# Simulating an Electrohydraulic Self-Levelling Loader by Means of CAN Bus Connected Devices

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The necessity for greener, flexible and more efficient equipment has led OEMs and manufacturers to create intelligent fluid power systems. The complexity of the design of these integrated solutions, involving many fields of expertise, provides significant challenges. Control Specialists and system designers have their own knowledge domains so there is an increasing need to use an integrated simulation platform so they can work together. Hybrid modelling methods of mechatronics software, integrating equation- or model-based modelling and data-mapping from test results– known as Machine Knowledge Management – have many benefits. By combining these fields of expertise using co-simulation between software and hardware, control specialists and application experts will be properly integrated in the design and analysis process.

**Keywords:** CAN bus, Fluid Power, Electronic controls, Simulation, Mechatronics
**Target audience:** Mobile Hydraulics, Control Design, Machine Design

## 1 Introduction

CAE and testing tools continuously evolve to meet the needs of OEMs and system integrators in terms of development time, system accuracy and energy efficiency.

Therefore, the industries want simulation tools that allow macroscopic machine simulation without neglecting the realism of simulation models. These tools will improve the understanding of a machine's key functions and help people focus on the important simulation details. The models created must also be adjustable by integrating test or performance data and the know-how. The capability to communicate with controllers via CAN helps reduce the gap between experts involved in the design process in making tests and verification of electrohydraulic systems more efficient.

This paper demonstrates the design and testing of a self-levelling loader using a fully integrated multi-technology platform and co-simulation with CAN bus components. It aims to prove that this method can significantly reduce development and prototyping time in the product life cycle. Both Electronic Self-Levelling (ESL) and Hydraulic Self-Levelling (HSL) technologies are modelled for a generic tractor front loader, using HydraForce hydraulic valve models. Both virtual systems are actuated by a generic CAN bus Joystick and the ESL control is implemented in a HydraForce ECDR Configurable Valve Drive.

Section 2 explains how the hydraulic circuits and dynamics of the mechanisms were modelled in Automation Studio™ software both for the HSL and ESL front loader. Section 3 demonstrates how the CAN bus communication is achieved and set up to make the virtual system co-simulate with Automation Studio™. Section 4 presents simulation results under different conditions. The conclusion includes final remarks on how this will help the work process between Hydraulics and Control specialists.

## 2 Hydraulic and Mechanical Models

This section details a system that is co-simulated and controlled using CAN bus communication. The whole model is developed using the Hydraulic workshop and the Mechanism Manager workshop of Automation Studio™. The purpose of this section is not to summarize or recreate simulation formalisms and theories but rather to simply bring together existing approaches to make the simulation world relatable and adapt it to real world practical needs, such as illustrated in /2/ and /7/.

The studied system is a front loader typically attached to a tractor, used in the agricultural and construction industries. The mechanism consists of a boom and a bucket, each actuated by two hydraulic cylinders. The loader's self-levelling function, meaning that the bucket angle in reference to the tractor remains constant even when the boom is moving, is analysed more in details.

### 2.1 Hydraulic circuit design

#### 2.1.1 Electronic Self-Levelling (ESL) Circuit Design

The hydraulic modelling of the tractor front loader has been created with HydraForce's library of preconfigured components. Details of modelling aspects can be found in /2/, /4/, /5/ and /7/. It consists of a manifold with two identical sections that drive the hydraulic cylinders of the boom and the bucket. For both movements, two identical cylinders are connected in parallel and are inherently synchronized by the mechanism. Flow speed and direction are defined by the movement of the main pilot-operated directional valve, HydraForce HPE16-S67K. Pressure at the pilots is controlled by two electro-proportional pressure reducing/relieving valves, EHPR98-T35.

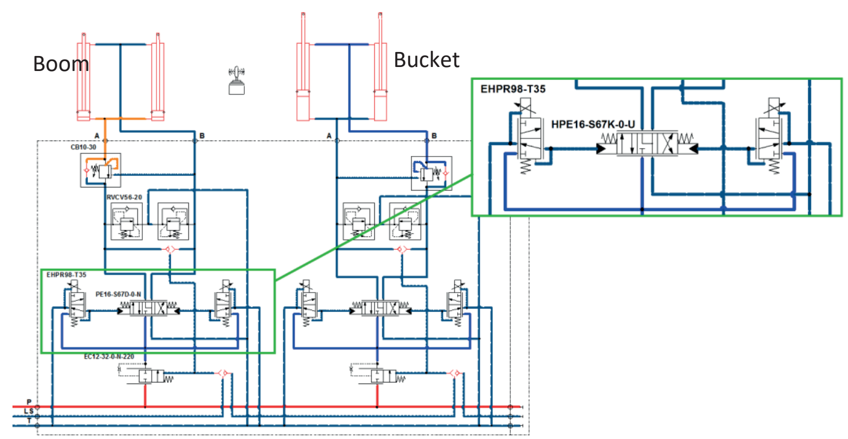


*Figure 1: Tractor loader hydraulic circuit design*

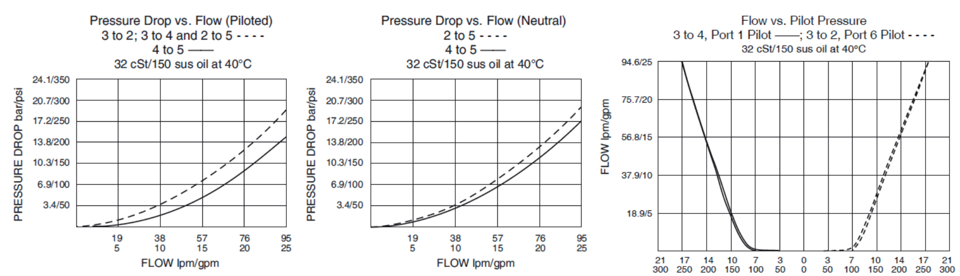


*Figure 2: Performance data of valve HydraForce HPE16-S67K /6/*

Both models were developed using data mapping to set the valve's aperture versus the course of the spool across the valve's stroke /6/. Figure 2 shows performance data used for mapping the model of the main spool HPE16-S67K: the first two graphs detail the pressure drop when the valve is fully open on either side and the third graph details the flow versus the pressure at the pilot ports for a pressure differential around 15 bar. Figure 3 shows the main performance characteristics used for their model of control valves EHPR98-T35.

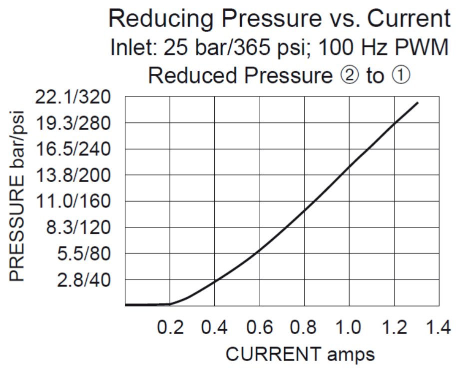


*Figure 3: Performance data of valve HydraForce EHPR98-T35 /6/*

The pressure differential is maintained across the main spool of the HPE16 valve by a pressure compensator valve EC12-32. Similar to other components, the compensator used has been preconfigured using theoretical relationship and tweak to match HydraForce performance results. Further adjustments can be easily made to improve model accuracy based on this specific application. Following figure shows an example of a virtual test bench used to set this component prior to add it to the system.

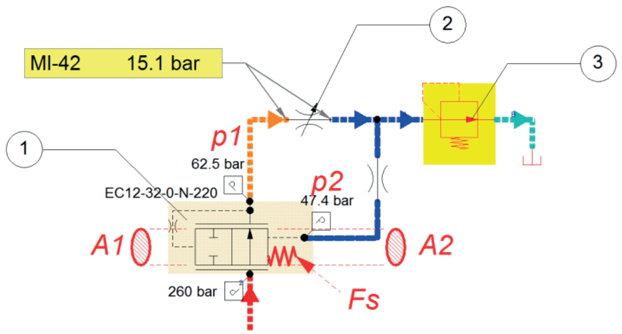


*Figure 4: Virtual test bench of pressure compensator*

The compensator EC12-32 is reaching a steady-state equilibrium point once the force on each side of to the spool of the valve will be equal (more details in reference /1/). From Figure 4, equilibrium point will be:

$$\sum F = 0 \tag{1}$$

Which yields to,

$$p_1 \cdot A_1 = p_2 \cdot A_2 + F_s \tag{2}$$

Assuming working area on each side of the spool of the valve equal, i.e. $A_1 = A_2 = A$,

$$\Delta p = p_1 - p_2 = \frac{F_s}{A} \tag{3}$$

By maintaining the differential pressure measured by (MI-42) proportional to the spring force $F_s$, which is set to get 15 bars in that case, flow to the actuators is maintained constant, regardless of the load pressure controlled by relief valve.

Two relief/anti-cavitation valves RVCV56-20 were added to maintain system pressure below 250 bar and to prevent cavitation. Motion control (counterbalance) valves CB10-30 were added for load holding and limiting retracting speed of the boom and bucket.

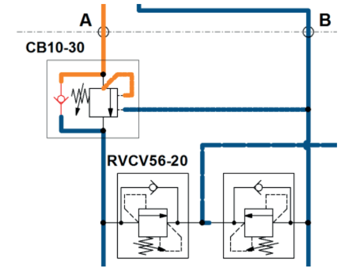


*Figure 5: Counterbalance and relief valves HydraForce CB10-30 and RVCV56-20*

Cylinders were sized to allow a full extension below time of 5s or less. Knowing that the nominal flow $Q_n$ of the main spool HPE16-S67K is 95 l/min and that the stroke $S$ (set by the mechanism geometry) is 780 mm, the piston diameter $D$ is found using Equation (4). Assuming a constant flow divided equally across two cylinders:

$$\int_0^5 \frac{Q_n}{2}\, dt \geq \frac{\pi D^2 S}{4} \tag{4}$$

The cylinders' rod diameter $d$ was sized so that retraction time is 75% of extension time as shown in Equation (5).

$$d \leq \sqrt{1 - 0.75}D \tag{5}$$

Results yield $D \leq 64.6\ mm$; $d \leq 32.3\ mm$.

More details on modelling and sizing methodology of different components can be found in /2/ and /7/.

### 2.1.2 Hydraulic Self-Levelling (HSL) Circuit Design

The circuit design for the HSL loader is almost identical to the design presented in section 2.1.1. To achieve levelling of the bucket when the boom is moving, an additional passive cylinder is added to the circuit as shown in Figure 6. The passive cylinder is attached to the boom and follows its movement, extending the bucket cylinders slightly when the boom is moving up and having the opposite effect when the boom is moving down.

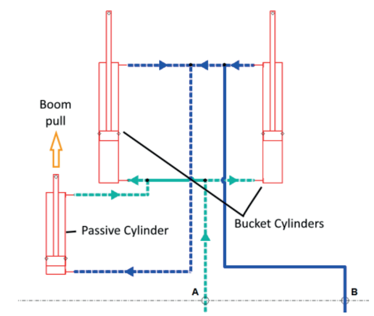


*Figure 6: Hydraulic Self-Levelling passive cylinder schematic*

### 2.2 Mechanisms Design

The mechanisms for both ESL and HSL front loader systems were developed using the Automation Studio™ Mechanism Manager. It allows creating 2D mechanisms that consist of bodies with mass and rotational inertia attached to each other by pivot, slider or rigid contacts at their nodes. A fixed body is always used as a reference.

Cylinder bodies in the mechanism have unique properties: their geometry and movement are defined by the hydraulic simulation. These properties can be easily adjusted.

Interaction/Co-simulation with the hydraulic simulation is done in two directions: forward dynamics, where the hydraulics simulation provides forces/torques and the mechanical simulation computes linear/angular accelerations, and inverse dynamics /2/.

#### 2.2.1 ESL Mechanism Description

The mechanism designed for this case study is a generic front loader that scales to a medium to large tractor. Bodies' geometry and parameters may be modified to match further design constraints. Figure 7 show a detailed view of the loader mechanism. Pivot joints are represented by transparent circles and bodies' centres of mass are represented by dowel symbols. $\theta_{boom}$ and $\theta_{bucket}$ represent the rotation angles of the boom and bucket around their main pivot, as a reference to the X axis. Table 1 lists all the bodies and their main parameters and values used for the analysis. A load identified as $W$, in the direction of Y-axis, follows the centre of mass of the bucket to simulate material carried by it. It is linked to a manual input by the user during simulation.

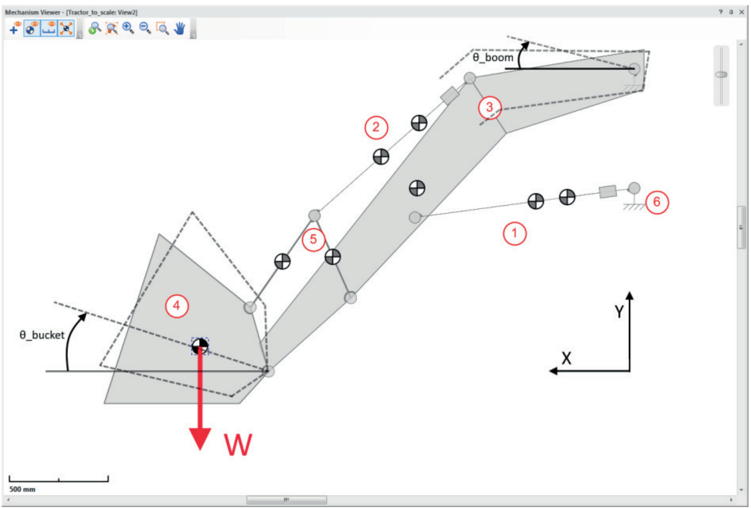


*Figure 7: Front loader mechanism without passive cylinder*

| No. | Body | Mass ($kg$) | Rotational Inertia ($kg \cdot m^2$) |
|---|---|---|---|
| 1 | Boom Cylinders (2) | Negligible | Negligible |
| 2 | Bucket Cylinders (2) | Negligible | Negligible |
| 3 | Boom | 150 | 0.36 |
| 4 | Bucket | 150 | 0.23 |
| 5 | Bucket Arms (2) | 10 | 0.052 |
| 6 | Frame (Reference) | - | - |

*Table 1: Loads of loader mechanism*

#### 2.2.2 HSL Mechanism Description

The mechanism for the Hydraulic Self-levelling loader is the same as the one described in section 2.2.1, with the addition of the passive cylinder attached by pivots to the boom and the frame. Like other cylinders in the mechanism, its mass and rotational inert are negligible.

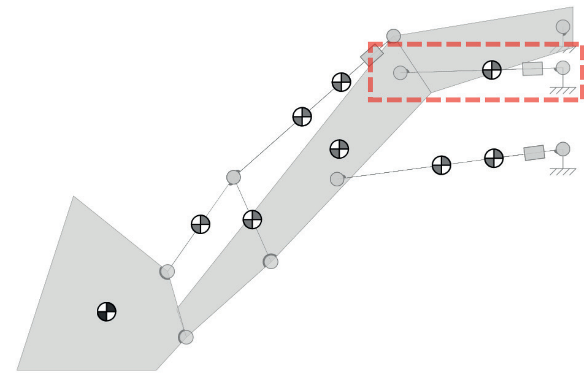

*Figure 8: Front loader mechanism with passive cylinder*

## 3 CAN bus Communication and Controller

This section describes the CAN bus technology and the components used for the case study, as well as the control methodology for the Electronic Self-Levelling (ESL) and Hydraulic Self-Levelling (HSL).

### 3.1 Connected devices

In this case study, two devices were connected to Automation Studio™ via a Kvaser Leaf Light HS v2 CAN /9/ to USB adaptor: a CAN bus joystick and a HydraForce ECDR-0506A /9/ Electronic Control Unit.

In Automation Studio™, the signal from joystick is received by a component Joystick CAN. The joystick CAN is associated with the dedicated PNG. The joystick gives the values in X and Y axis, as well as the state of the buttons. Specific function blocs have been created in Automation Studio™ to communicate with the controller: Customizable CAN Transmitter (ECU Tx) and Customizable CAN Receiver (ECU Rx). These items are customizable to give the user the possibility to modify the Identifier number and Data format and to communicate with nonstandard devices (Figure 10).

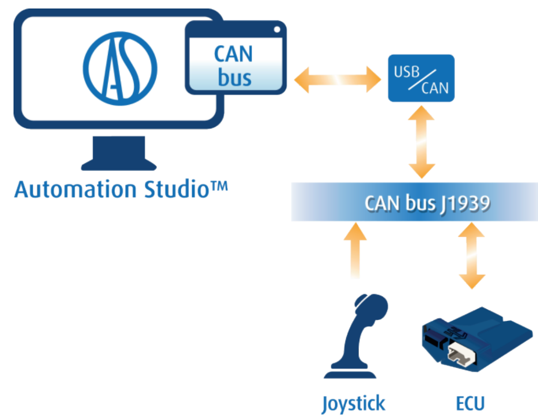


*Figure 9: CAN bus devices connectivity diagram with Automation Studio™*

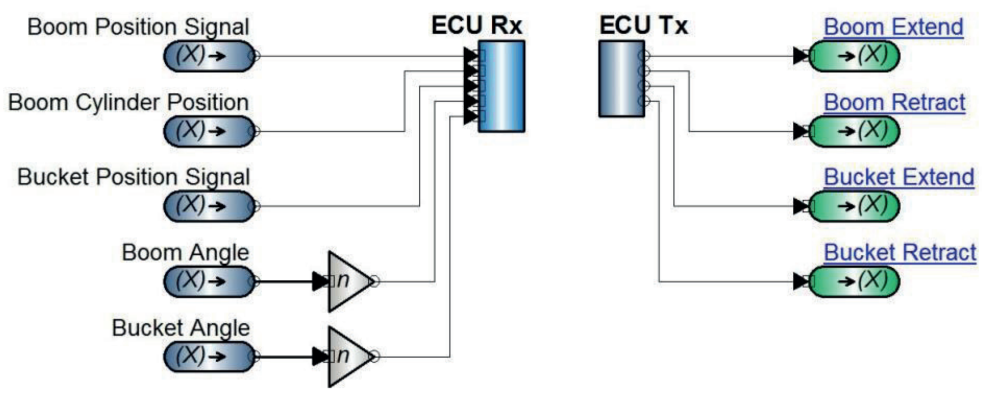


*Figure 10: CAN bus communication blocks*

### 3.2 Electrohydraulic Model and CAN Bus Data

Figure 11 illustrates how the different parts of the simulation environment are integrated together and how they contribute to generate this design and validation tool concept (Model and CAN bus devices). The figure shows that CAN bus communicates signals from joystick and ECU to the simulation software. The ECU receives output signals from the multi-technology software which are calculated to generate the response back to the software. The simulation model can integrate hydraulic, pneumatic and electrical component models and mechanism model. Control algorithms can be programmed in the software with mathematical block diagram module in order to validate a specific logic of the controller. Analysis tools such as measuring instruments recorder and plotter allow tracing results of the solution scenarios for validation.

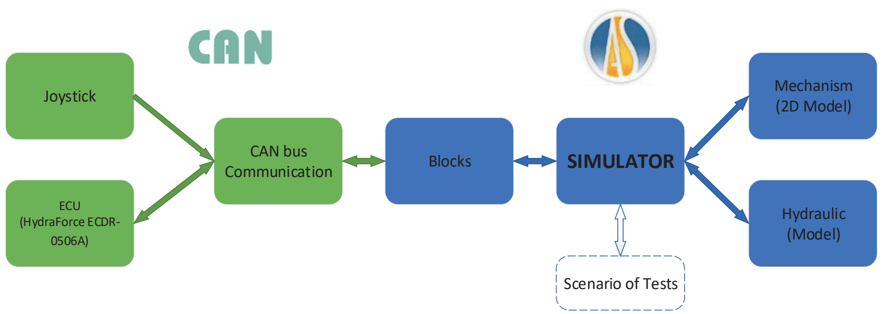


*Figure 11: Structure of communication between Automation Studio™ and CAN bus components*

### 3.3 Control methods

The control logic is designed and compiled using software HF-Impulse /6/, which is compatible with the HydraForce ECDR-0506A ECU /9/.

#### 3.3.1 Electronic Self-Levelling (ESL) Control

For the ESL loader design, the boom and bucket positions are controlled using PID (Proportional, Integral and Derivative) control logic. Both have their position set by an input signal generated by the joystick. Their feedback signals are generated by angle sensors used to measure their angular position.

For the control of the boom, two PIDs ($PID_1 and\ PID_2$), described in Equations (8) and (9), are used to generate the control signals in the directions of the extension and retraction of the cylinder. Set point $SP$ and feedback $F$ are the two input signals scaled to range from 0 to 1000. This range was chosen to allow decent precision and a minimal number of bits used in the CAN signal (10 bits). Moreover, the ECU may only process positive integer values /9/. For this reason, a positive error $\epsilon^+$and a negative error $\epsilon^-$are calculated in Equations (6) and (7).

$k_p$, $k_i$ and $k_d$ are the proportional, integral and derivative gains of the two PIDs. These values can be optimised during testing to improve the response and update the control algorithm easily for different hydraulic and mechanical system designs. $t$ is the time variable and $s$ the complex frequency (Laplace domain).

Equations (10) and (11) describe the logic of the two output currents $I_{ext}$ and $I_{ret}$, activating the extension and retraction solenoids, respectively, of the boom's control valves. An offset value $\varphi$ is added to both signals to compensate the dead band of both the electro-proportional pressure reducing valves and the pilot-operated main spool.

$$\epsilon^+(t) = SP(t) - F(t) \tag{6}$$

$$\epsilon^-(t) = F(t) - SP(t) \tag{7}$$

$$PID_1(s) = \epsilon^+(s)\left(k_p + \frac{k_i}{s} + k_d s\right) \tag{8}$$

$$PID_2(s) = \epsilon^-(s)\left(k_p + \frac{k_i}{s} + k_d s\right) \tag{9}$$

$$I_{ext}(mA) = \begin{cases} PID_1 - PID_2 + \varphi, & PID_1 > PID_2 \\ 0, & PID_1 \leq PID_2 \end{cases} \tag{10}$$

$$I_{ret}(mA) = \begin{cases} PID_2 - PID_1 + \varphi, & PID_2 > PID_1 \\ 0, & PID_2 \leq PID_1 \end{cases} \tag{11}$$

The control of the bucket uses the same equations described above. But, to add the self-levelling mechanism, input signal $S$ (used in Equations (3) and (4)) is replaced by $SP'$, which is the result of Equation (7). This added logic dynamically adjusts the set point of the bucket in order to compensate for the movement of the boom.

$$SP' = SP_{bucket} - SP_{boom} \qquad (11)$$

#### 3.3.2 Hydraulic Self-Levelling (HSL)

For the HSL loader design, the boom and bucket are not controlled by position but by speed, using proportional control on the valve as function of the joystick command. The mechanism position is then manually adjusted by the operator because there is no feedback from any mechanism sensors. The self-levelling function is done hydraulically using the passive cylinder described in section 2.2.2.

Equations (8) and (9) describe the logic of the two output currents $I_{ext}$ and $I_{ret}$, activating the extension and retraction solenoids, respectively, of the boom or bucket's electro-proportional valves. The input signal, $S$, generated by an axis of the joystick, ranges from 0 to 1700. An offset $\varphi$ is added to the signal in either direction to compensate for the valves' dead bands.

$$I_{ext}(mA) = \begin{cases} (S - 850) + \varphi, & S > 850 \\ 0, & S \leq 850 \end{cases} \qquad (8)$$

$$I_{ret}(mA) = \begin{cases} (850 - S) + \varphi, & S < 850 \\ 0, & S \geq 850 \end{cases} \qquad (9)$$

## 4 Simulation Results

This section presents the simulation results of the tractor loader for both designs (ESL and HSL). Simulation was performed using a time step of 1ms.

### 4.1 Electronic Self-Levelling (ESL) Results

To test the ESL control performance, a pre-programmed sequence was implemented to replace the joystick input as the boom and bucket angle commands, therefore making the test results more reliable and repeatable under different load conditions.

One test without load and one test with 10 kN as a load on the bucket (see Figure 7) were performed. Figure 12 shows the boom angle transducer response versus the command signal under and without load. Figure 13 shows the bucket angle transducer response versus the bucket command, which is constantly adjusted by the boom angle response.

These results show that the control logic paired with the hydraulic design are robust with or without loads on the bucket. The boom response shows very little error compared to the set point and no oscillations. The bucket, while very stable, shows a little delay in its self-levelling when the boom is raising and lowering. Depending on its set point angle, this could result in material spill when the boom is raising or lowering. Using the test environment already developed, changes in the hydraulic design could be analysed to reduce the bucket self-levelling delay, like allowing higher maximum flow across its main spool. Moreover, the control logic of the bucket could be modified in order to adjust itself to the boom command instead of the boom feedback angle, allowing for faster response time.

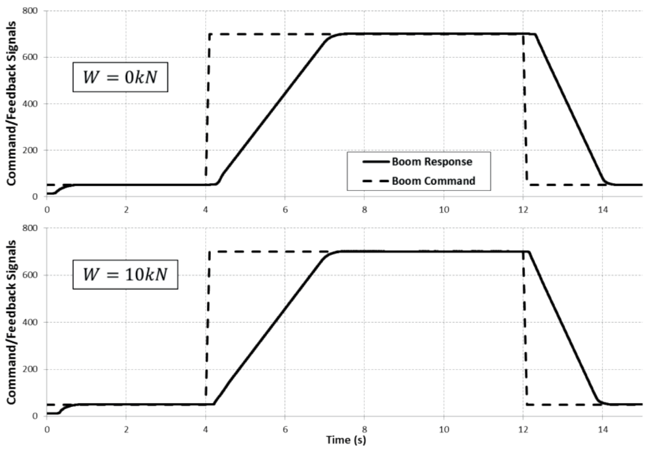


*Figure 12: ESL Boom response under different load conditions*

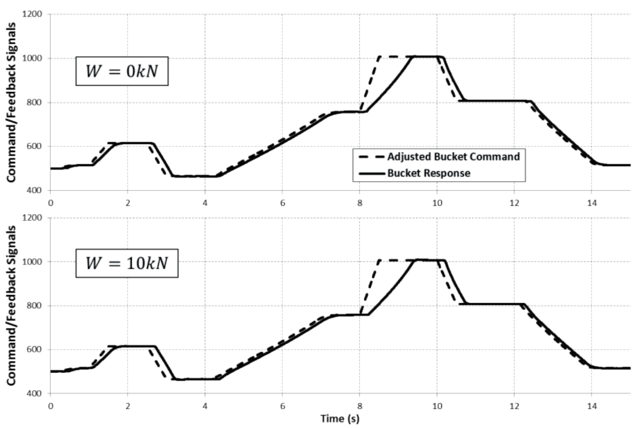


*Figure 13: ESL Bucket response under different load conditions*

### 4.2 Hydraulic Self-Levelling (HSL) Results

To test the HSL performance of the loader, a pre-programmed sequence was implemented to replace the joystick input as the boom command. The bucket command remained neutral. Figure 14 shows the angle response of the bucket compared to the boom angle response. In an ideal self-levelling system, the bucket angle should remain identical to the boom angle.

Results show that the load has close to no effect of the self-levelling performance of this design. Moreover, the bucket adjustment is almost fully synchronized with the boom movement in both scenarios. The biggest noticeable flaw is the angle offset that reaches $0.2\,rad$ (11.5°) at about mid-course of the boom. This offset may be reduced by modifying the loader's mechanism geometry and the passive hydraulic cylinder piston and rod diameters.

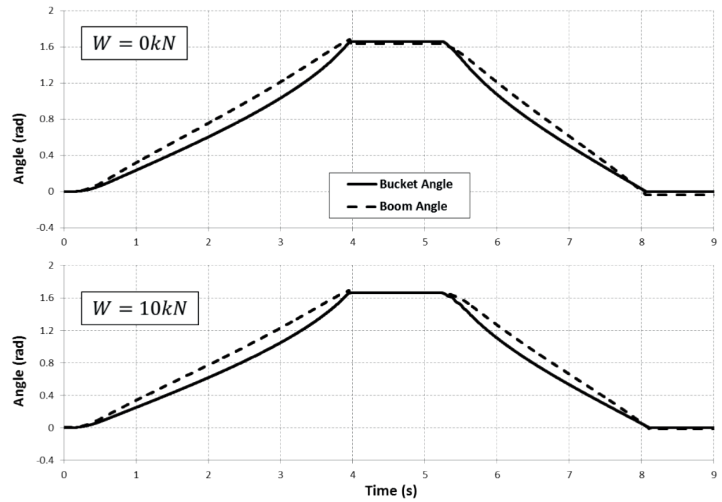


*Figure 14: HSL Angle difference between boom and bucket*

## 5 Summary and Conclusion

This article shows how it is now possible to combine physical hardware with simulation software to perform co-simulation, hardware calibration or to enhance the user experience making it more and more a training environment. The communication between virtual systems and physical devices is now using the CAN bus standard communication protocol, which is compatible with many manufacturers' components, that provides the following benefits: ease of implementation (2 wires, simple parameterization…), diversity of devices, adapted communication speed, reliability.

Using this method, a tractor front loader with electronic or hydraulic self-levelling was developed in a completely virtual environment and was controlled by physical devices such as a joystick and an electronic control unit. Simulation results showed that this type of environment allows tweaking the control parameters to different simulation parameters such as a varying load, duty cycle, temperature, fluid types, etc. In other words, many simulation model variants can be created to analyse different aspects that can be modified in the design:

- Hydraulic architecture of the systems and components;
- Machine geometry and mechanical design;
- Controller architecture and programmed algorithm.

Finally, this new design and testing methodology facilitate collaboration between Hydraulic and Automation Control Engineers, therefore reducing the actual gap of communication between teams. Even, the engineering work done using Machine Knowledge Management approach can make that work reusable in all project life cycle steps, in order to enhance training and troubleshooting material from the engineering work, as already initiated in the industry and demonstrated in /10/.

## Nomenclature

| *Variable* | *Description* | *Unit* |
|---|---|---|
| $p_n$ | Pressure at port n. | [bar] |
| $F$ | Force | [kN] |
| $I$ | Current | [mA] |
| $d, D$ | Diameter | [mm] |
| $W$ | Weight | [kg] |
| $Q_n$ | Nominal Flow | [l/min] |
| $\theta$ | Angle | [rad] |

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