OUTSMARTING HEAVY EQUIPMENT DESIGN

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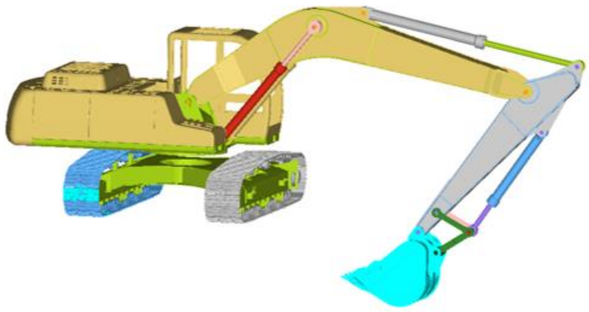

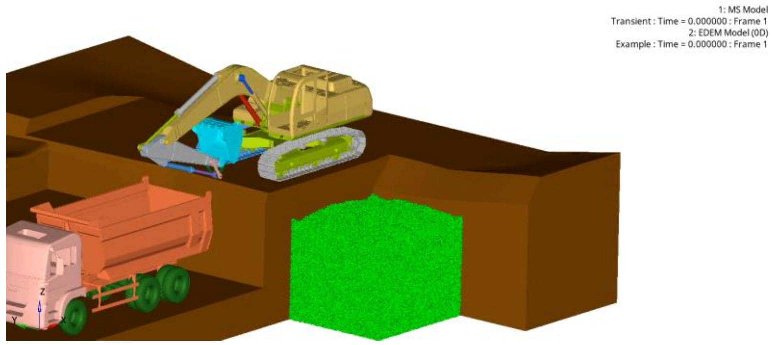

Abstract

Heavy mobile machines consist mostly of production equipment working almost twenty hours a day, year on year, in diverse harsh environments, undergoing extreme loads and overloads. Especially diggers and loaders such as hydraulic excavators, wheel loaders, and backhoes, cater to multiple applications with use cases such as digging, trenching, loading, lifting, breaking, and ripping. Many times, these machines undergo non-standard uses where the machine is subjected to unplanned forces and moments as in the case of self-loading on a trailer, or a bucket hitting a dump truck body.

It’s a challenge for OEMs to design these machines to perform against such conditions and invariably, designers fall back onto their legacy and tribal knowledge assisted with whatever physical test data that exists in the company. Over time, well established OEMs have garnered huge amounts of knowledge and data over decades of field experience. These OEMs have judiciously interfaced legacy with modern technologies to design products that are best in class.

Machine use cases occurring in the field puts multiple types of loads on the work equipment, which is essentially multi-physics in nature such as mechanical forces and system-generated forces, like hydraulic surges and machine-to-soil interaction forces. Among these forces, today’s technologies have well advanced to separately capture the forces using multi-body dynamics for mechanical forces, 1D model-based system simulation with the Modelica hydraulic library, soil interaction, and bulk soil forces using discrete element methods.

This extensive use of simulation technologies has enabled more reliable designs and a move away from the traditional workflow of ‘make, break, and fix it’. A simulation-driven design approach requires robust CAE solvers which can be used in an integrated manner.

Currently, Altair’s simulation portfolio offers integrated multi-physics solutions with products like Altair® MotionSolve®, Altair® Activate®, and Altair® EDEM™. Co-simulation and model exchange techniques are typically useful for FMI / FMU integrated simulation across multi-solvers to accurately capture multi-physics parameters. This paper highlights the workflow process and simulation-driven methods to integrate multi-physics with Altair’s industry-leading solutions. The latest generation of Altair simulation tools can capture a wider range of vehicle systems and environmental interactions including:

1. 3D multi-body representation of motion
2. 3D FE (finite element) representation of structures
3. 3D DEM (discrete element method) representation of soil and terrain
4. 1D representation of electrical and hydraulic controls
5. 0D math models of specific phenomena or physics

Introduction

The focus of this whitepaper is on demonstrating a user-level workflow on a mid-sized hydraulic excavator. An excavator is subjected to multiple rigorous use cases while in operation. The most critical use case operations are trenching, deep digging, ripping, maximum breakout force applications, truck loading, and self-loading. A fully instrumented excavator under consideration is shown in Figure 1 with 170+ channels of data acquisition comprising of strain gauges, LVDTs for cylinder lengths, pressure transducers, load cells, flow meters. A close-up view of sensors on the structure is shown in Figure 2.

Figure 1 – Fully instrumented test equipment

Figure 2 – Close-up view of sensors mounted on equipment

The physics of each of these operations are fairly different and complex resulting in wide variations of forces at hard points depending on the operation, soil conditions, and operator's and machine efficiency. A few images of deep digging are shown in Figure 3 and Figure 4.

Figure 3 – Deep digging operation

Figure 4 – Second view of a deep digging operation

For this exercise, a 'truck loading' operation was chosen where all the three elements of forces, namely kinematics, hydraulics, and soil reaction could be integrated for the analysis. A truck loading operation is shown in Figure 4.

Figure 5 – Truck loading operation

Listed below are the Altair simulation tools used and the role they played within the workflow:

- MotionSolve / Inspire Motion – Rapid setup of multi-body model from CAD
- Activate – 1D block-diagram model of hydraulics systems
- EDEM – Bulk material model of soil/structure interaction
- Altair® HyperMesh® / Altair® OptiStruct® – Preparation of flex body for boom and arm components
- Altair® MotionView® / MotionSolve – Multi-body system integration environment that combines all of the above
- Altair® HyperView® / Altair® HyperGraph® / Altair Compose® – Post-processing to visualize kinematics, loads and stresses

Multi-body Dynamics

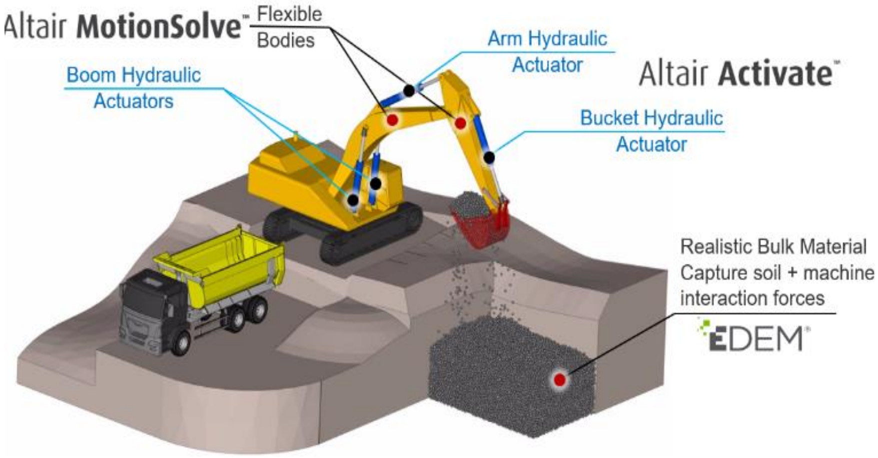

Figure 6 – MotionSolve, Activate, and EDEM work together for a full dynamic study

The modeling process began with using existing CAD geometry to create a simple functioning model of the excavator inside Inspire Motion. Here, it was validated for basic kinematic behavior prior to being transferred to MotionView for a more detailed setup and analysis. Running on the same MotionSolve engine that runs MotionView, Inspire Motion allows for quick and easy model organization, part grouping, joint creation, and basic motion assignments to validate the initial setup and kinematics of the excavator.

First, parts which do not move can be defined as “grounded". Then, parts that have no relative motion between them, such as components of the cab assembly, are organized into rigid groups. Rigid groups are treated as a single body, yet all mass and inertia of the grouped parts are collectively included. This helps facilitate a cleaner and more organized model when it comes to assigning joints to parts.

Next, joints between moving parts and between moving parts and rigid groups are added using Inspire Motion’s automatic joint detection capability. This feature uses the CAD geometry in the model to match similar geometry pairs, such as two aligned holes or a ball and socket, allowing several joints to be added in a matter of seconds. Following this, all joints are checked for proper degree of freedom assignments.

“Actuators” are added at each piston/cylinder pair in MotionView to represent the hydraulic system, shown in Figure 7. MotionView auto-finds the existing cylindrical joints between the piston/cylinder pairs and allows them to be converted directly to actuators. Using the Profile Editor, shown in Figure 8, simple time-dependent displacements are assigned to each actuator to verify the movement and proper joint connections.

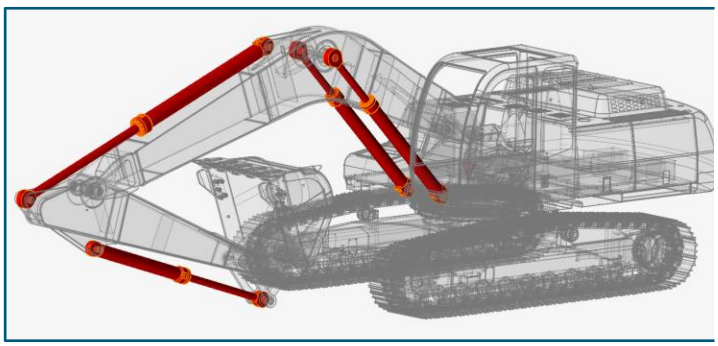

Figure 7 – Using the “Actuators” feature to assign simple validation inputs

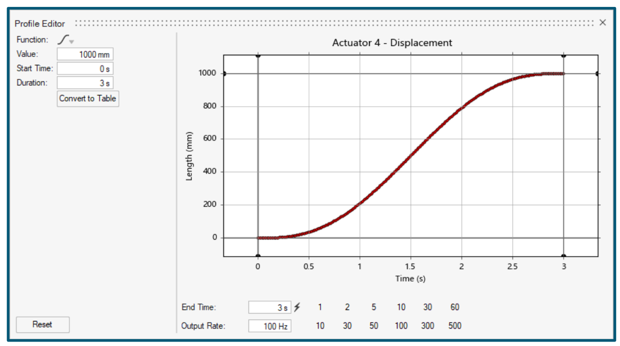

Figure 8 – Defining inputs with the Profile Editor feature

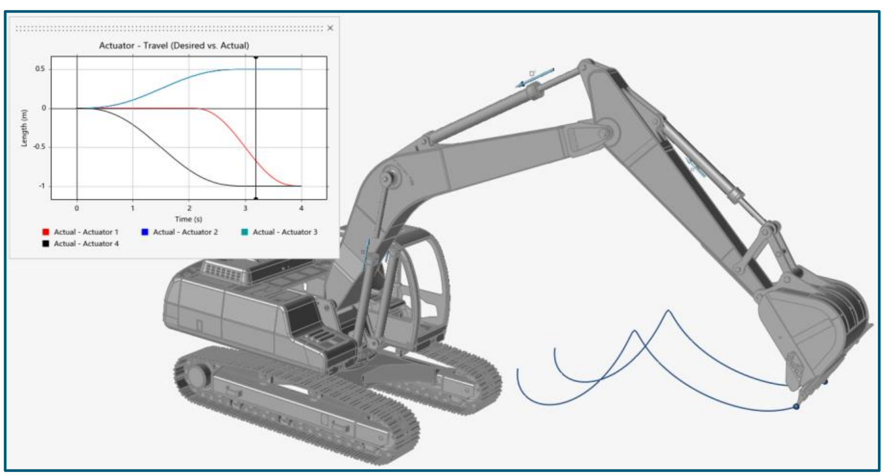

Figure 9 – Completed Motion model using stepped-displacement input functions

Finally, with the kinematics verified as working correctly, the model is exported as an *.mdl to be run in MotionView. This is a simple single-click process. During the export, units can be carried over or changed to another unit type. In this case, MMKS was used. Figures 7, 8, and 9 show the various motion set-ups.

MotionView Model (Multi-body Dynamics)

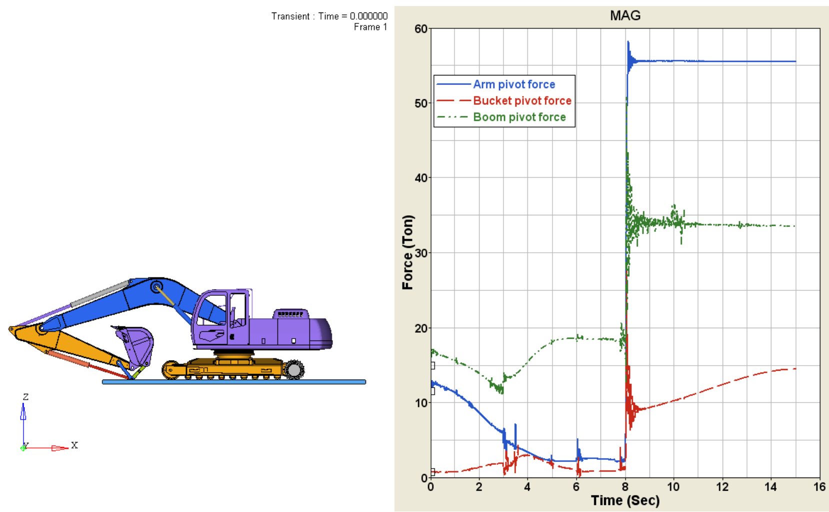

Figure 10 – Pure multi-body joint forces for truck loading operation

MotionView, Altair's general purpose multibody pre-processor, comes into the workflow at the point where advanced features such as flex bodies, 1D FMU, and EDEM integration are required. A .mdl file exported from Inspire Motion will open in MotionView and solve in MotionSolve directly. A joint force MBD analysis is shown in Figure 10.

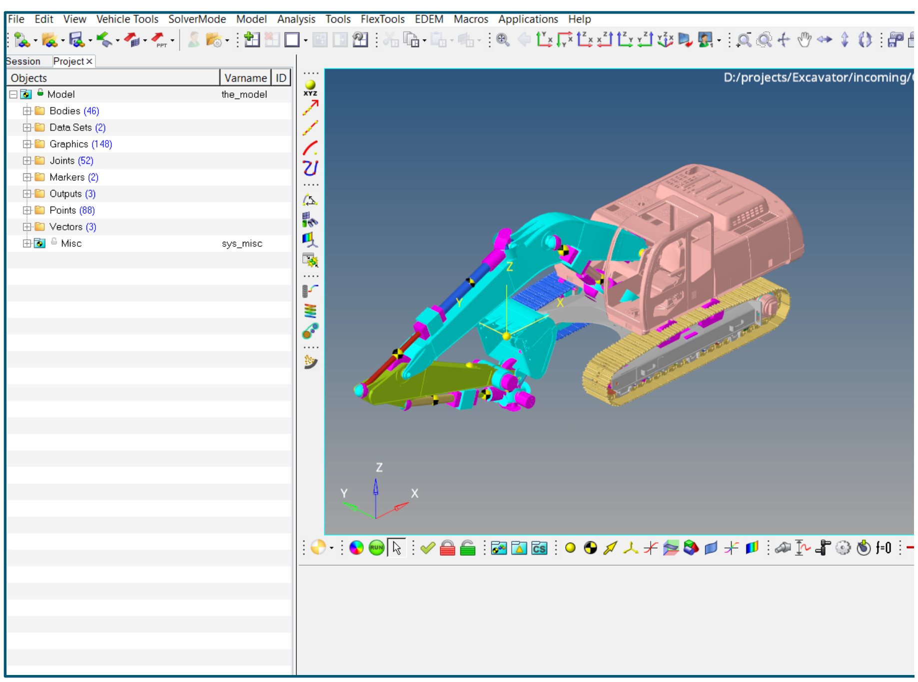

Figure 11 – Model viewed in MotionView

A user may want to re-organize the exported model into separate sub-systems, since it imports as a flat hierarchy which isn't conducive to convenient debugging and modularization later. This can be done using a cut and paste method in the context menu that appears by right-clicking in the Project Browser. After this is done, it's always a good idea to re-run this model and double-check the .log file output from MotionSolve for any redundant constraints or other issues. Although this is uncommon, it can happen due to the re-organization process being manual in nature. The MotionView model is shown in Figure 11.

Because the event chosen for the purpose of this paper, truck loading, does not involve mobility of the excavator over a road or soil surface, a user can simulate the excavator kinematics using the following steps:

1. Vehicle is stationary
2. Extend boom and link arm
3. Scoop sand
4. Lift bucket
5. Turn carriage
6. Dump sand

The excavator model was comprised of three parts: a kinematic model using MotionSolve, a hydraulic model using Activate, and soil to machine reaction forces using EDEM. This series of operations was performed using target cylinder lengths as time domain data and force control.

Before the 1D hydraulic model could be created and integrated, the model was actuated with motion constraints applied on each of the boom, arm, and bucket cylinders, as well as swing of the hood-cab. Filtered time history of the cylinder and cab displacements (positions) from physical test data was inputted as curves, which were then assigned to the motion constraints. These motion constraints serve a useful purpose – a baseline to verify the actuation of the hydraulics model. It is important to choose the correct sampling rate, filter, and interpolation method matched with the solver settings while reading in test data, so that the solver may run as efficiently as possible. The actuator displacement profiles are shown in Fig. 12.

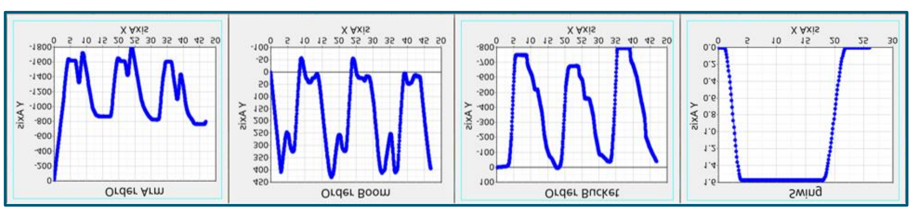

Figure 12 – Motion displacement profiles

Activate Model (Hydraulics)

The hydraulic system was modeled in Altair Activate utilizing the hydraulics block library. A hydraulic circuit schematic from a commercial excavator was the basis for the design. The hydraulic block diagram in simplified form is shown in Figure 13. Only the components necessary for the actuation of the boom, arm, and bucket are identified in the schematic and modeled in the Activate system diagram, namely:

- 3 motors
- 2 variable displacement pumps
- 4 hydraulic cylinders
- 3 three-way directional valves
- Relief and check valves

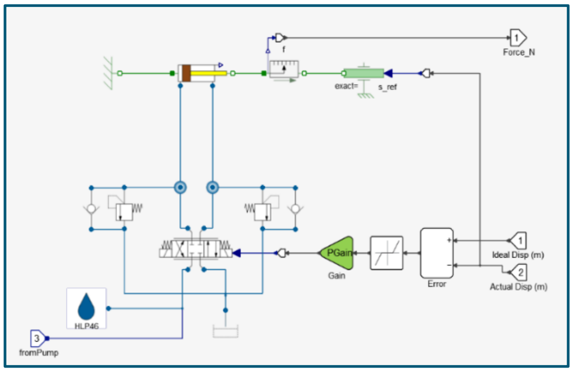

Figure 13 – Hydraulic circuit in Activate

Sizing and operational parameters of the cylinders matched those from the excavator specifications. A PID control was designed and implemented into the Activate model, which controls the swashplates of both pumps to maintain the required working system pressure during loading. Reference cylinder parameters are given in Table 1.

Parameters		Units	2.4m Arm
Main relief (Working) Pressure		bar	330
Cross port relief pressure		bar	380
Boom Cylinder	Pin to Pin - Max	mm	3170
	Pin to Pin - Min	mm	1850
	Stroke	mm	1320
	Bore dia in mm	mm	120
	Rod dia in mm	mm	85
Arm Cylinder	Pin to Pin - Max	mm	3873
	Pin to Pin - Min	mm	2198
	Stroke	mm	1633
	Bore dia	mm	135
	Rod dia	mm	95
Bucket Cylinder	Pin to Pin - Max	mm	2675
	Pin to Pin - Min	mm	1595
	Stroke	mm	1080
	Bore dia	mm	120
	Rod dia	mm	80
Max. Reach	Height	mm	9671
	Horizontal	mm	9612
	Depth	mm	-6264
Bkt Angle Rotation		deg	172

Table 1 – Cylinder parameters

Once the Activate hydraulic system was built, the multibody excavator model was introduced into the Activate system model as a plant for co-simulation. Unloaded, the hydraulic performance could be tested and verified against performance parameters set by the commercial excavator. Specifically, cylinder speeds for full extension and retraction could be measured to confirm correlation with the operating performance of the physical machine.

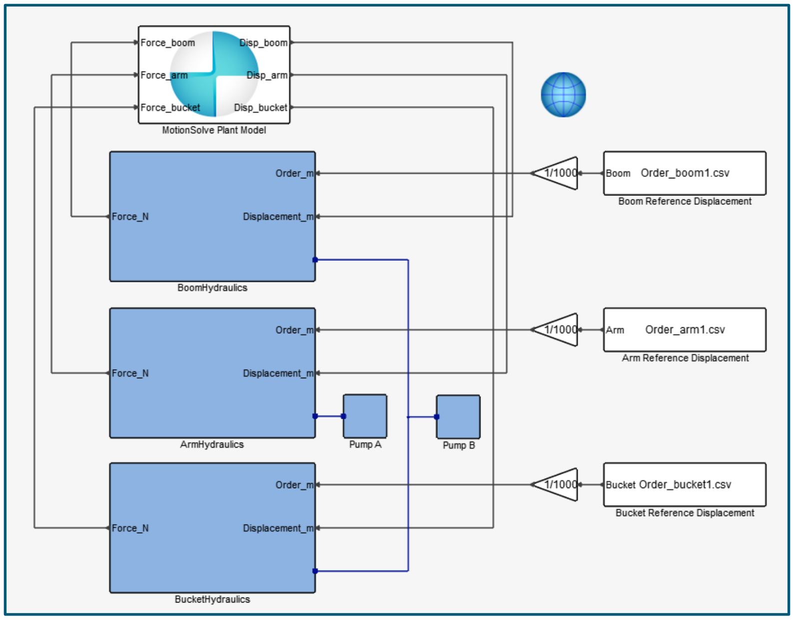

Figure 14 – Co-simulation inside Activate, hydraulics, and MotionSolve plant

With Activate as the primary tool in this co-simulation, hydraulic system parameters such as swashplate and valve command control can be tuned where necessary to reach the desired full system performance. The hydraulic subsystem had to be moved back into MotionView, however, to eventually be used in co-simulation with EDEM.

The hydraulics were packaged and exported as a functional mock-up unit (FMU). The inputs and outputs of the FMU were defined as follows:

- Inputs: Boom, arm, and bucket cylinder displacements
- Outputs: Boom, arm and bucket cylinder forces

The FMU was imported into the multi-body model in MotionView, the force signals were connected to drive each cylinder, and the excavator was now complete with a full hydraulic system. Plant co-simulation block diagram is shown in Fig. 14.

EDEM Model (Bulk Material) and Co-simulation

An accurate soil model was crucial to acquiring a complete load analysis of the excavator during operation. Often in commercial heavy equipment design, the effects of bulk material on system behavior are measured, painstakingly, through physical testing. With MotionSolve and EDEM co-simulation, however, this process was greatly streamlined.

Altair EDEM provides the GEMM Wizard tool for generating a baseline particle model based on a series of walkthrough prompts, namely range of bulk density (kg/m^3), angle of repose, and particle-to-particle:

- Coefficient of restitution
- Coefficient of rolling friction
- Coefficient of static friction

The baseline particle model generated by the Generic EDEM Material Model (GEMM) Wizard was further modified within EDEM Creator to fit the parameters of a moderately-dry sandy loam. An example of soil property screen is shown in Figure 15.

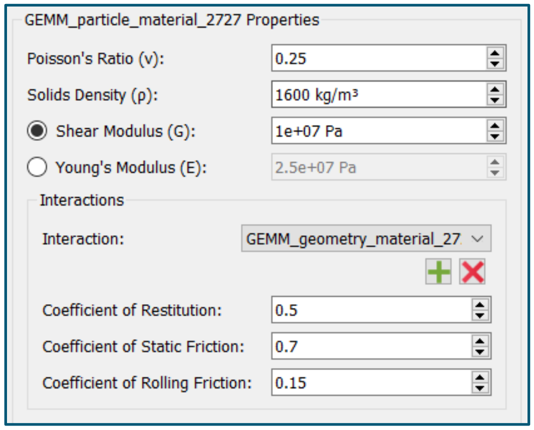

Figure 15 – Soil particle property editor inside Altair EDEM

Prior to introducing excavator geometry, a soil bed needed to be generated at the appropriate location for bucket loading. The commercial excavator specifications provide reach values for full extension of the excavator boom, arm, and bucket. These values were used to position the soil bed at the proper distance. The dimensions of the soil bed required for full bucket loading was determined with the help of the MotionView model. EDEM generated the bulk material within a virtual box and was then ready for interfacing with MotionSolve, as shown in Figure 16.

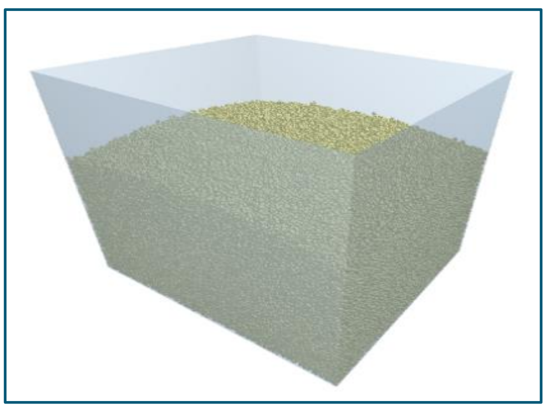

Figure 16 – EDEM-generated soil bed

The three bodies which contacted EDEM's particles were the bucket, the ground, and the truck bed. These CAD geometries were the only ones interfaced between MotionSolve and EDEM. To optimize simulation time, a dynamic domain was placed around the bucket from within EDEM, which allowed the solver to ignore all particles which were outside this boundary at any given timestep. The only time the particle dynamics were of concern was when they were near or in contact with the bucket. MotionSolve acted as the primary solver for this co-simulation. The co-simulation was launched from within MotionView and progress was monitored from EDEM Simulator.

After completion of the co-simulation, EDEM Analyst was used to verify and analyze the behavior of the bulk material during the loading cycle. Values such as the total loaded mass of the soil after bucket loading could be cross-referenced with physical test data to validate the soil model properties. Co-simulation post-processing within EDEM is shown in Figure 17.

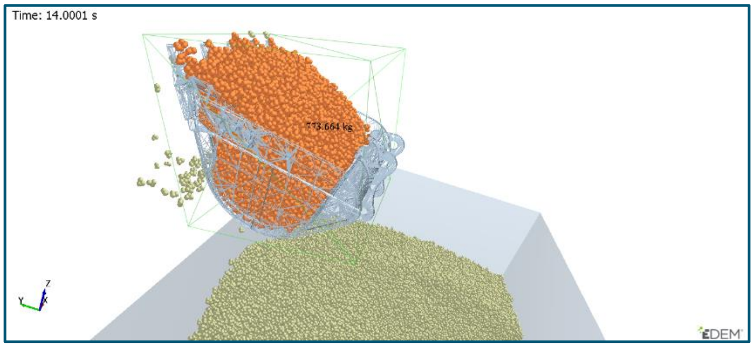

Figure 17 – Co-simulation post-processing inside EDEM Analyst

MotionSolve provided output data related to the bulk material forces acting on the bucket CG during transient simulation. For subsequent simulations where the analysis of particle behavior is not necessary, this force profile is a convenient way to implement a simplified representation of the bulk material load as shown in Figure 18.

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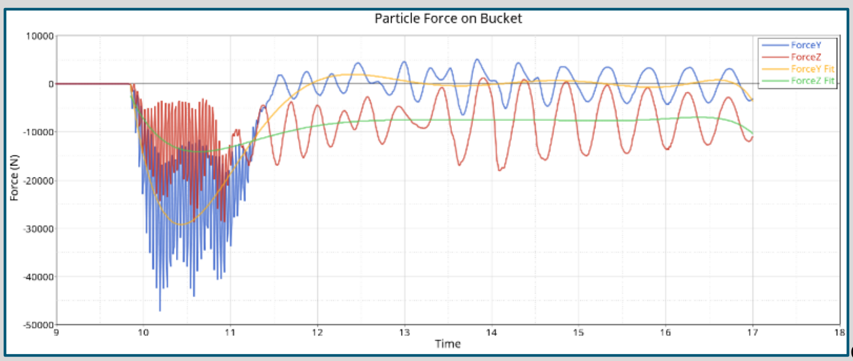

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Figure 18 – Soil loads on bucket CG

Results

The primary reason for incorporating a hydraulics system model into the multibody model was to validate performance of the subsystem during operation. If during the truck load test the hydraulics were unable to produce enough force to drive the cylinders and carry the bulk material effectively, components would have needed to be considered for resizing. One of the main ways this performance was validated was by viewing a plot of actual (measured) cylinder displacements vs. desired cylinder displacements, as shown in Figure 19.

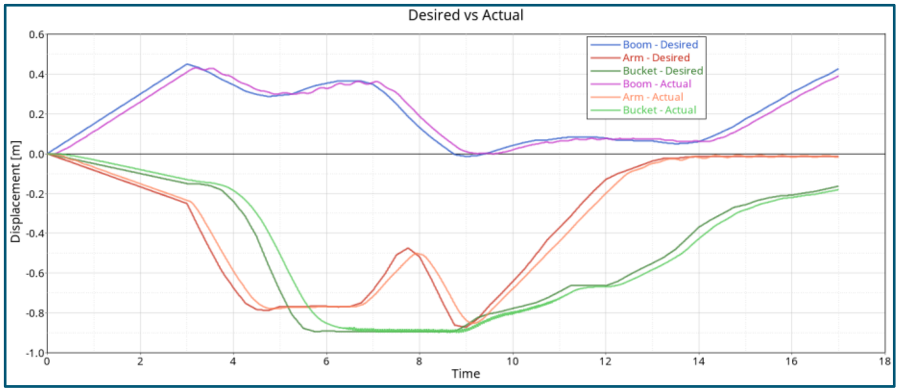

Figure 19 – Cylinder displacements (desired vs. actual) to validate hydraulic performance

The hydraulic system's ability to follow the desired signals rather closely confirms that the hydraulic pumps, valves, and cylinders were sized effectively for this excavator's truck loading routine.

Principal stresses for various locations on the boom and arm were plotted from the MotionSolve output (.h3d) using HyperView as shown in Figure 20. A report template was defined to repetitively plot multiple iterations. In addition, a user can plot displacement, velocity, acceleration, or loads at available locations in the multibody model per their requirements.

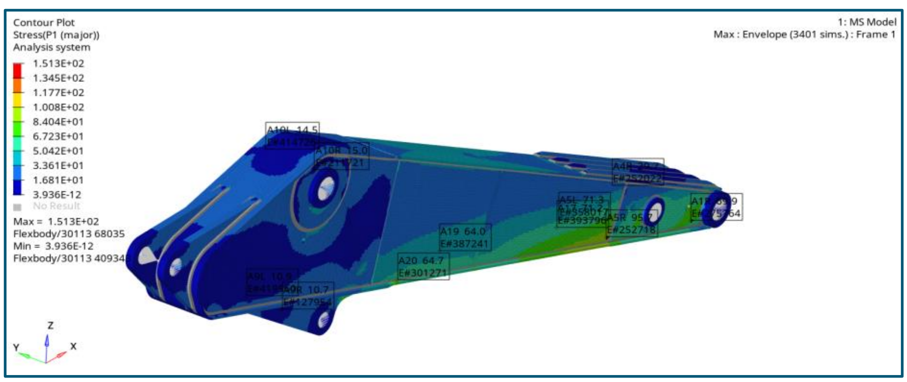

Figure 20 – Minimum principal stresses on arm

Post processing of results can be automated with Altair Compose, an integrated development environment with open matrix language, which has built-in API's (functions) to read CAE output files and do math operations efficiently and robustly. Output from MotionSolve (.h3d) is read into Altair Compose by "read case" function, which extract stress results – P1 Major and P1 Minor at specific elements on the flex bodies for different timesteps. For insights into the CAE Reader library please refer to the article: Extracting and Post-Processing CAE/TEST Results in Altair Compose in the Altair Community website.

Once the stress values were extracted for each element of interest at different timesteps, maximum and minimum was found for each element and compared with experimental results. The following table from an early set of runs demonstrates how different levels of fidelity with the systems model can affect stress results. Table 2 shows results from two levels of model fidelity:

- **Baseline** – Dig force represented with time-history and cylinders actuated by motion constraints
- **EDEM+FMU** – Dig force from EDEM and cylinders actuated by 1D hydraulics FMU

The “baseline” run was representative of a simple MBD-only model that is typical of what an established manufacturer might use. Such a model is only able to cascade dig force into the structure and joint loads for component sizing. It assumes that dig force time-history is available, either from instrumented testing on a physical prototype, or from analytical methods that make broad assumptions about operating conditions. The cylinder actuation is purely driven by a motion constraint (enforced displacement).

The “EDEM+FMU” run was a full multi-physics model. This is most useful when dig-forces cannot be adequately determined by analytical methods, or where physical testing is impractical – the dig force comes directly as a function of simulated structural interaction with bulk material. The stresses in this run were comparable to baseline as shown in Table 2. Representative flex body stress plots on structural members are shown in Figures 21 to 24.

	Base line		EDEM+FMU	
Channel	**Max**	**Min**	**Max**	**Min**
AI_R	97	-87	97	-86
A4_R	143	-119	117	-119
A5_R	133	-150	112	-109
A9_R	109	-114	91	-97
A16_R	151	-141	141	-141
A17	99	-110	99	-92
A18	211	-240	185	-172
A19	251	-282	199	-203
A5_L	103	-105	102	-87
A9_L	105	-108	91	-93
A10_L	143	144	141	-144

Table 2 – ARM principal stresses in MPa

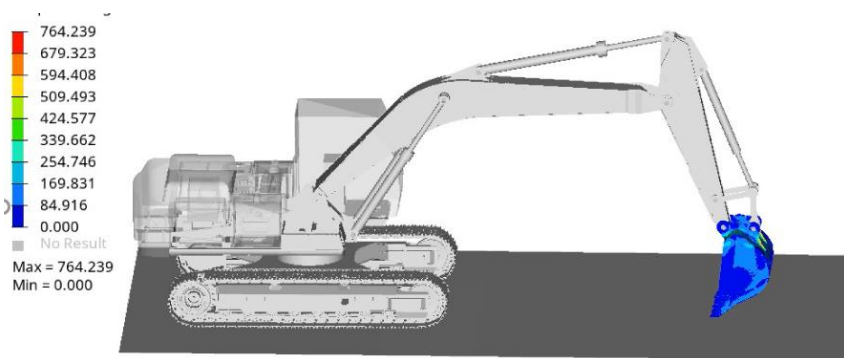

Figure 21 – Stresses in bucket

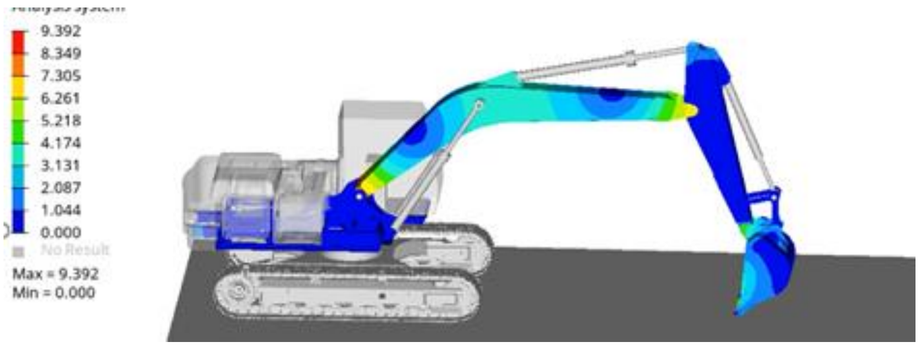

Figure 22 – Stresses in boom

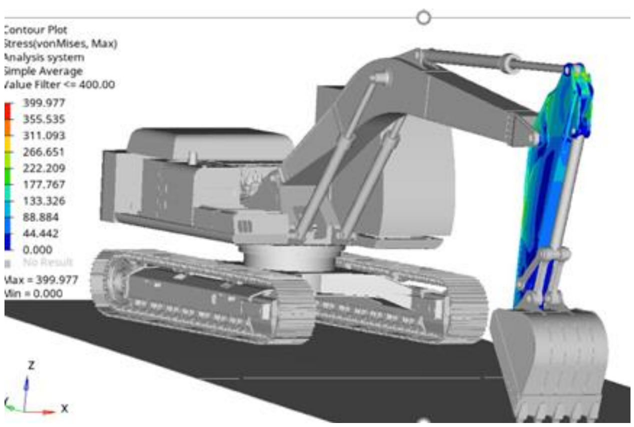

Figure 23 – Stresses in arm

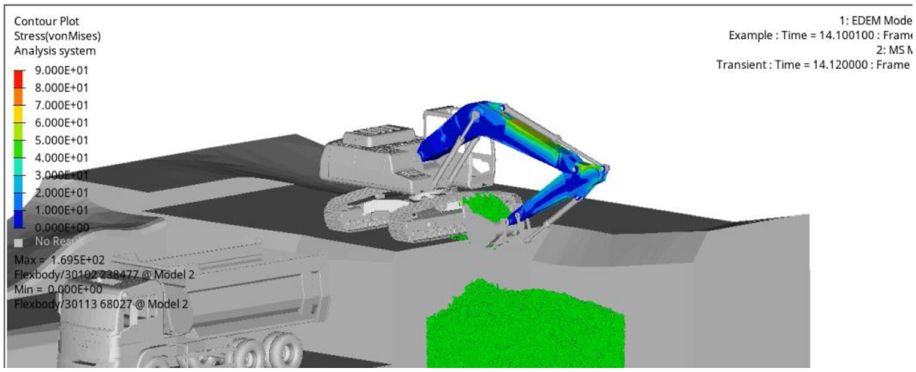

Figure 24 – Integrated co-simulation flex stress plot

Conclusion

A multi-physics co-simulation holds great value for manufacturers in the heavy machinery and agriculture industries as it provides a high-fidelity virtual simulation analysis alternative to time consuming and expensive physical testing and evaluation procedures, or analytical methods with broader than ideal assumptions. This system-of-systems approach allows engineers to make quick design choices at a subsystem level and measure the holistic performance improvement based on these changes. From component sizing to durability studies, co-simulations such as this are pivotal to understanding full-system behavior and making informed, reliable design decisions regarding complex systems.

To conclude, the use of 1D system modeling and EDEM with FMU is effective for early-stage design exploration as it enabled an efficient evaluation workflow processes towards systems' performance coupling multi-disciplines.

It is not out of place to mention that the designers need to capture the forces truly mimicking the real time work envelopes which would invariably need a deep domain knowledge of the equipment and application in construction, mining, or road making applications. For detailed FEA study, the loads from the joints can be extracted and mapped to the detail FEA models for further welds or fatigue evaluation under various critical loading conditions.

Moving forward, further work can be done to optimize the work equipment links with respect to load handling capability and to structurally optimize the critical elements like boom, arm, upper, and lower frames. Further taking into considerations the probable percentage of event occurrences of each use case during product life cycle, it would be possible to design the machine to a desired useful life using fatigue solvers. Much deeper understanding of the structural life can be made regarding weld strength and its life analysis using linear elastic fracture mechanics and hot spot stress methods.

Each use case can be customized into a Design Verification Plan (DVP) for product virtual validation much before a prototype is built. This proven integrated workflow is a boon to emerging and follower OEMs to design a more reliable product with least or no legacy background. This workflow enables capturing the right forces for each use case and when used as design inputs, the product comes out in shorter time with almost zero failures.

Acknowledgments

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