The Simplified Interaction Tool for efficient and accurate underwater shock analysis of naval ships

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Abstract

In order to satisfy the need for good quality UNDEX response estimates of naval ships, TNO developed the Simplified Interaction Tool (SIT) for underwater shock analysis. The SIT is a module of user routines linked to LS-DYNA, which generates the UNDEX loading on the wet hull of a 3D finite element model of the ship structure by means of sophisticated physical approximation. This eliminates the need for a 3D mesh of the surrounding water, such as necessary for advanced coupled finite element/hydrocode simulations. The SIT models both the shock wave stage with reflections and cavitation and the subsequent gas bubble loading. The SIT was tuned and validated using experimental data from full-scale ship shock trials. A typical simulation of a detailed 3D finite element model of a naval ship takes only hours for the shock wave stage, against at least days for a comparable coupled simulation. This presentation provides a short overview of the physical approximations of the SIT, recent enhancements and examples of applications.

1. Introduction

An underwater explosion (UNDEX) and its loading on a ship structure are characterized by two distinct physical phenomena and loading stages:

- Early time stage: the primary shock wave and cavitation, caused by its reflection against the free surface and hull
- Late time stage: gas bubble oscillation and migration, resulting in a whipping loading.

When the migrating gas bubble comes relatively close to the ship structure, a third physical phenomenon may occur: bubble-structure interaction, possibly followed by jetting. This close-proximity UNDEX effect typically occurs for any detonating charge below or immediately aside a ship.

Over the years, there has been a gradual development of UNDEX simulation tools within the Netherlands' Organisation for Applied Scientific Research, also known as TNO. Modelling fluid-structure interaction with cavitation with acceptable accuracy has been a challenge for many years. The first successful simulations of actual surface ship structures were those of a floating cylinder using 2DCAV in 1996 [1][2]. 2DCAV is a DYNA3D based hydrocode simulation model for standoff UNDEX, using a single layer of Lagrangian fluid elements, and is capable of modelling interaction and cavitation. This tool was typically used for the analysis of 2D cross sections, thereby assuming a plane shock wave.

A promising first analysis of a cylinder trial was published [1][2]. 2DCAV was validated using the cylinder shock trials and subsequently used in various projects. 2DCAV was later extended to so-called 2½D models with a few elements in thickness direction. Although typical analysis durations decreased over the years from days to hours, further development toward a full 3D tool was given low priority because of the foreseen large computation duration for full ship models.

Nevertheless, there was a growing need for an efficient tool for the analysis of complete ships to standoff UNDEX. Around 2000, TNO started development of the so-called Simplified Interaction Tool (SIT), in close cooperation with the Defence Material Organisation (DMO), part of the Netherlands' Ministry of Defence. The SIT describes interaction with the spherical primary shock wave, cavitation and reloading in a simplified way and applies the resulting estimated UNDEX loading directly to the wet hull [3][4]. This eliminates the need for modelling a large volume of water around the ship by means of finite elements or cells. This gives the SIT an enormous computational advantage compared to hydrocodes, which require a fine mesh of a large volume of water to be included in the model, and makes the SIT a very efficient tool. The SIT is implemented by means of a set of FORTRAN user routines linked to the finite element code LS-DYNA. LS-DYNA replaced DYNA3D as dynamic analysis code within TNO about 15 years ago. The SIT has been extensively tuned and validated by comparing calculated responses against measured responses during full-scale shock trials of Royal Netherlands' Navy (RNLN) frigates and 2DCAV results [3]. Typically, a SIT analysis takes a few hours for analysing the shock wave stage with a detailed finite element model of a complete 3D ship structure. The duration increases to one or more days for a simulation through the gas bubble stage.

Current research is focused on further developing and validating SIT toward a general UNDEX response model for standoff, below keel and close-proximity UNDEX. The ultimate objective is to be able of performing an overall vulnerability analysis of surface ships related to any UNDEX threat.

The SIT has been used as a design analysis tool in various projects, of which various examples will be shown later in this paper.

2. Background of SIT

The SIT consists of simplified models for various physical UNDEX phenomena:

- The free-field spherical shock wave is modelled using similitude equations
- The pressure loading on the wet hull elements is based on the plane wave fluid-structure interaction equation

$$p_h = C_{ref} \cdot p_{in} - \rho c v_n \quad (1)$$

where p_h is the hull pressure, C_{ref} a reflection coefficient with a value between 0 and 2 (depending on the incident angle), p_{in} the free field pressure, ρ the water density, c the sonic velocity and v_n the wet hull velocity in normal direction.

- Surface cut-off occurs on arrival of the surface reflected shock wave, which is a tensile shock wave. From this moment onward, the pressure loading on the wet hull elements is set to a negative pressure with a magnitude equal to the ambient pressure
- Hull cavitation occurs when equation (1) results in a negative pressure with a magnitude equal to the ambient pressure
- Approximations are used for describing cavitation and cavitation closure (reloading)
- The gas bubble loading is based on the semi-analytical Geers-Hunter gas bubble model [5][6], combined with a source and image source model for calculating the free field water particle motions
- Calculation of the bubble induced loadings requires an external and internal added mass matrix of the wet hull. These two added mass matrices are obtained from a boundary element code.

In the first SIT development, priority was given to the shock wave loading. The gas bubble loading was implemented later and gradually improved. Because LS-DYNA is based on explicit time integration, the full added mass matrix of the wet hull is transformed into a lumped added mass description. A weak point remained the lack of an accurate reloading model for describing the transition from the shock wave stage to the gas bubble stage.

3. Reloading

Reloading, the transition from shock wave to gas bubble stage, is visualized in figure 1. On a short time scale, the UNDEX response of the keel of a ship is shown in figure 1-a. The shock wave results in a rapid velocity increase to a maximum value, immediately followed by a slower decrease due to cavitation.

On a longer time scale, typically seconds, the ship responds to the oscillating and migrating gas bubble. The gas bubble radius history is presented in figure 1-b and the ship response on a longer time scale in figure 1-c.

The blue and green response curves in figure 1-a and 1-c show the measured responses during shock trials with the RNLN Multi-Purpose Frigate (M-Frigate), while the red and purple curves show the calculated responses using SIT. Simulation results from a former SIT version, which lacked a proper reloading model, are presented in figure 1-a. The measured responses show a clear 'reloading' due to cavitation closure, which is missing in the former SIT results.

Implementation of a reloading model, which ensures an accurate and seamless transition from shock wave to gas bubble stage, has been a major recent achievement. Figure 1-c shows the responses, calculated with SIT using one of the recently implemented transition models. The new transition model correctly describes the response through the first gas bubble period for two different shots. For later times, a fair comparison is impossible because the measurements show too much drift because of integration inaccuracies of accelerometer signals.

It must be emphasised, that reloading mainly occurs in the surrounding water and not on the wet hull. This hindered the development and implementation of a proper transition model. Finally, various different transition models were implemented and validated.

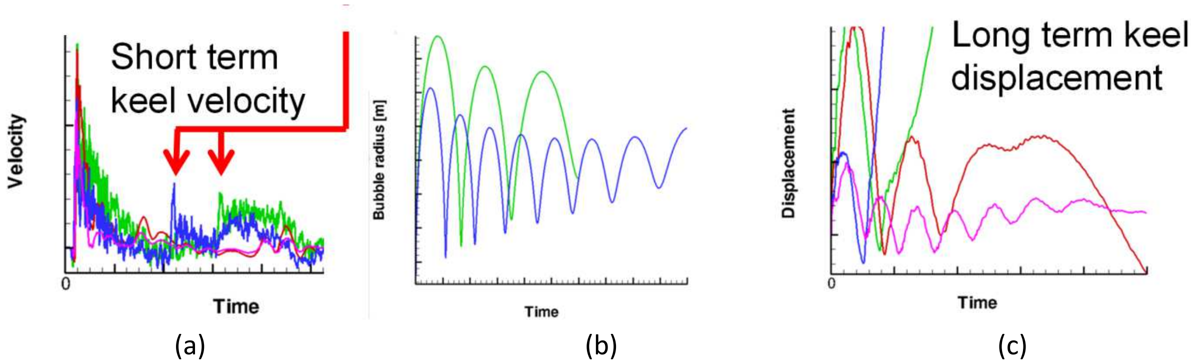


Figure 1 – Measured and calculated responses, showing early-late time transition

Validation was done for the shock trials of RNLN M-Frigate with two finite element models of different refinement. Additional validation was done for the shock trials of RNLN Air Defence and Command Frigate (LC-frigate). The validation results indicated that one reloading model clearly outperforms the other reloading models.

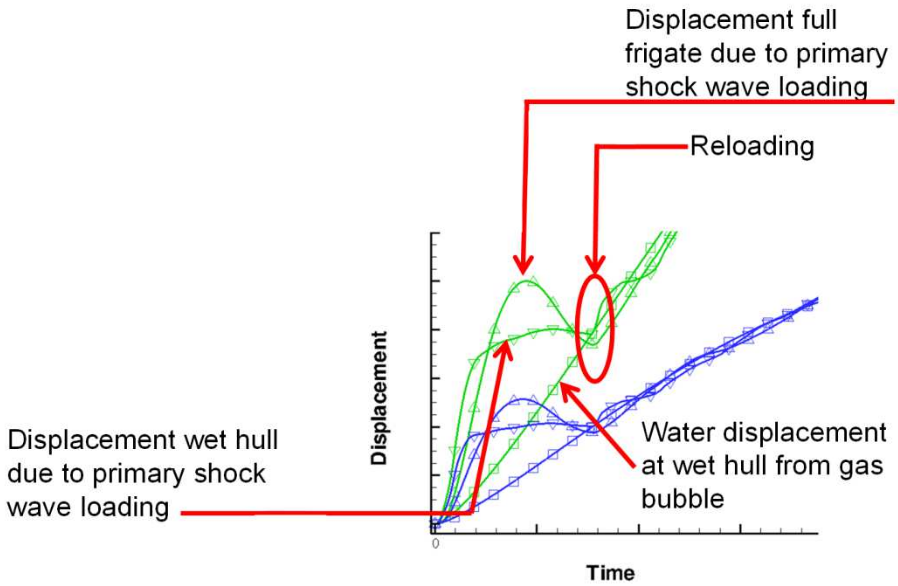


Figure 2 – Physical background of reloading model. Curves with block symbols □ show the bubble induced water particle displacements at the wet hull, curves with the triangular symbols △ show the average displacement of the full ship finite element model and curves with the gradient symbols ▽ show the average displacement of all wet hull nodes of the finite element model.

The physical background of the reloading model is visualised in figure 2. Results are presented for the results of two shots (blue and green curves). Obviously, the average wet hull response precedes the average full ship response. At a certain time, both displacements become equal to the water particle displacement at the wet hull position. This is defined as the moment of reloading.

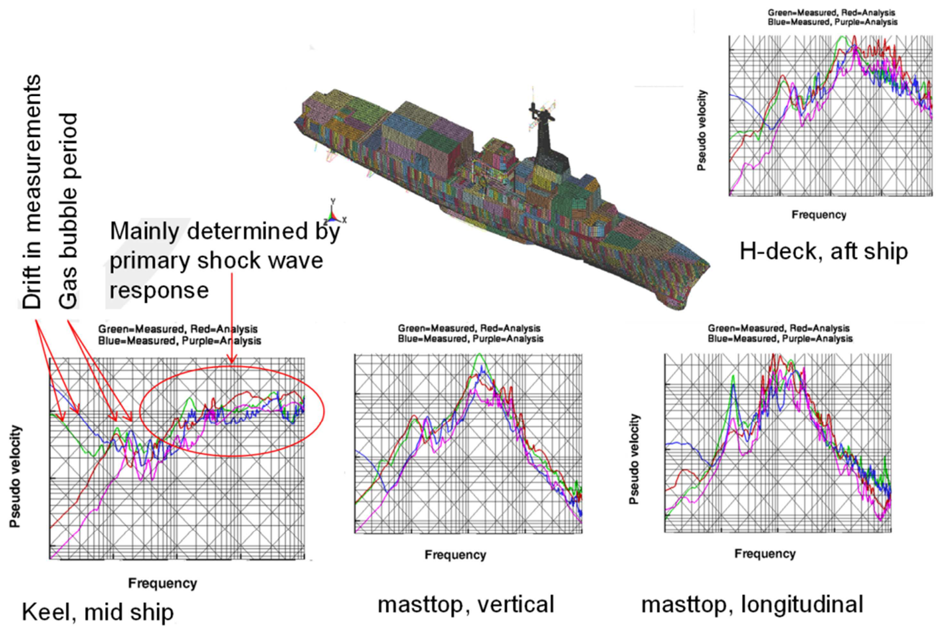


Figure 3 – Comparison of measured vs. calculated SRS for RNLN M-Frigate shock trials: measured for two shots (blue, green), SIT prediction for same shots (purple, red)

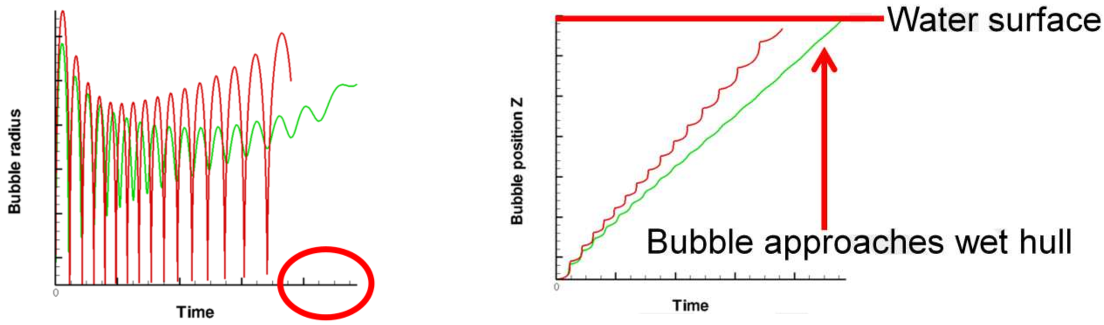
A comparison of measured and calculated shock response spectra (SRS) of the responses for the RNLN M-Frigate shock trials is presented in Figure 3. The duration of both the simulation and measurement is identical, so that the SRS is inaccurate below the same low cut-off frequency. In the measurements, these low frequencies are also affected by drift due to integration errors. The gas bubble induced response, visible as the first peak for the SIT predictions, shows a perfect agreement between measurement and SIT in terms of frequency and amplitude for two different shots. The shock wave induced response, which is responsible for higher frequencies including the overall SRS peak, shows a good agreement between measurement and SIT, although with some variation over frequency.

Similar conclusions apply to the longitudinal mast response, see figure 3-right-bottom. An exception is the gas bubble induced response peak occurs at a different frequency, where the SIT result underestimates the measured response.

4. Below keel UNDEX

After above validation, the effects of a below keel detonation have been investigated for a frigate. The charge is detonated below the keel at a large depth. As a result, the gas bubble exhibits many oscillations until venting. The results are presented in figures 4 through 6. Figure 4-a shows the gas bubble radius history for two different analytical gas bubble models and figure 4-b the associated vertical position histories. Figure 5 shows the bubble induced vertical water particle velocities and displacements at the wet hull. Figure 6 shows the bubble induced vertical ship response for this UNDEX loading.

It must be noted that close-proximity effects, such as gas bubble-structure interaction, are missing yet in the SIT. A simplified model for close-proximity UNDEX is currently under development and which will be implemented later.



(a) (b)

Figure 4 – Gas bubble radius and vertical position history for below keel detonation

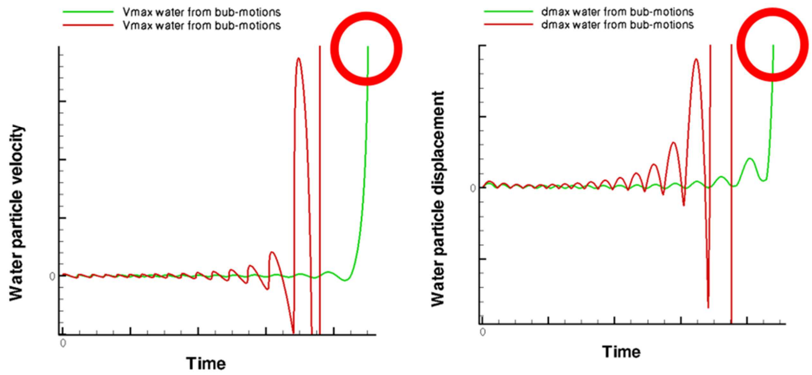


Figure 5 – Gas bubble induced water particle velocity and displacement at wet hull

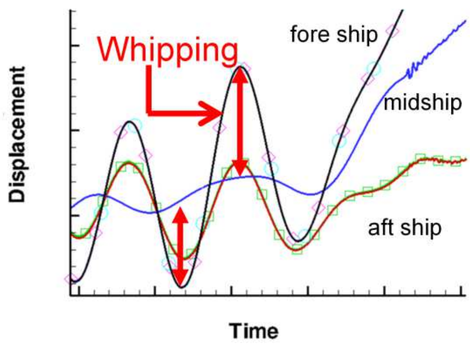


Figure 6 – Whipping displacements (vertical) in fore ship, aft ship and mid ship

5. FLOATEX

FLOATEX is detonation of a floating charge on the water surface. This invokes physical phenomena that are very different from those for which SIT was originally developed. A FLOATEX resulting from a marine improvised explosive device (IED) close to a ship is a serious threat.

Some years ago, a series of FLOATEX tests was carried out with three shots of different severity. These were analysed by means of both SIT and sophisticated Arbitrary Lagrangian Eulerian (ALE) simulations with LS-DYNA. A comparison of the experimental and simulation results, in terms of damage, is presented in figure 7. This demonstrates that the SIT is well capable of predicting the onset of rupture in Shot 1 (just one crack in experiment and simulations, hardly visible in figure 7) and the large-scale damage of Shot 2. Furthermore, SIT also simulates Shot 3 accurately, which showed large plastic deformation without rupture.

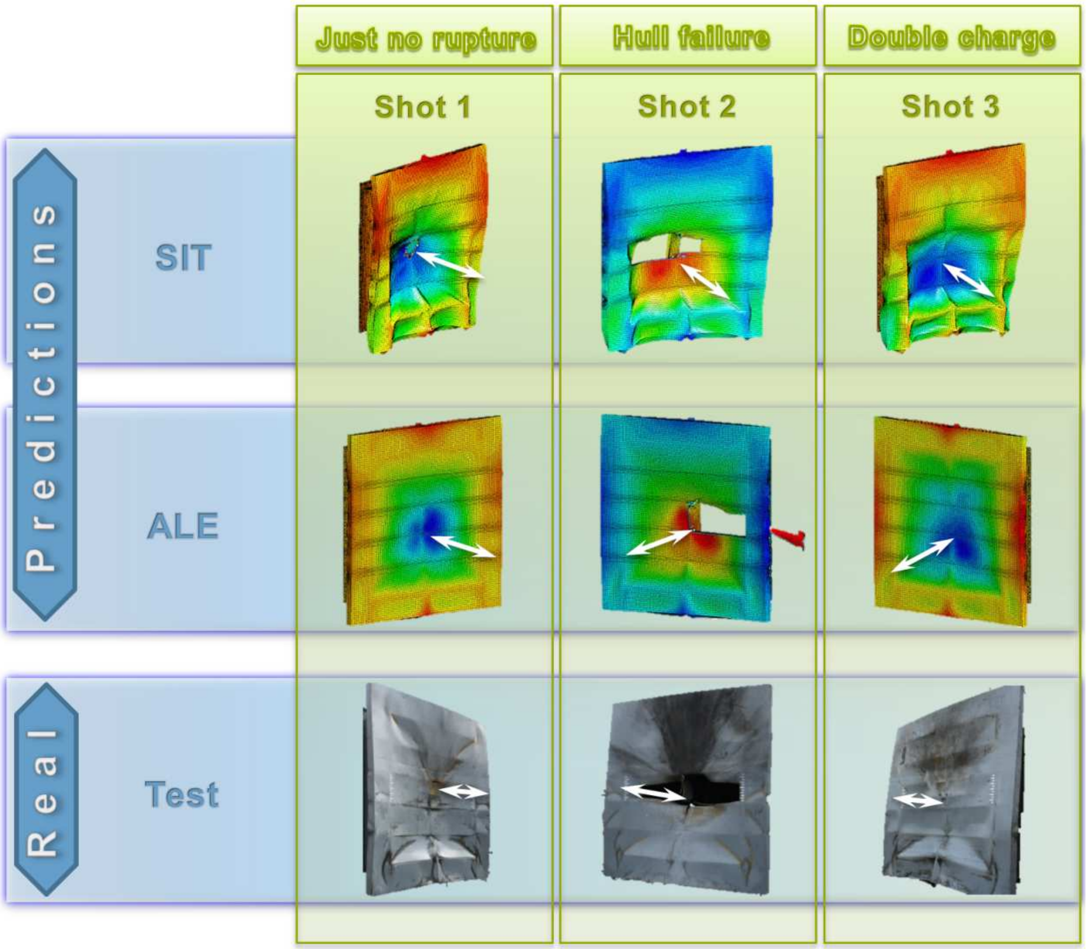


Figure 7 – Comparison of SIT prediction (top) against ALE simulation results (centre) and experimental results (bottom) for three different FLOATEX cases

Subsequently, the SIT was used for simulating a frigate compartment for a FLOATEX case, see figure 8. For a number of charge sizes, limit distances were determined associated with the onset of plastic deformation, the onset of rupture and the occurrence of a large size hole (several square meters).

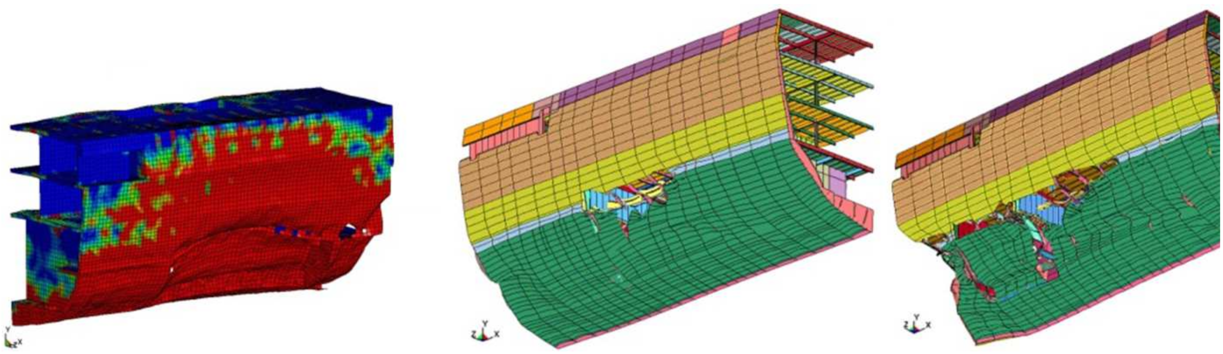


Figure 8 – SIT predictions for a frigate compartment for a FLOATEX case

6. M-Frigate new sensor mast

The RNLN M-Frigates are undergoing a substantial upgrade, including a new sensor mast. SIT simulations were performed for finding out how far the shock environment in the new mast differs from that in the old mast. The detailed finite element model of the RNLN M-Frigate with its new sensor mast is shown in figure 9.

Figure 9 – Finite element model of M-Frigate with new sensor mast

7. Other applications

Over the past decade, the SIT has been used in many projects. For example, the SIT was extensively used for verifying the shock response of the main radar sensor systems on board of the RNLN LC-Frigate. This resulted in a successful shock trial without damage, see figure 10.

Figure 10 – RNLN LC-Frigate with its two main radar sensors during shock trial

Another recent application has been simulation of the new RNLN Joint Support Ship (JSS), the largest vessel of the RNLN. The JSS is fitted with an integrated sensor mast from THALES. The finite element model is shown in figure 11. Earlier simulations of a frigate with an integrated mast structure were presented in [7].

Figure 11 – Finite element model of RNLN Joint Support Ship with integrated sensor mast

A last example is the simulation of heavy UNDEX shock trials on a floating cylinder [8]. Once again, the SIT provided accurate UNDEX response estimates as seen in figure 12.

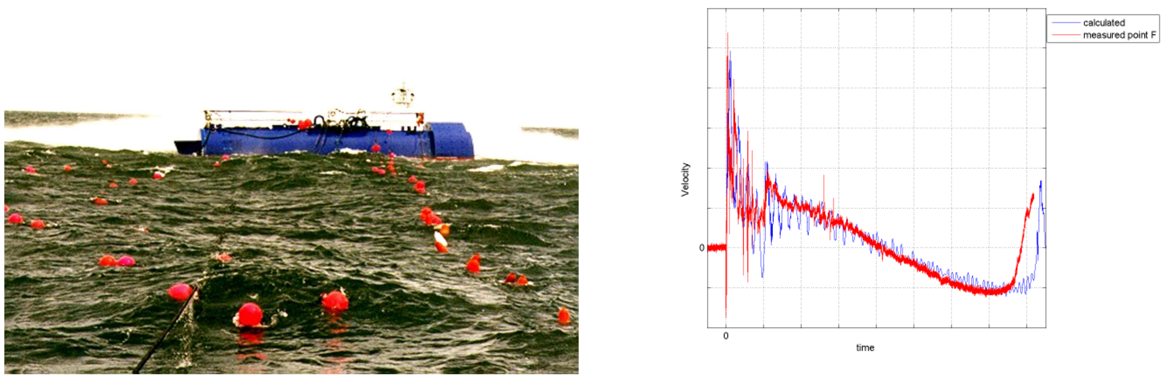


Figure 12 – Heavy UNDEX trials and simulations of a floating cylinder

8. Conclusions

The Simplified Interaction Tool (SIT) is well suited for simulating the effects of UNDEX on detailed 3D ship models accurately and with high computational efficiency. The results show a good agreement with results from full-scale ship shock trials. Reliable results are obtained for the shock environment in a naval ship hull, its superstructure and in sensor masts with radar and other sensor systems. The SIT is also capable of predicting hull damage.

9. Future developments

Future developments will include simplified models for close-proximity UNDEX effects, further validation for very high shock levels and capabilities for the simulation of submarines.

10. Acknowledgement

The SIT was developed by TNO with funding from and in cooperation with the Defence Material Organisation (DMO), part of the Netherlands' Ministry of Defence. The Defence Materiel Organisation is gratefully acknowledged for this.

11. Literature

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