Stef W. Lommen
PhD Candidate
Delft University of Technology
Faculty of Mechanical, Maritime and
Materials Engineering

Dingena L. Schott
Associate Professor
Delft University of Technology
Faculty of Mechanical, Maritime and
Materials Engineering

Gabriel Lodewijks
Professor of Transport Engineering and
Logistics
Delft University of Technology
Faculty of Mechanical, Maritime and
Materials Engineering

Multibody Dynamics Model of a Scissors Grab for co-simulation with Discrete Element Method

This research aims at validating a co-simulation of Discrete Element Method and Multibody Dynamics of a scissors grab for the purpose of virtual prototyping. Both components should be validated before the overall model is validated and applied in the design process. The goal of this paper is the validation of a multibody model of a scissors grab. A scissors grab was modelled, including the pulleys and cables. For the input of the model, a virtual crane operator was used which opened and closed an empty grab. The torques of the winches predicted by the simulation compared well with measurements, and therefore the MB component of the co-simulation has been validated.

Keywords: *multibody, simulation, scissors, grab, discrete element method, co-simulation, validation, cables.*

1. INTRODUCTION

Grabs are used for unloading cargo vessels; they grab dry bulk material such as iron ore or coal in the vessel and transfer the grabbed material to a hopper on the quay. The current design process of bulk handling equipment such as grabs consists of designing a prototype, building it in the factory and evaluating it at a test site. This is an expensive process involving high risks and long R&D times.

Predicting the performance of a prototype grab is difficult, as continuous models are not very suitable due to the particulate nature of the dry bulk material [1,2]. A simulation using the Discrete Element Method (DEM) could be a promising solution in predicting the performance of grabs. However, most DEM codes use motion driven geometries, neglecting the effect of resistance from the bulk material on the motions of the grab. A co-simulation (Figure 1) computing both bulk material and grab behaviour would be able to take into account the load of the bulk material and could compute resulting geometry motions.

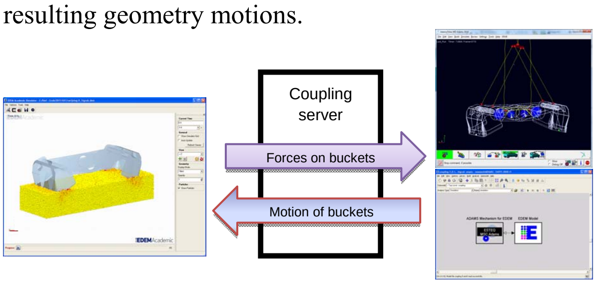

Figure 1. Co-simulation

Previous research has identified a multibody analysis as a valuable tool in simulating dynamic equipment [3]. The calculated results of a hydraulic excavator of Yoo [4] were in good agreement with experimental results. A complex, large scale rigid-body mechanism was simulated and validated by Langeroc et al. [5], demonstrating the ability of predicting the system's response to the input given. However, a validated multibody model of a grab is still missing.

The goal of this paper is to model and validate a multibody dynamics model of a scissors grab, which is required before an overall validation of a co-simulation can take place. First, the grab will be described and the model of this grab will be presented. Next, the virtual crane operating the grab will be presented, which will provide the input to the model. Finally, the output of the model will be compared to experiments, validating the multibody model of a grab.

2. MODELLING THE GRAB

A four rope scissors grab for iron ore as displayed in Figure 2 is used as reference in the modelling. CAD geometry and dimensions were supplied by a grab manufacturer. A 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 wireropes which go through two pulleys each.

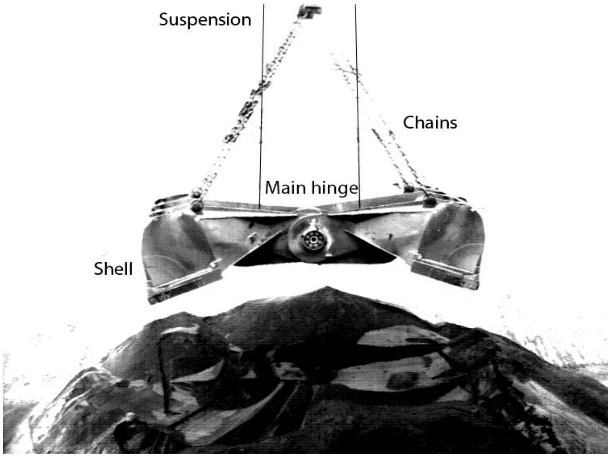

Figure 2. Scissors grab approaching iron ore

Received: July 2012, Accepted: November 2012
Correspondence to: Stef Lommen,
Faculty of Mechanical, Maritime and Materials Engineering
Delft University of Technology
Mekelweg 2, 2628 CD Delft, The Netherlands
E-mail: s.w.lommen@tudelft.nl

For comparing the model to an analytical approach, the equations of equilibrium on the main hinge point have been derived:

$$\sum M = F_{ch,y} r_{ch,x} - F_{ch,x} r_{ch,y} - F_z r_{cm,x} - F_c\left(\sum r_c\right) = 0 \quad (1)$$

Here is F_{ch} the force in the chain, r_{ch} the distance from the main hinge point to the connection of the chain (Figure 3, left). F_z is the weight of the shell, r_{cm} the distance between the centre of mass, F_c is the force in the closing cable and Σr_c is defined as:

$$\sum r_c = r_1 + 2r_2 + 2r_3 \quad (2)$$

Node equations on the suspension result in the following set of equations:

$$F_{ch,y} = F_h \quad (3)$$

$$F_{ch,x} = F_h \tan\phi_{ch} \quad (4)$$

$$F_z = F_h + F_c \quad (5)$$

where F_h is the force in the hoisting cable and ϕ_{ch} is the angle of the chain. Substituting (3) and (4) in (1) results in

$$\sum M = F_h r_{ch,x} - F_h \tan\phi_{ch} r_{ch,y} - F_z r_{cm,x} - F_c\left(\sum r_c\right) = 0 \quad (6)$$

For the multibody model of a scissors grab (Figure 3, right), MSc. Software's ADAMS program was used, a multibody tool capable of communicating with external programs such as a DEM package. Cables, sheaves and winches were modelled with the help of the TKC toolkit provided by SayField International.

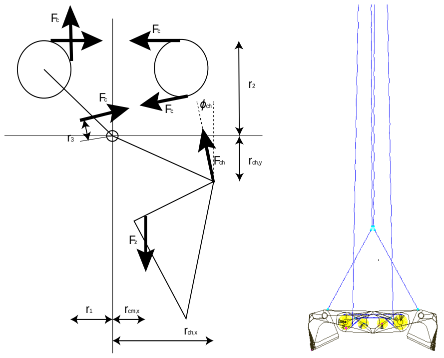

Figure 3. Schematic of grab (left) and Multibody model of scissorsgrab (right)

In order to accurately predict the movement of a grab, it is essential that all masses and moments of inertia are correctly modelled. The effect of higher and lower values was examined as well and showed that the inertia and the position of the centre of gravity affected the movements of the shells. The values used in the model were based on a calculation in a 3D CAD program.

The cables were modelled using the following equation [6]:

$$F_{cable} = k\left(\left(\delta + \delta_{init}\right) + c v_{delta}\right) \quad (7)$$

Where δ is the elongation, δ_{init} the initial elongation to adjust the natural length to the initial load, c the damping coefficient and v_{delta} the difference in velocity between the two endpoints of the cable. The constant k is based on the Young's modulus E, metallic area A and length of the cable l:

$$k = \frac{EA}{l} \quad (8)$$

However, the elasticity of a wire rope is nonlinear and dependent on the tensile stresses present in the wire rope [6]. For stranded wireropes used in grab operation, the elasticity modules cannot be calculated analytically but can only be evaluated by measurements, and – due to the nonlinearity – will only be valid for the given definition of loading.

An investigation on the effect of cable stiffness on grab behaviour showed an influence during opening and closing, as forces and therefore elongation shift from hoisting cables to closing cables and back. The elasticity modulus was determined based on measurement data of CASAR's stratoplast [7] and applied in the linear cable model. A suitable value of damping coefficient was chosen based on empirically realistic values.

The chains between the shells and the suspension have been modelled in a similar fashion, only using different values for E and A. Chains were modelled using a single element and also using multiple elements, resulting in a midpoint cable. Based on a comparison it was concluded that chains modelled with a single element were sufficient and could capture the relevant motions.

The pulleys have been modelled to connect both cable ends, minus frictional torque caused by bearings: ($T_{bearing}$)

$$T_{bearing} = n\left(\mu_t F_t + \mu_n F_n\right) \quad (9)$$

using the rotational speed n, friction coefficients μ_t and μ_n, and bearing forces F_n and F_t. The bearings in the main hinge point have been modelled in a similar fashion. Friction coefficients are based on specifications provided by the bearing manufacturer.

The model was equipped with additional contacts, in order to limit the minimum opening angle to 0 degrees, in other words, preventing the two shells from overlapping during closing. The maximum opening angle was limited as well to meet the specifications of the actual design.

3. CONTROL OF THE CRANE

For the control of the grab, in practice provided by the crane and its operator, a virtual crane operator was modelled. Four winches were created, using velocity input data obtained from measurements on a crane at a bulk terminal. These winches represented both the electric drives and gearboxes. The gearboxes were eliminated by scaling the moments of inertia of the drives. The gearbox factor was retrieved by comparing the cable length required to close the grab to the number of rotations during one cycle.

As input to the winches, measurements were performed at a bulk terminal, displayed in Figure 4. The result of these winch velocities is that the grab opens and closes, as can be seen in Figure 5. It can also be seen that the position of the suspension does not change during opening, but lowers during closing due to movement of the hoisting cable.

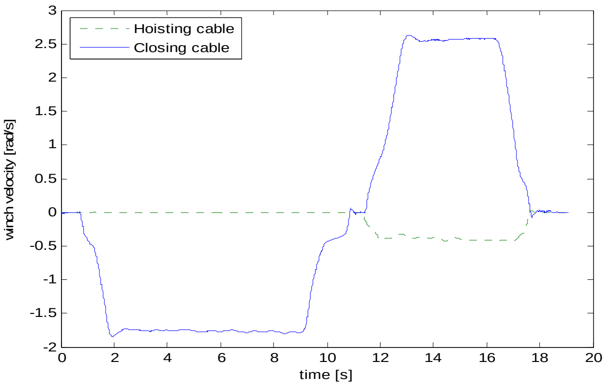

Figure 4. Input signal

The original measurement data of winch velocities turned out to be heavily discretized, resulting in very erratic winch accelerations. An analysis comparing the original signal to a filtered signal was performed, using different spans and both the moving average smoothing technique and the Savitzky-Golay filter. A cubic spline interpolation algorithm was used in ADAMS to create the continuous input signal required. Compared to the Akima algorithm, the cubic has smoother derivatives, which result in smoother torques in the winches as winch acceleration $\ddot{\varphi}$ has an effect on winch torque:

$$T_{winch} = I_{winch}\ddot{\varphi} + F_{cable} r_{winch} \tag{10}$$

with I_{winch} the inertia of the winch, F_{cable} the cable force and r_{winch} the radius of the winch. Based on inspection of the filtered signal and its derivative the Savitzky-Golay filter with a span of 17 ($\Delta t = 0.17\ s$) was chosen.

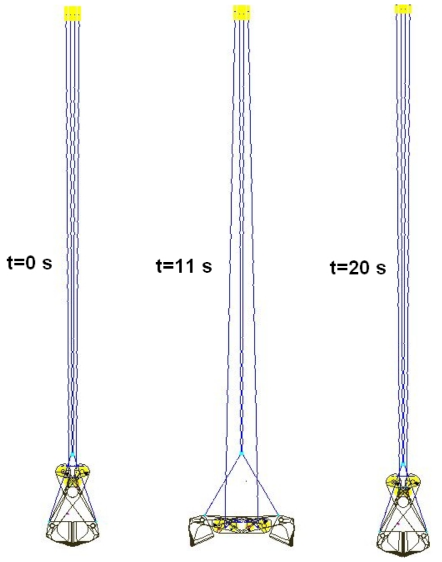

Figure 5. Position of the grab at different moments.

In order to prevent cable slack during lowering of the grab towards the surface of the bulk material, a detection mechanism was implemented to stop crane winches when cable forces dropped to zero. This enabled the winches to start the closing curve without winding up excessive cable length first.

4. VALIDATION

Now that the model and input to the model have been described, the multibody model can be validated in two steps: kinematic and static verification and dynamic validation.

Grab kinematics in the simulation were compared with the theoretical movements of the mechanism. All points on the grab behaved as expected. The length of cable required to open the model matched also specifications. Static verification was achieved by opening the grab at different opening angles and comparing cable forces of the model with calculations based on the equations of equilibrium. The model was verified for all the angles (Figure 6).

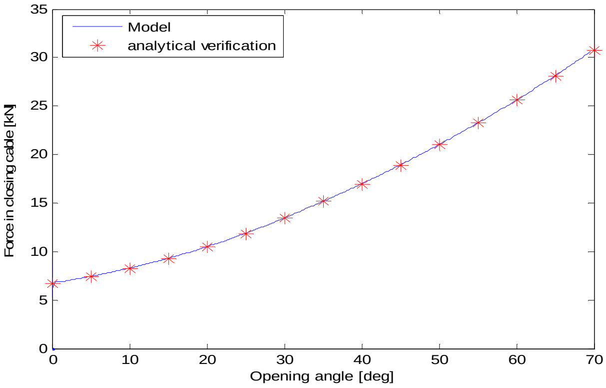

Figure 6. Force of the closing cable

For the dynamic validation, torques computed in the winches are compared with motor torques recorded during experiments. In these experiments, motor rotational velocity and torques were measured during the opening and closing of an empty grab. Two experiments were conducted: one where opening and closing speeds were half lower than normal operation (opening and closing in 20 seconds), the other one using normal operating speeds with opening and closing in 12 seconds. The input consists of the rotational speeds of the drums (Figure 4), resulting in opening and closing of the grab. The input is used in the model and the output of the model should compare well to the output of the real system (Figure 7).

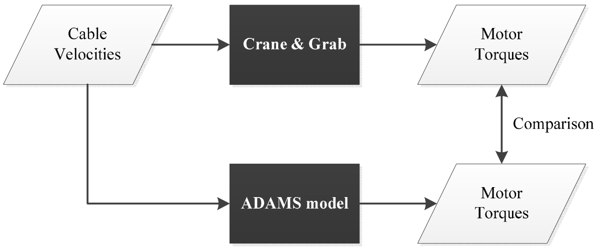

Figure 7. Comparison used during validation

The output of the model using the unfiltered input is shown in Figure 8 with R^2 of 0.32. The noise in the output is caused due to the strong influence of the derivative of the input. When a filtered signal is used as input, the R-squared increases to 0.91, as can be seen in Figure 9. The difference at the end of the simulation is caused by the not completely closing of the grab, this results in high forces on the hoisting cables instead of dividing the load between the closing and hoisting cables. Also a faster input, e.g. opening and closing in 12 seconds was examined as well. The model predicted the outcome very well, with $R^2 = 0.97$ for the closing cable.

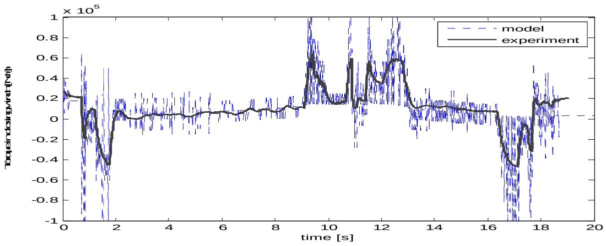

Figure 8 Model output using unfiltered input compared to measured signal from experiment. $R^2 = 0.32$

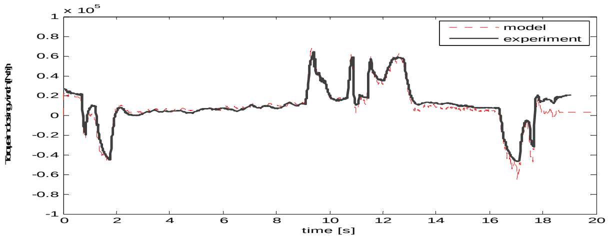

Figure 9. Model output using filtered input compared to measured signal. $R^2 = 0.91$

Figure 10 shows the torque of the hoisting winch, both the output predicted by the model as well as the measured output. The measured output drops to zero during the opening of the grab, which is caused by the brake of the winches. The modelled winches have no brake and have to hold the cables in position. At the end the model predicts higher torques than measured; this is also caused by the grab not completely closing. The R-squared between t = 11.4 and t = 18 reaches 0.71. In the faster scenario, similar agreement was reached with R^2 of 0.76. If the input is adjusted so the grab completely closes, this model is acceptable for a co-simulation and can be used for design purposes.

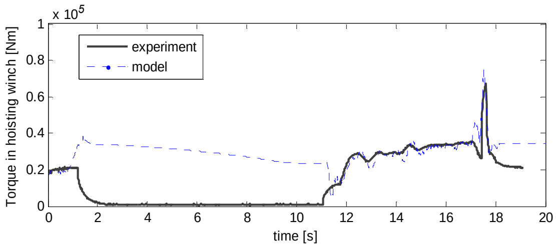

Figure 10. Model output of hoisting torque compared to measurements. $R^2 = 0.71$ for $11.4 < t < 18$ s.

5. CONCLUSION AND OUTLOOK

This paper has shown the steps towards a validated multibody model of a grab, ready for co-simulation with a DEM software package. The predictions of the model compared well with the measured output, but only after smoothing was applied to the input signal. Influencing factors on the behaviour of a scissors grab were the weight and inertia, the cable properties and friction caused by the bearings.

For the co-simulation with the DEM software package, the coupled geometries will be equipped with markers and force elements at the centre of mass. Using these markers the coupling will send the position of the geometry to the DEM package which will compute the corresponding load on the geometry. This is send back to the multibody simulation using the mentioned force elements. With this validated grab model and a validated material model, the overall co-simulation has to be validated.

ACKNOWLEDGEMENTS

The work described here was supported by grab manufacturer NEMAG, the Netherlands. Their support is gratefully acknowledged.

REFERENCES

[1] Scheffler, M., Pajer, G., and Kurth, F.: *Grundlagen der Foerdertechnik*, Berlin VEB Verlag Technik, 1976.

[2] Miedema, S.A., Becker S., Jong, P.S., and Wittekoek, S.: On the closing process of clamshell dredges in water saturated sand, in: *Proceedings of WODCON XIII*, Bombay, India, 1992.

[3] Yoo, W.S., Kim, K.N., Kim, H.W and Sohn, J.H.: Developments of multibody system dynamics: Computer simulations and experiments, Multibody System Dynamics, Vol. 18, No. 1, pp. 35–58, 2007.

[4] Park, J.Y., Yoo, W.S., and Park, H.W.: Matching of flexible multibody dynamic simulation and experiment of a hydraulic excavator, in: *Proceedings of ACMD2004*, Seoul, Korea, 2004, pp. 459–463.

[5] Langerholc, M., Česnik, M., Slavič, J., and Boltežar, M.: Experimental validation of a complex, large-scale, rigid-body mechanism, Engineering Structures, Vol. 36, pp. 220–227,. 2012.

[6] Feyrer, K.: *Wire Ropes: Tension, Endurance, Reliability*, Springer, 2007.

[7] CASAR Drahtseilwerk Saar GmbH.: http://www.casar.de.

ДИНАМИЧКИ МУЛТИБОДИ МОДЕЛ МАКАЗАСТЕ ГРАБИЛИЦЕ ЗА КО-СИМУЛАЦИЈУ МЕТОДОМ ДИКРЕТНИХ ЕЛЕМЕНАТА

Штеф Ломен, Дингена Л. Шот, Габријел Лодевајкс

Циљ овог истраживања је провера Методе дискретних елемената и мултибоди динамике маказасте грабилице у циљу виртуелног прототајпинга. Обе компоненте морају бити проврене пре провере целукупног модела и његове примене у процесу пројектовања. Циљ овог рада је провера мултибоди модела маказасте грабилице. Маказаста грабилица је моделирана са обухваћеним котуровима и ужади. Као улаз у модел коришћен је виртуелни дизаличар који затвара и отвара празну грабилицу. Моменти на витлу одређени су симулацијом и у сагласности су са измереним вредностима па је самим тим и мултибоди компонента ко-симулације проверена.