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Completing the design cycle

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INDUSTRIAL SCALE VALIDATION OF DEM SUPPORTED GRAB DESIGN – COMPLETING THE DESIGN CYCLE

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Key Words: grab, DEM-MBD co-simulation, validation, in-situ tests, design cycle

Abstract

This paper describes the DEM simulation supported design approach leading to a breakthrough in grab design. More specifically it aims to demonstrate the full design cycle including evaluation of the grab prototype on full-scale in realistic operational conditions and comparison with the predictions by the DEM-MBD model. Most of the researches involved in improving or optimizing equipment design do not include the practical performance of the optimized design and as such it is hard to judge whether the predicted performance matches the obtained one in full-scale industrial practice. We show the successful prediction of the new design's performance by comparing the DEM-MBD model to in-situ tests with the newly designed grab prototype. By this a true validation has been established and a validated model has been achieved that is independent of a specific grab design.

1. INTRODUCTION

Many researches describe the analysis of bulk handling equipment and improvement of design with the aid of DEM possibly coupled with other computational methods such as FEM or MBD. An important aspect is the validation of these models required for experimenting with the models in the search for an improved design. The validation is either achieved by small-scale laboratory experiments (e.g.[1-3]) or by full-scale in-situ tests (e.g. [4-6]). Obermayr, et al. [7] validated draft forces on blades in cohesive soil both on a laboratory and full-scale. The validated model can then be used to explore the design space and predict behavior under various operational conditions [3, 5, 8-11]. However, the extent to which the validated models are valid for the newly designed or virtually optimized configurations is not well described in literature since a demonstration of the performance in full-scale is not included. Likely, this is because the resulting designs are not publicly shared due to confidentiality agreements, whilst from a scientific perspective an essential part of the full design cycle is the proof of concept.

Therefore this research addresses the approach for extending the model validation by the testing of a newly designed and full-scale built prototype, and thus confirming the true validation of the model. More specific, the missing link is an evaluation of the full-scale prototype resulting from the DEM supported design process. Filling this gap will prove that the use of developed models is not restricted to existing equipment types, and as such completes the full design cycle. For this purpose, here, the design of a new generation of grabs for iron ore pellets is used.

In an earlier stage of this research a four rope scissors grab for iron ore as displayed in *Figure 1* was used as reference for the modelling. The four rope scissors grab consists of three parts: a left and right scissor half and a suspension part. Two hoisting cables are connected to the suspension part, which is connected to the two shells with chains. The grab is operated with two closing cables which go through two pulleys each. Two winches are mounted on the crane to operate the hoisting and closing cables respectively. As the required torques on the winches is a response of the interaction of the grab with the bulk material a DEM-MBD co-simulation is required.

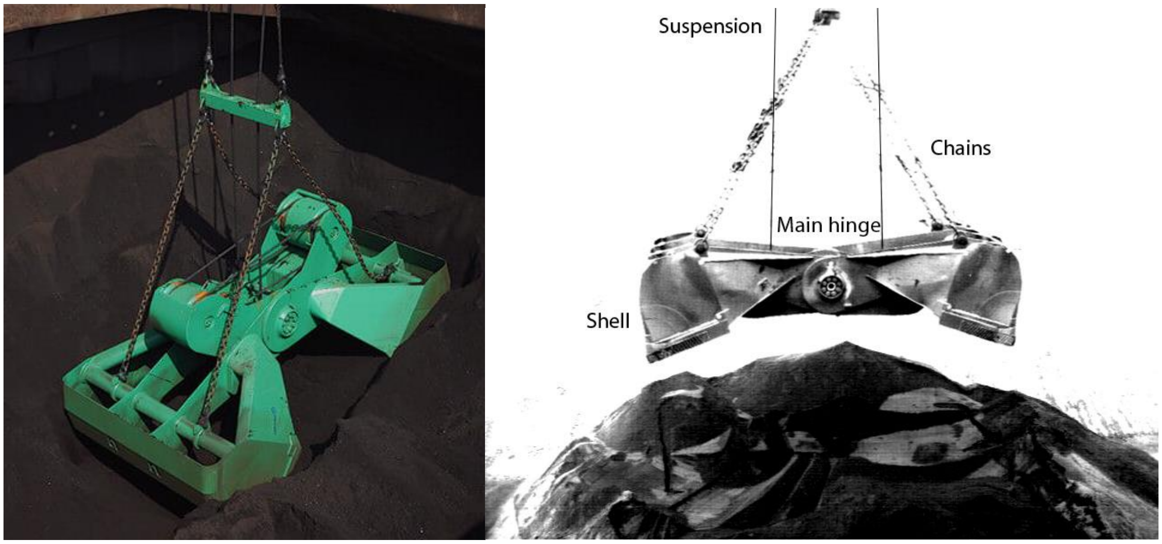

Figure 1 – Scissors grab (left: courtesy NEMAG BV, right: [12])

This paper aims to demonstrate the full design cycle including evaluation of the grab prototype on full-scale in the daily terminal operation and comparison with the predictions by the DEM-MBD model. This will result in a true validation of the DEM simulation supported design approach.

2. MATERIALS and METHODS

The complete DEM supported design cycle for a new grab type is shown in *Figure 2*. This full design cycle will be described here with emphasis on steps 5 and 6; the evaluation and the true validation of the model.

Step 1. First a validation of a multibody model of a scissors grab including pulleys and cables was done [12]. To operate an empty grab a virtual crane operator was used to open and close the grab. The torques of the winches predicted by the simulation compared well and therefore the MBD component of the co-simulation was validated. At the time we needed the DEM-MBD co-simulation a verified co-simulation with MBD software was not available. Therefore a generic coupling was created and tested, and in addition a framework for development, verification and application of the co-simulation was developed [13]. Furthermore a guideline has been developed for achieving stable and efficient co-simulations.

To arrive at a calibrated co-simulation model for iron ore pellets that next to representing material behavior also includes material-equipment interaction, first a DEM material model of iron ore pellets was calibrated employing a set of laboratory experiments [14]. This contained angle of repose tests as well as the penetration test with several tool shapes to account for the material-equipment interaction. Together with the verified DEM-MBD co-simulation this allowed to create a full-scale model of a scissors grab. To achieve reasonable computational times, several techniques were applied including stiffness reduction [15] and coarse graining [16].

Step 2. Before the actual design of a new grab could be started, first it was necessary to validate the full-scale model of an existing scissors grab. This was achieved by full-scale in-situ experiments with a bulk handling crane in the Netherlands. Several operational parameters were varied while the payload and the torques on and angular velocities of the winches were monitored. The grab's kinematics was captured by video tracking. The output of the model compared well with the experimental results and therefore we had established a validated model of the scissors grab.

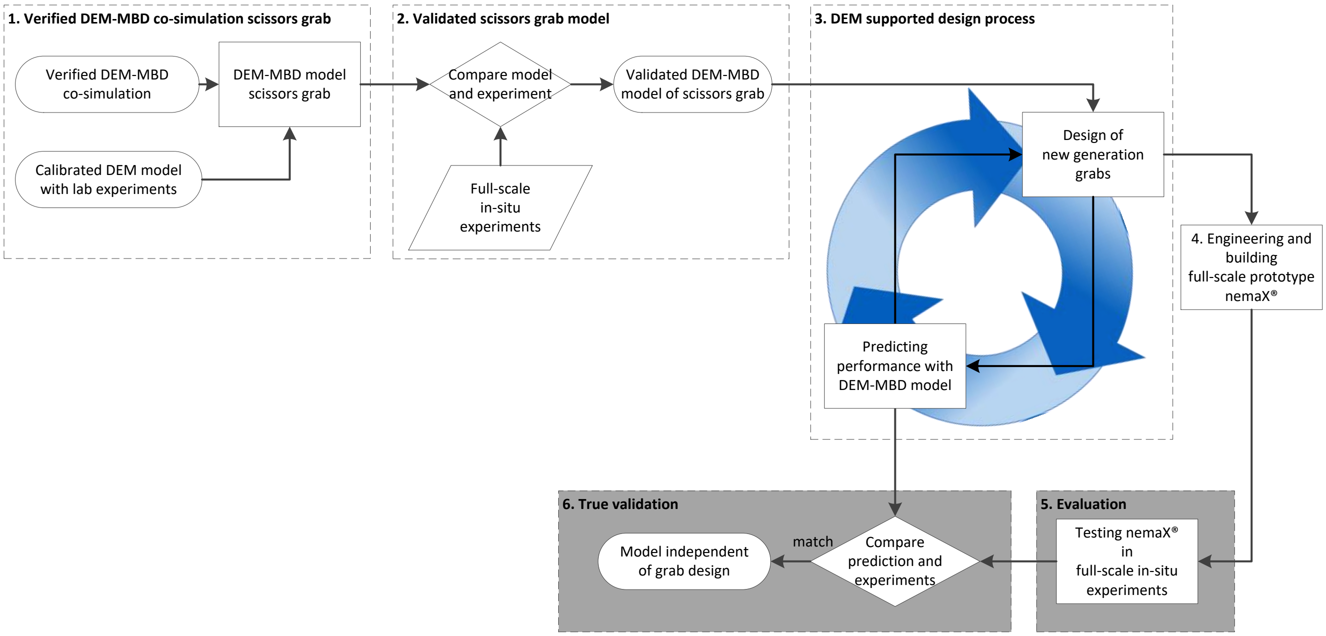

Figure 2 – Completed design cycle for development of a new generation grabs resulting in a true validation

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Step 3. With the validated model the effect of several design parameters on the grab's performance were investigated. To assess the performance several indicators were developed, such as payload, digging path, spillage and closing resistance. For further details the reader is referred to the PhD thesis of Lommen [14]. The detailed insight in the grab's performance was then used in the design stage to develop a new generation grabs. Although the model is validated with full-scale in-situ tests, the question can be raised whether the predicted performance of a new design will meet the behavior in reality. For this purpose a prototype needs to be built and tested to confirm the predictions.

Step 4. The development of the nemaX® was the result of an iterative design process and in-house engineering and simulation supported design of step 3, where the performance of new designs could be tested using the validated model. The virtual prototype was then engineered in detail to meet the structural and manufacturability requirements. Finally a full-scale prototype of the nemaX® was built (see *Figure 3*). In brief, this new grab type compares to existing grabs by having a 30% larger footprint, reduced weight of 15% and increased opening and closing speed of 20%.

Step 5. A new series of in-situ tests were planned and executed to test the nemaX® under different operational conditions such as on a prepared heap of iron ore pellets with a horizontal and inclined surface as well as in the ship. Also the grab was tested on a variety of bulk materials, but for the focus of this paper here only the results of iron ore pellets are presented. Again several operational parameters were varied while the payload and the torques on and angular velocities of the winches were monitored during grabbing of material. The grab's kinematics was captured by video tracking. The results of these experiments are presented in Section 3.

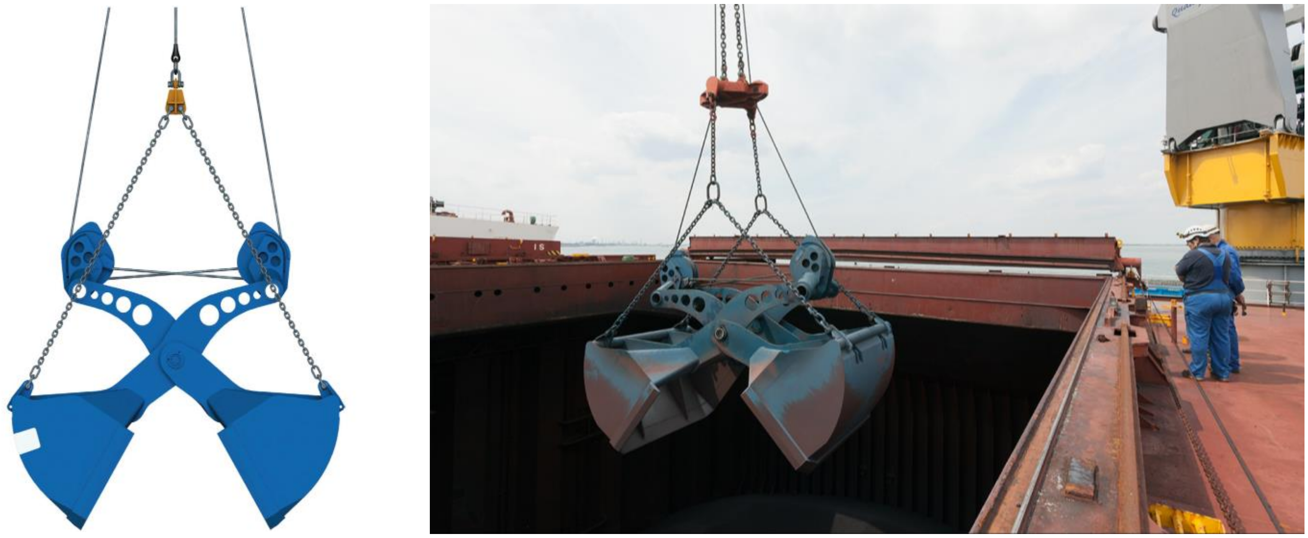

Figure 3 – nemaX® (images: courtesy of NEMAG BV)

Step 6. To predict the performance of the nemaX® a new virtual grab was created, as the relevant grab characteristics were different from the scissors grab on which the model was initially validated. Moreover, the input for the closing and hoisting winches operated by the crane driver was updated to the values obtained from the in-situ tests. The comparison between the predicted performance and the grab's performance in the field tests were compared; these results are shown in Section 3.

3. RESULTS

Three flat surface experiments are selected for the validation test, since these can be conveniently recreated in DEM simulation. As shown in *Table 1*, the experiments and simulations compared well in terms of the average mass of 33.9 and 34.3 ton of iron ore pellets per cycle, respectively. Similar to [14], this small difference is probably caused by the variation in the bulk material surface, operating characteristics and numerical scatter.

Table 1. Grabbed material (payload) in experiments and simulations

	mass [ton]
Experiment 1	32.8
Experiment 2	34.0
Experiment 3	35.0
Average experiments	33.9
Margin of error	1.2

	mass [ton]
Simulation 1	31.5
Simulation 2	35.4
Simulation 3	36.0
Average simulations	34.3
Margin of error	2.8

To validate the co-simulation from various aspects, experiment 2 and simulation 2 are selected for further analysis as these showed the largest difference in the grabbed material. *Figure 4* compares the total load on the cables in experiment 2 and simulation 2. The empty weight of the grab is apparent from the figure in the initial stage until 3 seconds. Although the grab touches the material faster in simulation (at t=3 s), most importantly the closing and hoisting starts at the same time (t=11 s). The load during the closing and hoisting stages is predicted adequately with an overall correlation coefficient of 0.968.

The winches of the crane control the grab motion; therefore to validate the grab dynamics, the torque of the closing and hoisting winches during a grab cycle are compared in *Figure 5*. Similar to the load data (*Figure 4*), the torque in the closing and hoisting winches are predicted adequately. Only during closing the grab, the torque starts to deviate from the experimental data, for both hoisting and closing winches. This can be explained by the difference in the time that grab touches the material, which causes a difference in cable slack between model and experiment. Also a brake is activated in the experiment after the hoisting to prevent overheating the electric drives resulting in a torque decrease, while the simulation lacks a winch brake and the torque remains constant. If we ignore the data after activating the brake, the predicted closing and hoisting winches have correlation coefficients of 0.937 and 0.863 respectively. These results confirm that the grab's dynamics are correctly predicted in the simulation.

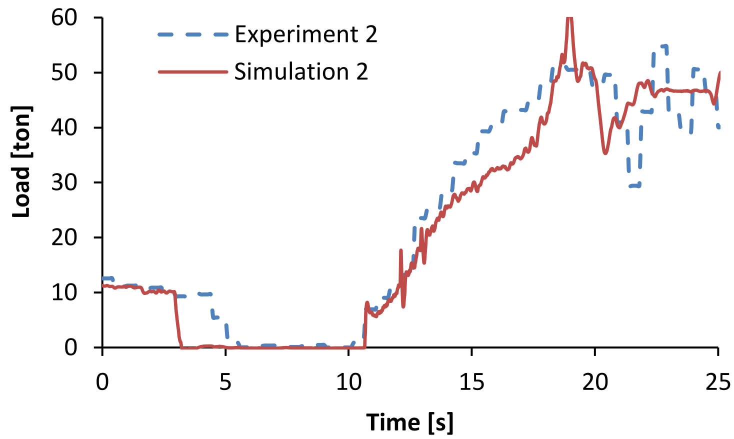

Figure 4 – Load comparison between experiment 2 and simulation 2

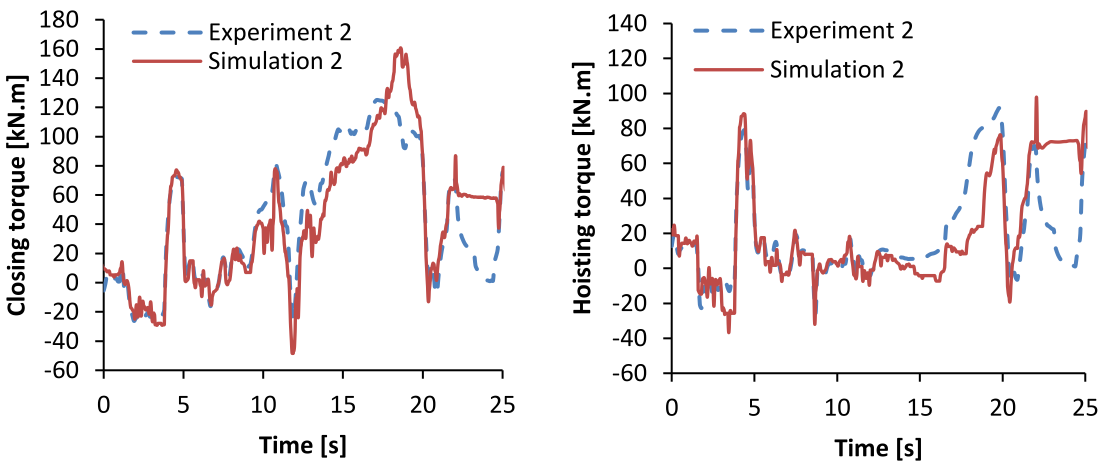

Figure 5 – Comparing torque in the winches. Left: closing winch; right: hosting winch

4. CONCLUSION

This paper successfully demonstrated the true validation of the grab design cycle. The in-situ tests with the newly built prototype compared well to the predictions of the validated DEM-MBD model. With this a true validation has been established and a model has been achieved that is independent of a specific grab design. With this the design cycle is closed.

Further work will focus on developing model that captures cohesive materials in interaction with grabs. For this purpose a new series of tests will be setup to acquire the necessary input for the model validation.

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