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Examples of simulating multibody systems and hydraulic systems in the field of mobile machines

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Introduction

Mobile machines such as tractors plus implements, agricultural machines, harvesters and construction machines consist of hydraulically driven multibody systems. Examples of interlinked mechanical structures in tractors are the back and front 3-point-linkages combined with lifting device and p.t.o. (power take off). In construction machines, these mechanical structures are various lifting frames for wheel loaders and excavators, their chassis as well as swinging and steering devices.

The units composing the individual machines may have both rotary and linear drives. Apart from numerous different 4-bar-linkages, the system is mainly composed of more complex multi-bar-mechanisms. Simulation helps to set up extensive parameter variations in order to analyse and optimize the described systems.
Especially with agricultural machinery, field tests can only be carried out within determined cycles depending on weather and season. Additional simulations carried out beyond the season save time for effective system analysis. Furthermore, the product range shows a big variety of variants with partially a small number of items. Given sufficient statistical relevance of the test results, this requires a huge number of tests which can be minimized by simulation.

In order to examine mobile machines movement processes, the Institute of Agricultural Machinery Sciences and Fluid Power carries out multibody simulation using ADAMS. Simulation of hydraulics dynamic behaviour is done using MATLAB which is also utilized to design and develop controllers.

As an example of ADAMS utilization, here are two models:

- Lifting frame and bucket of a wheel loader

  This model calculates the external loads acting on the bucket's edge, which represent the causal relation between reaction forces and movement determined by doing field tests.

- Position-controlled tractor front loader

  This model is used to design an electro-hydraulic position control for rocker arm and implement.

Using ADAMS/Linear, existing MATLAB hydraulic models are extended to become linearized overall models. According to the chosen controller, a non-linear ADAMS overall model will be utilized to check the desired control process.

Lifting frame and bucket of a wheel loader

During the period of construction machinery operation, different forces and torques are acting on the individual implement, depending on the variety of work.
In order to check the implement's operating strength, engineers have to do either experimental or arithmetic, software-aided determination of the unit's life. With arithmetic operating strength estimation, there may be huge deviations. The task is not to determine the unit's life but to compare different construction varieties.
Both experimental and computer-aided solutions require the load acting on the implement to be well reflected. Usually, these loads influencing directly the machines can hardly be determined by measuring. Provided that the joint and cylinder reaction forces, which are easier to be measured, are known, they can help to calculate these loads.

As an example of external loads affecting a construction machine, the forces and torques acting on the bucket edge's centre are calculated using ADAMS. Calculation can be done reflecting the shearing forces of two joint bolts as well as the pressures and positions of the hydraulic cylinders which are the measured quantities. The measured values are delivered by field tests, with a wheel loader being run in V-cycle.

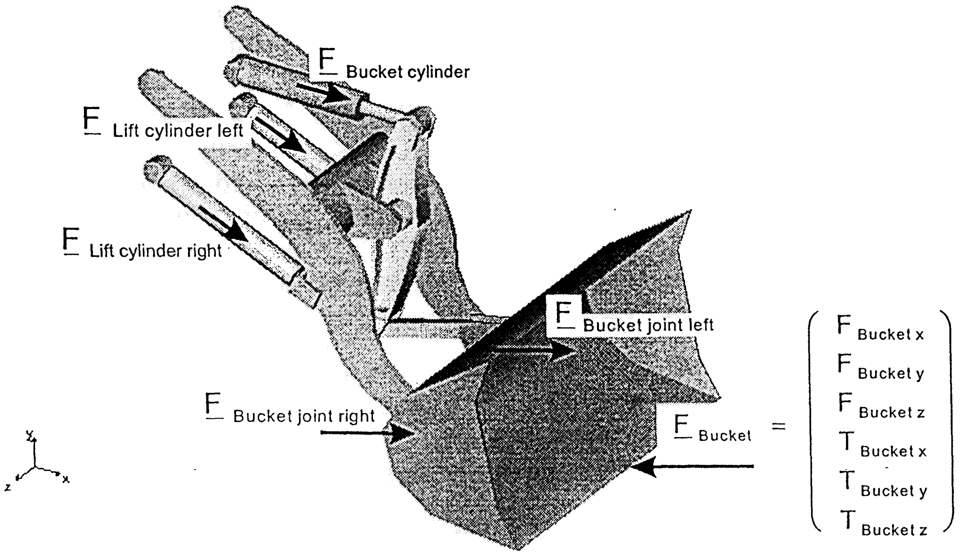

Figure 1: Lifting frame, affecting forces and moments

Multibody simulation's main task is to determine the movements of systems using given forces. Another approach is calculating the constraint reactions on the basis of imposed movements. Regarding the wheel loader's bucket, however, simulation has to calculate the external loads with given joint reactions and movements. This is not a typical task for multibody simulation.

As it is not possible to calculate external loads in principle, it is useful to create an additional revolute joint and two additional translational joints. These joints connect the bucket with the ground via two dummy parts. The additionally modelled dummy parts are massless units having no geometry. This procedure helps to change the system limits of the lifting frame. The load forces, having affected the bucket edge's centre externally before, are now represented as internal reaction forces and torques in the model.

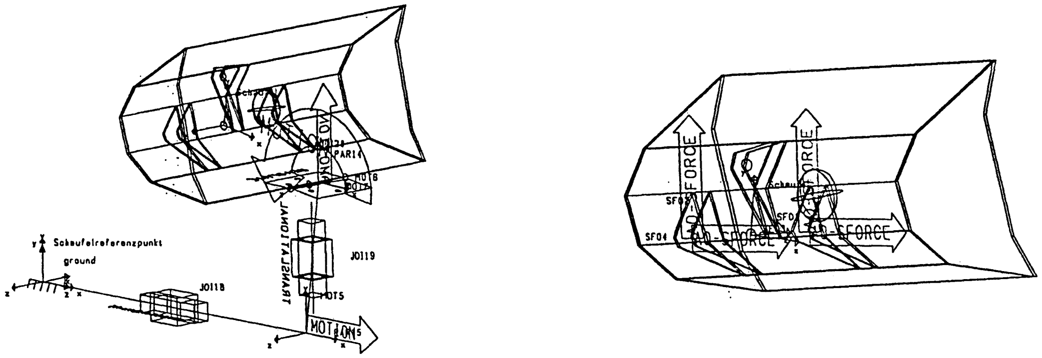

Figure 2: Forces and moments acting on the bucket, shown by simulation

In the course of simulation, the bucket's movements are created via the additional revolute and translational joints using motions. At the same time, the bucket is affected by the shearing forces measured on the joint bolts acting as single component forces. The measured hydraulic cylinder's pressure necessary to run the implement also influences the bucket as a single component force. This force acts indirectly on the bucket via rocker arm and rod. In order to precisely fix the suspension point of the rocker arm, another motion is necessary to move the lifting frame.This movement is realized by preliminary setting of the piston rod position of the lift cylinder.
A force output request helps to achieve the forces and torques transmitted by the two markers of the additional revolute joint. In the model, it is these forces and torques which are necessary to keep in line with the imposed movement state. They represent the loads to be simulated, which affect the bucket edge's centre and which are stored into an .out-file.

The motions necessary to move the bucket are unknown and they have to be calculated by preliminary simulation. Predetermining the piston-rod motions of lift and bucket cylinders, the mechanism's pure movement is reproduced. These motions are the simulation's only input data. The bucket's position necessary for the simulation is achieved by a corresponding displacement Output Request.

The models used for simulation are simple rigid-body models neglecting clearance and elasticities. Any constraints utilized are designed so as to produce a statically determined system. If bucket and lift cylinder have imposed movements, the whole model performs constrained movements.
Various User-Written Subroutines produced in C are used as Motion- (MOTSUB) or Force-Subroutine (SFOSUB) in order to read in the measured data. These simulation input data are given as ASCII files. Necessary interpolation of these data is also done in the individual subroutine.

Fig. 3 shows a charge cycle's movement process. During the first ten seconds, the bucket is charged with gravel. In order to pick up the goods, the bucket has to per-

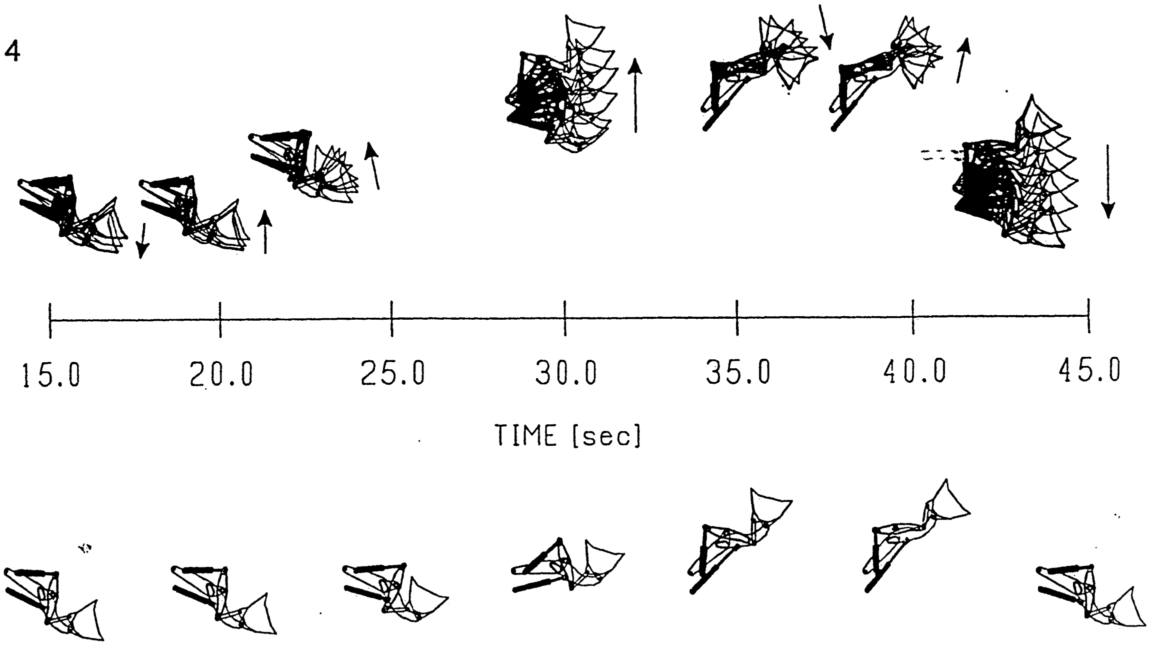

Figure 3: Animation of a lifting cycle

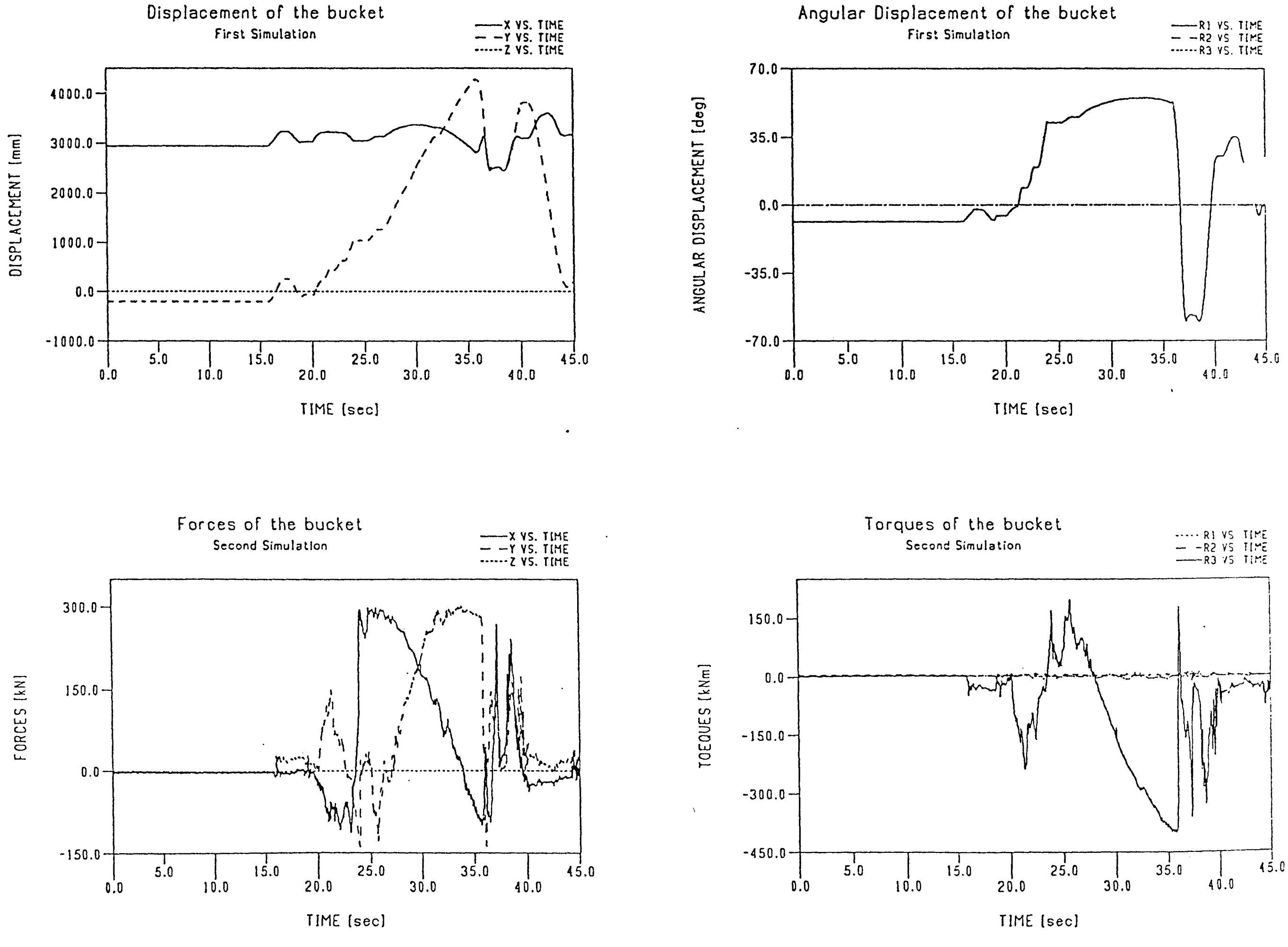

Figure 4: Results regarding bucket movement process and load

form short nodding movements. After having charged the bucket, the wheel loader reverses and heads for a waiting lorry, the bucket being lifted by the lifting device simultaneously. After the bucket has reached the appropriate height, it is unloaded, performing short nodding movements again. The cycle ends with the lifting device lowering again and the bucket reaching its starting position.

Fig. 4 shows the appropriate plots of bucket position and calculated bucket loads. The curves shown above represent the bucket's positions and twisting movements in relation to the ground, determined in the course of the first simulation.
Below this, the forces and moments acting on the bucket's edge are shown. The plots contain the positions and forces in x and y direction, according to up and down movement. The lifting device's displacement in z direction has not been measured during the tests, as well as tractive and compressive forces acting on the joint bolts. Therefore, there is no load affecting the bucket in z direction. The acting moment mainly consists of one component around the z axis, because the shearing forces measured have only little effect on the two other moments.

Position-controlled tractor front loader

Mobile hydraulics uses different concepts to provide the hydraulic power. Apart from constant flow and constant pressure systems, also the so-called Load-Sensing systems are realized. In this case volume flow rate and pressure level are adjusted to the practical needs. In order to examine the dynamic behaviour of the system varieties mentioned above, the Insitute of Agricultural Machinery Sciences and Fluid Power uses a test station to electro-hydraulically drive two consumers. These consumers are the cylinder pairs in a front loader often utilized with tractors.
The test station is either stationary or mobile, connected with a system tractor (fig 5).

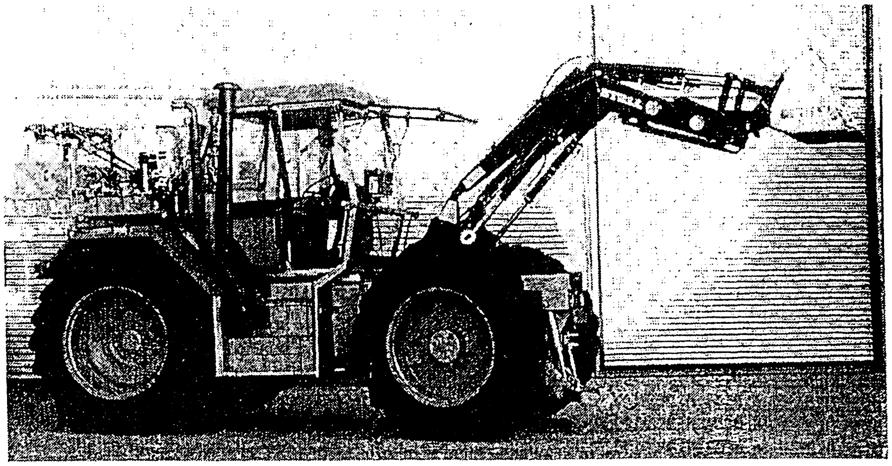

Figure 5: System tractor equipped with front loader and hydraulic system

In order to develop an electro-hydraulic position control for rocker arm and implement, the Institute of Agricultural Machinery Sciences and Fluid Power uses ADAMS and MATLAB/Simulink as software tools. On the one hand, an interlinked simulation model serves to compute the dynamic behaviour, on the other hand, the tools provided by MATLAB are used for the controller design.

The mechanical elements of the stationary front loader test station are designed as an ADAMS model. Regarding the hydraulic components, an already existing simulation model on MATLAB/Simulink basis may be applied. Fig. 6 shows both models, with hydraulics being implemented as a constant pressure system. The individual blocks represent the characteristics of valve actuator position, in and out flow through the valve as well as pressure synthesis on the surface of the cylinder piston or the piston ring.

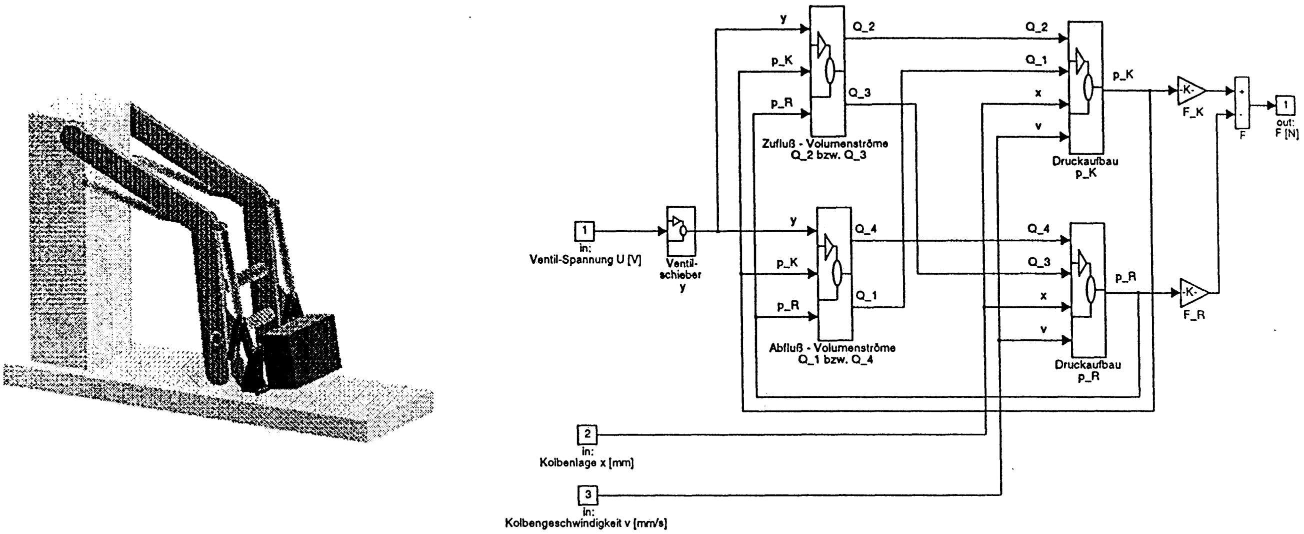

Figure 6: Mechanics (ADAMS) and hydraulics (MATLAB/Simulink) models

By coupling both partial models using a GSESUB User-Written Subroutine, it is possible to compute the dynamic behaviour of the overall model within the user ground of ADAMS/view. With this so-called co-simulation, ADAMS and MATLAB simulators simultaneously calculate the individual model behaviour implemented using a special ADAMS/MATLAB interface. Using the MATLAB real time workshop, the hydraulic model requires generating the C code for an independently working simulation executable. This code is added by the ADAMS/MATLAB interface designed in C as well. After compiling, the linker of the applicable compiler (Visual C++ 4.0 for ADAMS PC version) generates an ADAMS/Solver executable from the object files.
In the course of simulation, there is data transfer between both models. Simulink model's input values are the latest data of valve voltage as well as cylinder positions and velocities. The output values the ADAMS model receives are the resulting forces acting on the piston rods.

In order to design a position controller, ADAMS/Linear serves to generate the front loader's mechanical system behaviour linearized in one operating point, shown in state-space representation. By using the system matrices $\underline{A}$, $\underline{B}$, $\underline{C}$, $\underline{D}$ thus developed, it is possible to extend an existing linear MATLAB hydraulic model.
The root locus process is one way to design the controller. In this process designed for stability tests and controller synthesis, the roots of the closed loop are plotted in the complex number plane. The Laplace transformation helps to generate the transfer function F(s) of a control process:

$$F(s) = \frac{Y(s)}{U(s)} = \frac{b_m \cdot s^m + \ldots + b_2 \cdot s^2 + b_1 \cdot s + b_0}{a_n \cdot s^n + \ldots + a_2 \cdot s^2 + a_1 \cdot s + a_0} = \frac{Z(s)}{N(s)}$$

Numerator and denominator polynomials Z(s) and N(s) can be factorized into linear variables:

$$F(s) = \frac{Y(s)}{U(s)} = \frac{b_m \cdot (s - s_{N1}) \cdot (s - s_{N2}) \cdot \ldots \cdot (s - s_{Nm})}{a_n \cdot (s - s_{P1}) \cdot (s - s_{P2}) \cdot \ldots \cdot (s - s_{Pn})} = \frac{Z(s)}{N(s)}$$

The zeros s_{pi} of the characteristical equation N(s) are called poles or roots of the system. Their position within the complex number plane characterizes the control behaviour of the closed loop. For stable control, the real parts of all roots have to be negative, i. e. in the number plane, their position must be left of the imaginary axis. With a feedback gain controller being used in the position-controlled cylinder, there are e. g. two real poles and two pairs of conjugated complex poles (fig. 7).

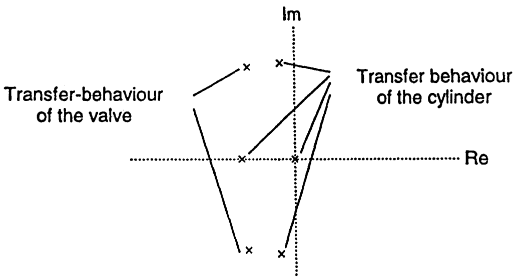

Figure 7: Poles of the position-controlled cylinder, with gain = 0

Fig. 8 shows the appropriate root locus curves with a varying controller gain. With a controller gain being too high, the hydraulic drive quickly loses stability.

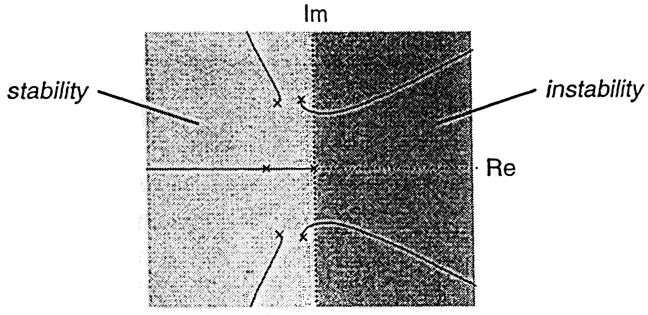

Figure 8: Controller selection with root locus curves

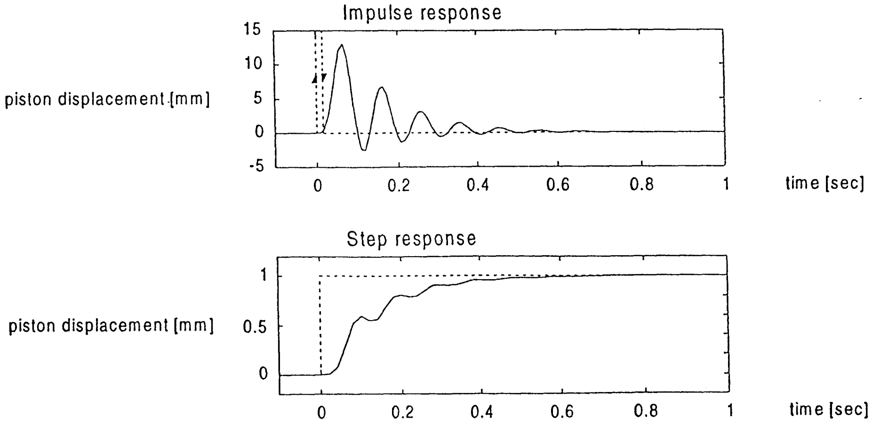

Figure 9: Impulse and Step responses of the linearized controlled system

Fig. 9 shows impulse and step response occuring for the example of a stable control process. Impulse and step response illustrate the behaviour of the system linearized in one operating point.

In order to assess the dynamic behaviour regarding the front loader's overall operating area, there has to be simulated again using the non-linear model. The model first has to be extended to a model of the closed loop control. Additionally, the control algorithm and the necessary comparisons of desired and actual control values are implemented. With desired values appropriately designed, it is possible e. g. to realize parallel drive of the implement relative to ground. Fig. 10 shows the curve lines for desired and actual positions of the piston rods (lift cylinder pair and implement cylinder pair).

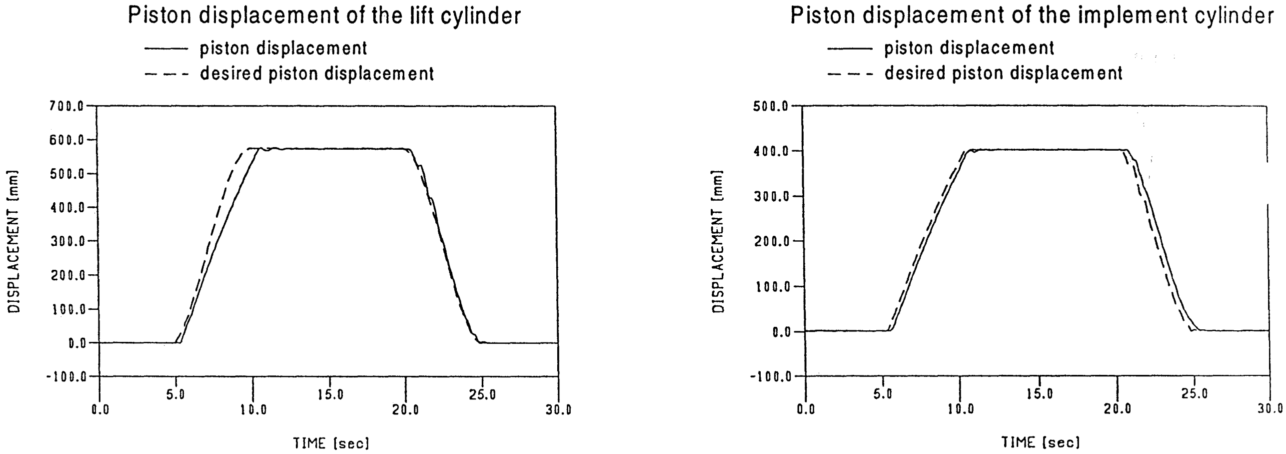

Figure 10: Simulation of the position control, using the coupled model

With the two lift cylinders moving out, there is a certain lag error of the actual position with regard to the desired position. In this phase, the valve is completely opened, and the valve actuator has reached its limits. A certain lag error is therefore inevitable, but it can be tolerated in this case. With lowering lift cylinders, there is a slight vibration. As the control was designed for lifting a load, it shows worse behaviour when lowering the implement. It would be helpful to adapt the control to the case of tractive load acting on the hydraulic cylinder pair, as is the case when the rocker arm is lowered. Fig. 11 shows the movement process when lifting and lowering the implement.

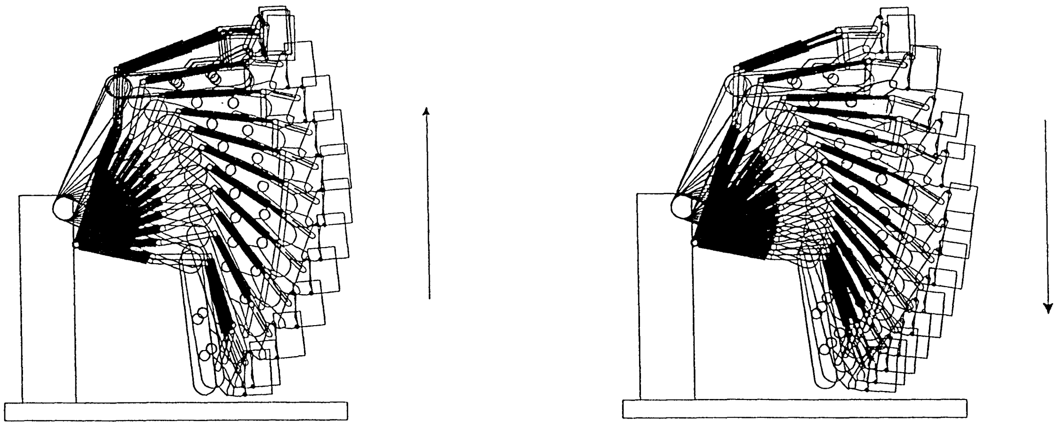

Figure 11: Animation of parallel drive when lifting and lowering the bucket

Summary

The examples delivered above show the experiences the Institute of Agricultural Machinery Sciences and Fluid Power has gained with the ADAMS program. By open design using User-Written Subroutines, it will be possible to considerably extend the functional varieties.

Subroutines designed to define motions and forces help to calculate the loads acting on the bucket of a wheel loader during operation.Thus, measured data can be read in, serving as simulation input data after appropriate interpolation. The simulation results may then be used for further examination of the individual units (by FEM), setting up load collectives, estimating operating strength, etc..

With model design of the front loader test station built up at the institute, a user-written Subroutine is used to couple the programmes of MATLAB/Simulink and ADAMS. The partial systems of hydraulics and mechanics are represented by the individual simulation ground, with both simulators working separately being very advantageous. The integration processes applicable with MATLAB/Simulink are more stable for the simulation of high-frequency signal processes in hydraulic systems than the integration processes used by ADAMS especially for mechanical applications. Permanent data transfer organizes the simulation of the overall system's behaviour.

References

[1] Eberle, C. , Harms, H.-H. :
Simulation eines Frontladers
Löwenschule - Simulation dynamischer Systeme, Braunschweig, Germany, 1997

[2] Esders, H. :
Elektrohydraulisches Load Sensing für mobile Anwendungen
Fortschritt-Bericht, VDI Reihe 14, Nr. 75, VDI-Verlag, Germany, 1996

[3] Hoffmann, M. , Richter, B. :
The balancing briefcase: Interfacing ADAMS and MATRIXx
International ADAMS User's Conference, Ypsilanti, USA, 1992

[4] Mechanical Dynamics: ADAMS manuals, USA, 1995

[5] The Math Works Inc. : MATLAB manuals, USA, 1995