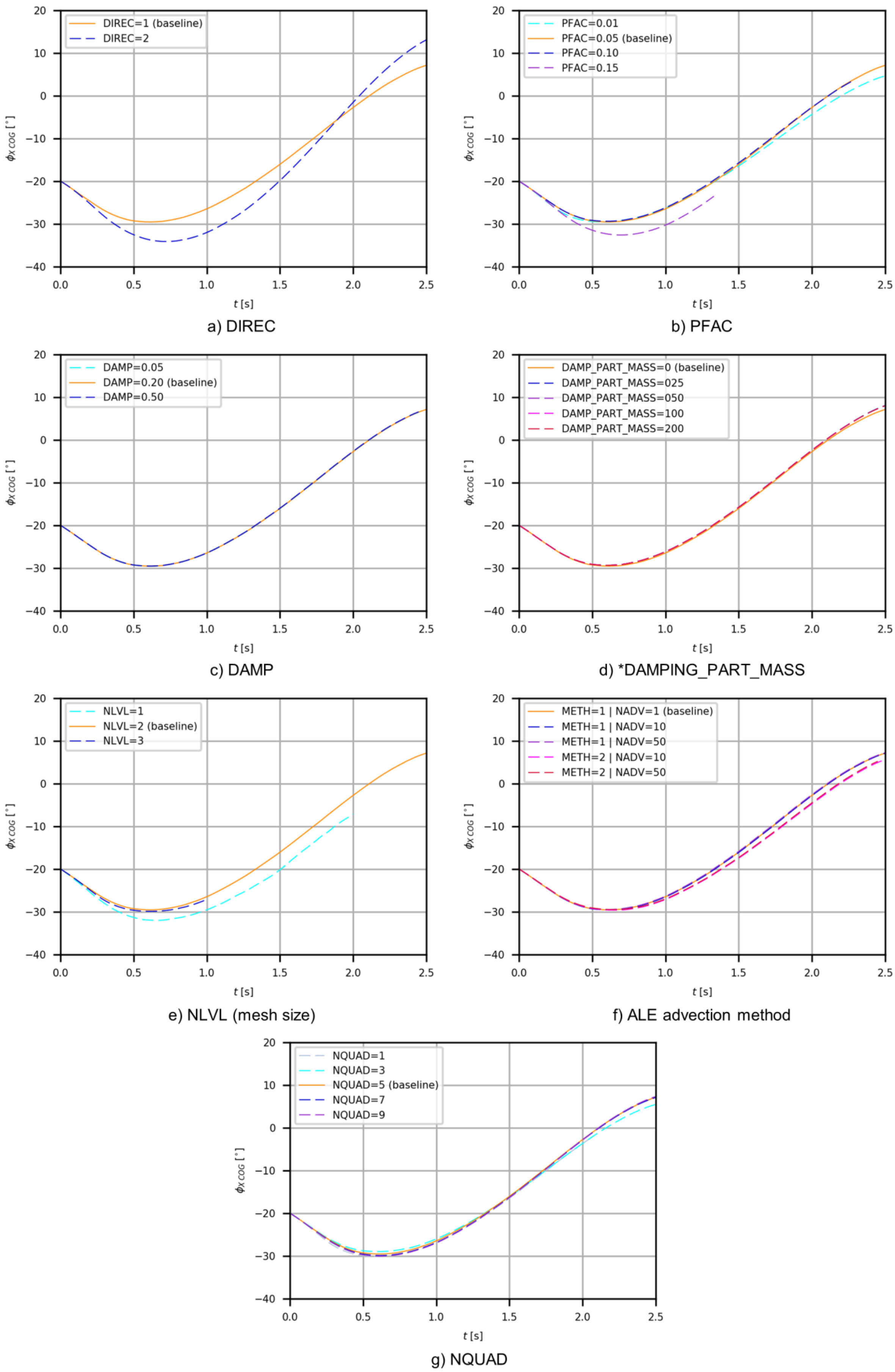
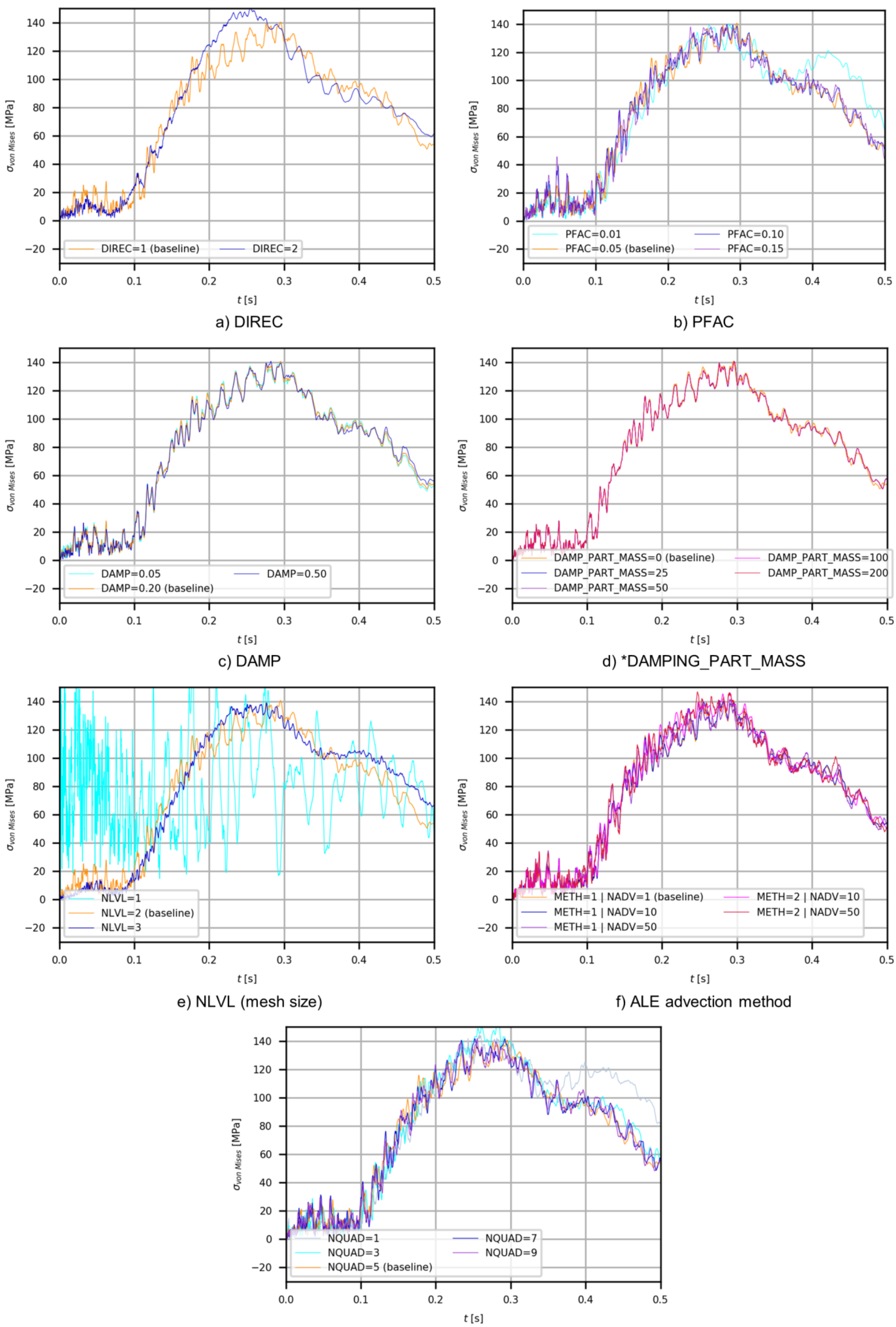


Fig.6: Influence of different parameters on the heeling angle of the box structure



a) DIREC

b) PFAC

c) DAMP

d) *DAMPING_PART_MASS

e) NLVL (mesh size)

f) ALE advection method

g) NQUAD

Fig.7: Influence of different parameters on the stresses inside the side plating of the box structure

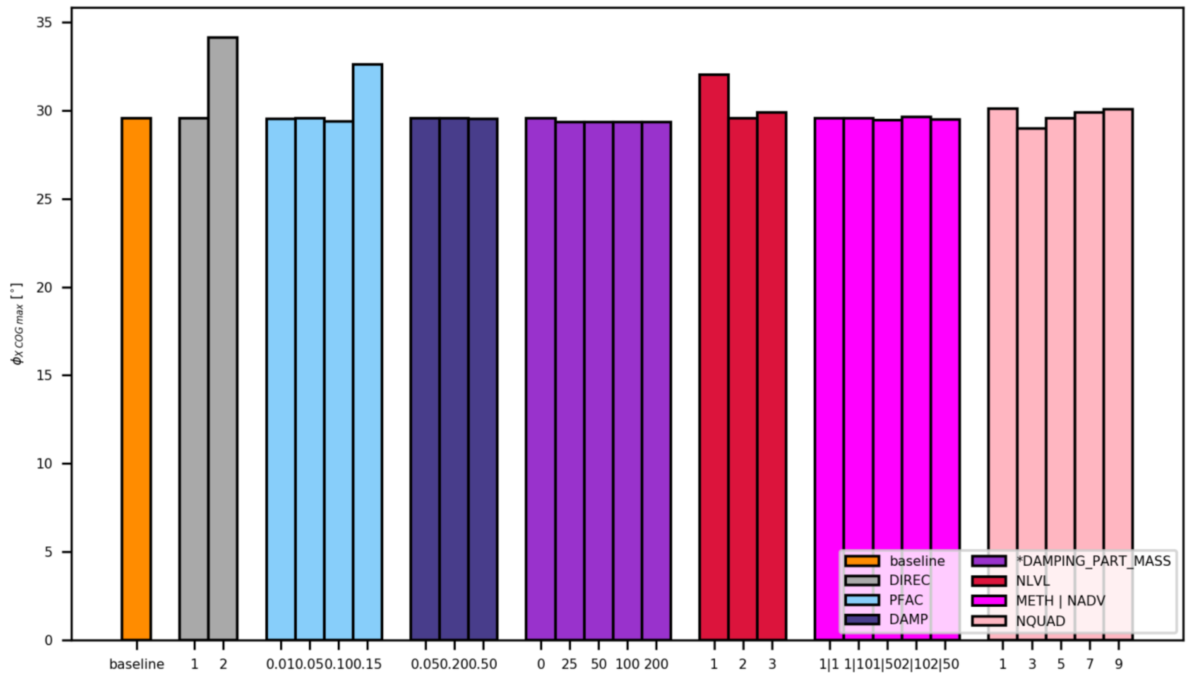


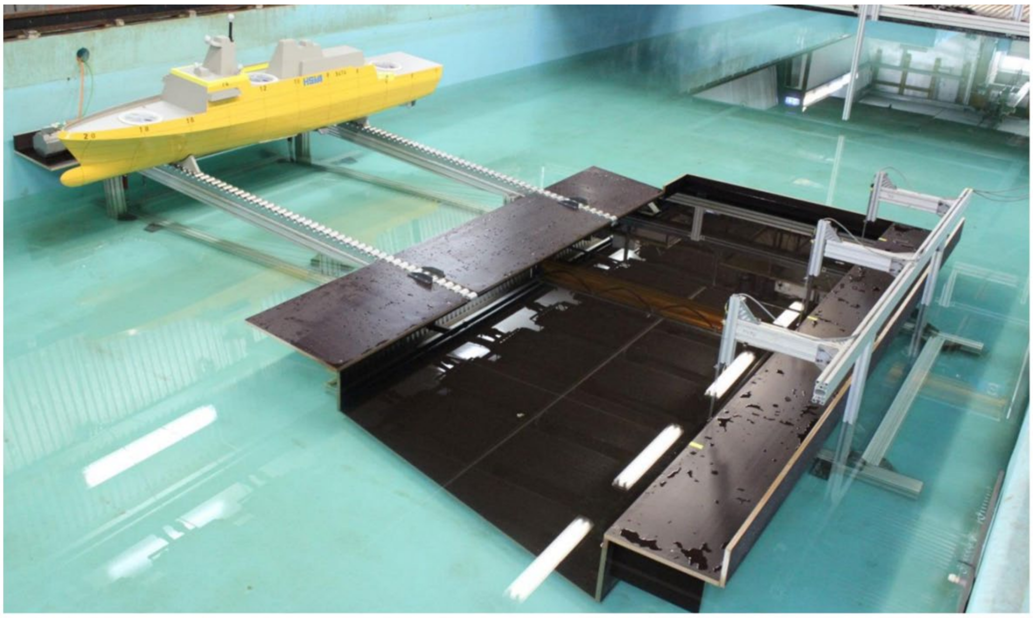
Fig.8: Influence of different parameters on the maximum heeling angle of the box structure

5 Verification based upon model tests of sideways launching process

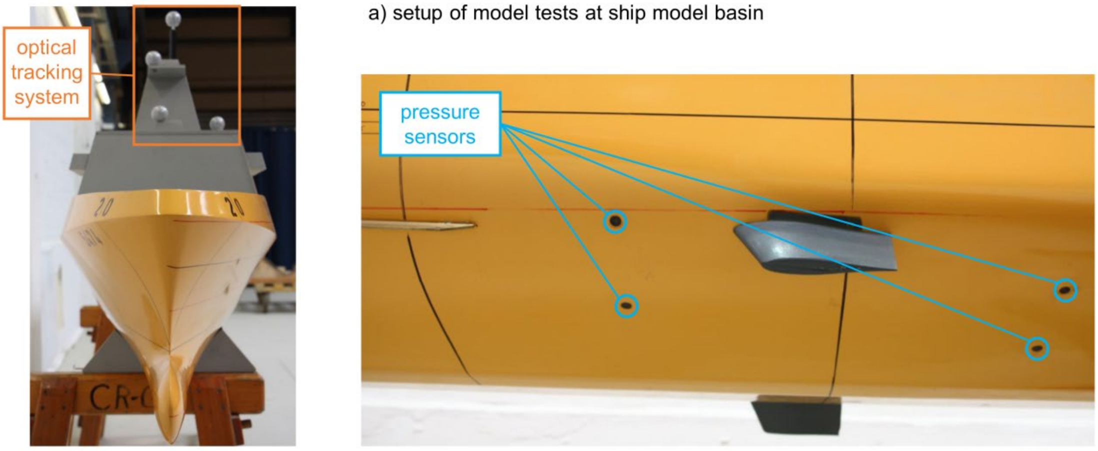
After verifying relevant physical phenomena and investigating the influence of different parameters while using the ALE-approach, a comprehensive verification of the ALE-approach for the use case of a sideways launching process of a ship is conducted based on corresponding model tests is conducted.

5.1 Setup of model tests and corresponding FE-model

Model tests of a sideways launching process of special purpose ship have been conducted in 2020 at a ship model basin. In total, 26 measurement series with 17 different model test setups have been conducted. During the model tests different parameters were varied (e.g. sliding speed, height of center of gravity / metacentric height among others). In addition, different “worst cases scenarios” were tested to get a understanding of feasible limits for this special purpose ship. The setup of the model tests is shown in Fig.9: a). The setup used for the model tests resembles the condition given at the construction shipyard for this special purpose vessel.
During model tests the 6-DOF movement of the ship is measured via an optical measurement system (see Fig.9: b)) as well as with accelerometers. Additionally, the pressure on the ship hull is measured with pressure sensors with a sampling rate of 4.8kHz at four different positions. The positions of the pressure sensors are shown in Fig.9: b). The obtained pressure-time-histories are used to evaluate the resulting loads on the ship hull at the impact with the water surface as well as for verification of the ALE-approach. Due to the dynamic nature of the sideways launching process, the pressure-time signal is subjected to certain deviations. This is especially true for the initial pressure peak at the impact of the hull with the water surface. Therefore, two different test conditions were measured multiple times (4x each). In addition, different setups of the water surface were considered during these multiple runs to account for a possible influence of the surface tension of the water (glass smooth vs. rough surface).
A FE-model is set up, which is as close as possible to the conditions of the model tests at the ship model basin. This FE-model is depicted in Fig.10:. This FE-model considers all relevant appendages as sued during model tests. Shell elements with ELFORM=2 (Belytschko-Tsay element formulation) are used to model the hull and appendages. The average element size can be obtained from Fig.10:. In total, around 45,200 shell-elements are used to describe the ship model. Relevant masses during model tests (measurement equipment, trimming weights) are modelled with **`*CONSTRAINED_NODAL_RIGID_BODY_INERTIA`** according to a weight calculation sheet provided by the ship model basin.



a) setup of model tests at ship model basin



b) measurement equipment used during model tests at ship model basin

Fig.9: Setup of model tests of sideways launching process at a ship model basin

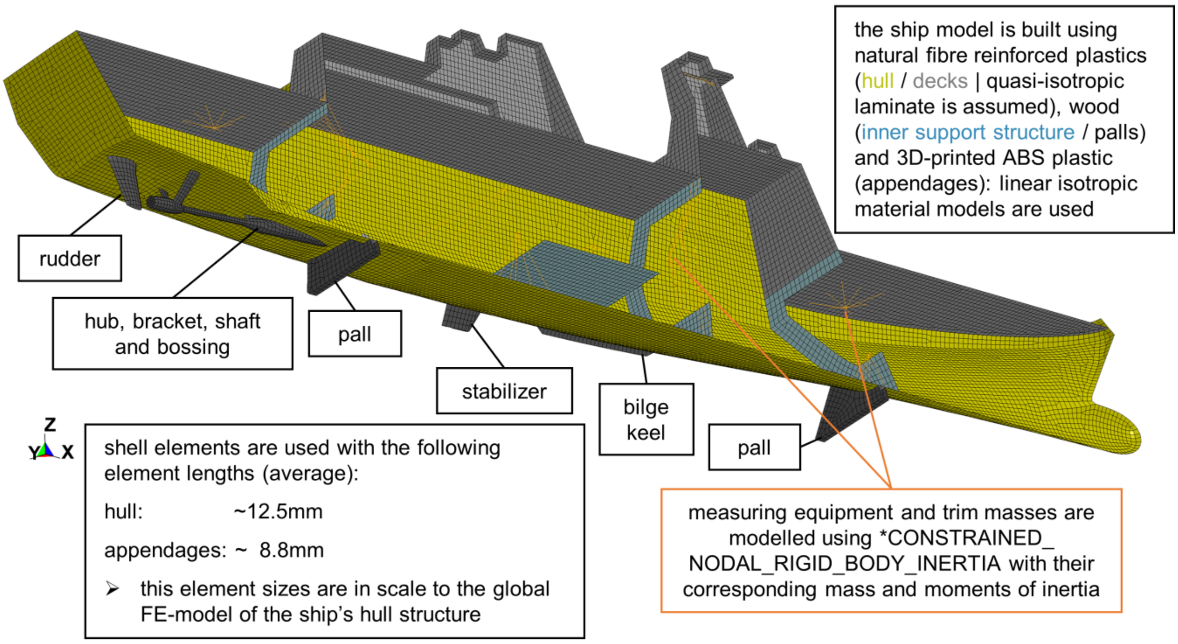


Fig.10: FE-model of ship model used for model tests of sideways launching process

The ALE domain is modelled like the basin in the test setup as shown in Fig.9: a). This includes the walls of the basin. 3D-ALE elements with ELFORM=11 (1 point ALE multi-material element) are used to model water and air. The element size chosen is about 15.6mm. To keep the number of elements as well as calculation time to a feasible level the refinement function for the ALE-domain is used via ***CONTROL_REFINE_ALE**. The refinement is used for the area, where the ship will immerse into the water. In this area of refinement, the element size is halved to about 7.8mm. Due to the size of the basin, the ALE-domain consists of about 7,585,000 elements in total. For comparison: If the finer element size of 7.8mm has been used continuously for the whole domain, the domain would consist of about 12,642,000 ALE-elements.
The coupling of the ALE-elements and the FE-model of the ship model as depicted in Fig.10: is done by ***CONSTRAINED_LAGRANGE_IN_SOLID**. The setting and parameters used are given in Table 4:. As shown in section 5.2, the results obtained using these parameters are in very good accordance to the conducted model tests of the sideways launching process. These settings have been derived after about 10 iterations utilizing the knowledge gained by the parametric study presented in section 4 of this paper.
The simulation starts right before the first contact of the hull with the water surface. The initial conditions are obtained from the data of the model tests. This includes the position of the ship relative to water surface (e.g. heeling angle) as well as the velocity (transversal and rotational). The transversal as well as rotational velocities are input via ***INITIAL_VELOCITY_GENERATION**. In addition, gravity is set using ***LOAD_BODY_Z**.
To optimize the calculation time needed for this model further, the cycles between ALE-advection is increased to from 1 up to 10 by setting NADV in ***CONTROL_ALE** accordingly. As the results in section 4 are showing, NADV does not have an influence on the obtained results. A higher number of cycles between ALE-advection did however result in instable numerical behavior. Van Leer with HIS (METH=2 in ***CONTROL_ALE**) is used as the ALE-advection method during simulations.
Besides the movement of the ship via ***DATABASE_HISTORY_NODE_SET**, the resulting pressure-time histories are monitored using ***DATABASE_TRACER_GENERATE**. A tracer is generated at the positions of the pressure sensor of the ship model (compare Fig.9: b)) with a frequency of 10kHz to capture the peak at the first contact with the water surface sufficiently.

parameter	value
NQUAD	2
CTYPE	4
DIREC	2
PFAC	0.05
FRIC	0.10
FRCMIN	0.30
DAMP	0.20

Table 4: Relevant parameters used in ****CONSTRAINED_LAGRANGE_IN_SOLID*** *for the simulation of a sideways launching process*

5.2 Results

Analogously to the parametric study, only relevant results of the sideways launching process will be presented and discussed within this paper. Fig.12: compares the movement observed during the sideways launching process. In Fig.12: a) the heeling angle as well heeling velocity are compared. The heeling angle resulting with the ALE-approach shows very good agreement with heeling angle observed during the conducted model tests. The maximal heeling observed is virtually identical. Therefore, the most critical parameter of the sideways launching process can be assessed using the ALE-approach.

Similar observations can be made for the period of the heeling angle, indicating the dynamic behavior of the ship can be assessed well with the ALE-approach. Additionally, the heeling velocity – as shown in Fig.12: a) – shows good agreement between the ALE-approach and the model tests. One important aspect can be observed using the ALE-approach: the ship will upright itself (heeling velocity > 0). Only slight deviations of the heeling velocity can be observed. These deviations are mainly due to the model scale. During model tests a lot of very fine spray and braking of the resulting waves can be observed, which is too fine to be correctly covered by the ALE-approach with the chosen element size of the ALE-elements.
The trajectory of the ship resulting with the ALE-approach at the center of gravity is also in good accordance with the trajectory measured during model tests. Slight deviations can be observed. However, on a global scale these differences are negligible during the sideways launching process.
A comparison of the pressure-time signals of the ALE-approach with the results from the model tests at the different positions of the ship hull is shown in Fig.11:. Due to the fluctuating nature of the pressure-time signal and especially the first peak at impact, a 95% confidence interval obtained from model tests is shown as well in Fig.11:. The pressure-time signals of the ALE-approach are lowpass-filtered with a cutoff frequency of 1kHz. As Fig.11: shows, all peaks at first contact with the water surface at each of the four pressure sensors lies within or closely below the 95% confidence interval of the conducted model tests. As already shown with the slamming experiments in section 3.1, the loads at impact with the water surface can be assessed on the basis of the ALE-approach. The accurate movement using the ALE-approach as shown in Fig.12: is proof, that the loads on the ship's hull structure are covered correctly on an integral scale.

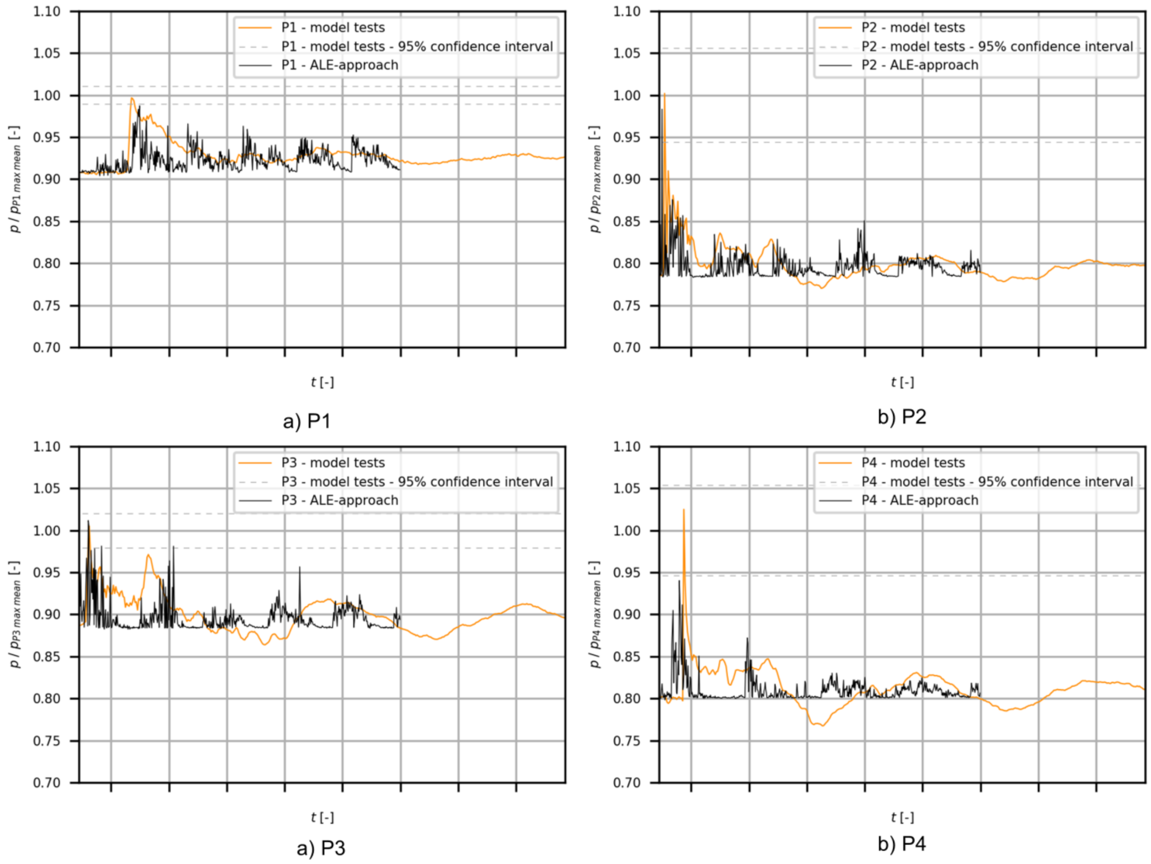
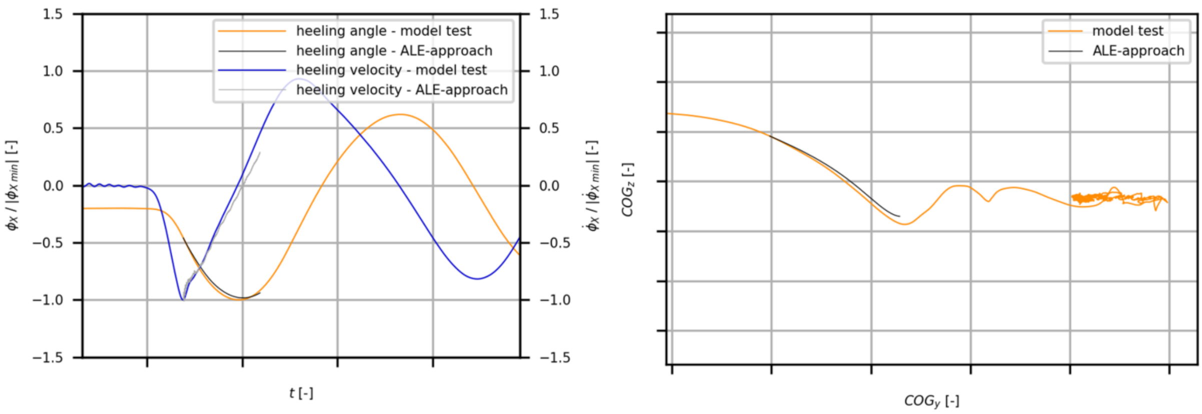


Fig.11: Results of the ALE-approach compared to model tests of a sideways launching process – pressure-time histories at different points of the ship hull



a) heeling angle and velocity b) trajectory of center of gravity

Fig.12: Results of the ALE-approach compared to model tests of a sideways launching process - movement of the ship

6 Conclusion and Outlook

Based on different verification processes, the ALE-approach in LS-DYNA® is very suitable to simulate the sideways launching process of a special purpose ship. Besides the verification of the underlying physical phenomena – e.g. based on slamming experiments found in literature – a verification based on model tests of a sideways launching process is presented. Using adequate parameters and settings for **`*CONSTRAINED_LAGRANGE_IN_SOLID`** (see Table 4:) combined with a suitable mesh size of the ALE-domain the results of the ALE-approach does cover the physics and results of the conducted model tests very well.
In addition, a parametric study regarding the influence of different parameters relevant for the ALE-algorithm is presented. It can be shown, which parameters can be used to shift the behavior of the fluid into one of the two directions: make the fluid "more stiff" or "less stiff". However, a lot of investigated parameters or settings do not majorly influence the physical behavior and results of the sideways launching process – emphasizing the robustness of the ALE-approach for this use case.
After these verifications, the ALE-approach will be used for assessing the loads on and stresses resulting inside the hull structure of the special purpose ship as presented in section 5. Two different FE-models will be used for this purpose. At first, a global FE-model of the ship's hull structure is used considering all relevant structural members using a coarser mesh size of about 300x300mm (see [7] for examples of such global FE-models). This model will be used to assess the stresses on a global scale and to identify critical / highly loaded areas of the ship's hull structure. Afterwards, a more detailed FE-model of the highly loaded areas / compartments will be set up using an element size of roughly 50x50mm. This model will be used to evaluate the resulting stresses and to check if modifications of the hull structure will be needed down to the last detail of the hull structure.
One drawback of the ALE-approach for the presented use case of a sideways launching process is the size of the calculation models and the resulting computational time needed. The computational time of the FE-model in section 5 is about 500h on 12 computational cores to gain the results as presented within this paper. Although some optimizations regarding the computational time are already implemented (local refinement of ALE-domain, number of cycles for ALE-advection) further improvement could be gained by using the MPP-version instead of the SMP-version of LS-DYNA®. The potential is to be investigated in future work.

7 Literature

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