

A Simulation Environment for Excavator Dynamics

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Abstract

A dynamic model is essential for dynamics-related studies of an excavator, e.g., controllability, ride comfort, durability, and so on. Since the hydraulic system, which controls the actuators of an excavator, has its own dynamics due to compressibility of hydraulic oil, it is required that the dynamics of the hydraulic system be incorporated into that of the mechanical system to study the coupled dynamic behavior of the excavator. In this presentation, a simulation environment, which includes both the hydraulic and mechanical dynamics of an excavator, is explained. MSC.ADAMS and MATLAB/Simulink are chosen as the implementing tools for the dynamics of the mechanical parts and hydraulic system respectively, and the coupled dynamic behavior of the excavator is simulated using the co-simulation method provided by MSC.ADAMS.

1. Introduction

Excavators are used in a wide variety of ways in construction fields, from digging and soil-moving operations to rock-breaking tasks that require an optional attachment called a breaker. Their common structure consists of a traveling body, a swing body and a front manipulator. The boom, arm and bucket, as shown in Fig. 1, are three main links comprising the front manipulator of an excavator. Swing, boom, arm and bucket motions are the most frequent motions of an excavator when it works in a parked condition. In this paper, the mechanical dynamics refers to the multi-body dynamics of the traveling body, swing body and front manipulator, as opposed to the hydraulic system dynamics.

Hydraulic actuators such as hydraulic motors and cylinders drive the swing body, boom, arm and bucket of an excavator. Specifically, a hydraulic motor is used as a driving mechanism for swing motion, and hydraulic cylinders are used for boom, arm and bucket motion respectively. Since the hydraulic system has its own dynamics due to compressibility of hydraulic oil and has highly nonlinear characteristics, it is necessary to consider its effect on the overall dynamic behavior of the excavator.

An exact knowledge of the coupled dynamics is crucial for designing the hydraulic system, determining the required mechanical strengths of the major parts, improving ride comfort for excavator operators, and so forth.

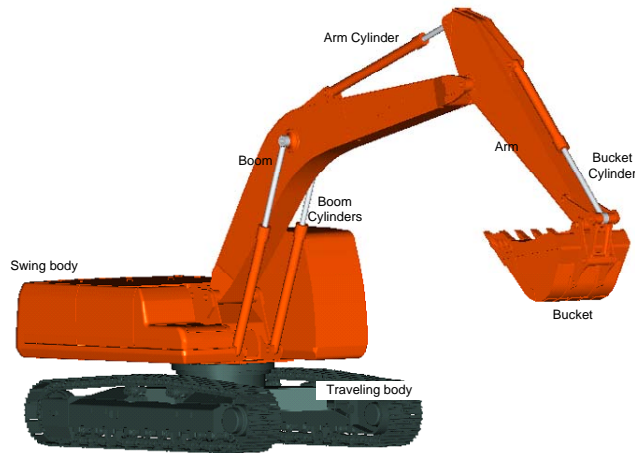


Fig. 1 Swing, boom, arm and bucket motion of an excavator

For example, one can optimally tune the area curves of control valves for improved excavator motion by iterating the coupled dynamic simulations, without performing cost-intensive experiments with precision-machined spools which have varied area characteristics. One can also increase durability of the various mechanical parts of an excavator by using information on the dynamic forces obtained from simulations of the real working conditions of the excavator. One can simulate the transient dynamic behavior of an excavator on the computer, and get insight into how much effect each mechanical or hydraulic design parameter has on the ride comfort. Furthermore, the coupled dynamic model is indispensable for designing a model-based control system for an automated excavator.

In all these processes, a simulation environment for an excavator, in which not only the mechanical dynamics but also the hydraulic actuator dynamics can be considered, plays an essential role. It can greatly help to reduce the development costs and shorten the time to market.

Most of research papers on excavator dynamics primarily considered the robotic manipulator dynamics of excavators. Only a few merely considered simplified hydraulic system models of excavators. It is believed that both the complication of coupled dynamics and the computational difficulty have prevented the progress of research in this field.

In this paper, a simulation environment for the combined mechanical and hydraulic dynamics of an excavator is explained. MSC.ADAMS and MATLAB/Simulink are chosen as the modeling and simulation tools for the mechanical and hydraulic dynamics, respectively, of the excavator. The background of choosing these commercial programs as the modeling and simulation tools is briefly addressed, and then the simulation results are presented and compared with the experiment ones.

Since the main purpose of this paper is to present a simulation environment using MSC.ADAMS and MATLAB/Simulink, the detailed governing equations of the mechanical and hydraulic system are omitted.

2. MSC.ADAMS Mechanical System Model

Considering the various applications of dynamic simulation of an excavator, the software for the mechanical dynamics of an excavator should be able to give an easy tool for modeling the multi-body dynamics which includes flexible bodies as well as rigid bodies. Some of the vibration modes of the structural frames of an excavator need to be considered when the vibrational behaviors are important, for example, when the dynamic forces at the mounting location of a certain massive object are sought.

MSC.ADAMS provides a few convenient tools for incorporating flexible bodies into a multi-body dynamic model through ADAMS/Flex plug-in module.

MSC.ADAMS also supplies a variety of tire models in ADAMS/Tire and ADAMS Tracked Vehicle (ATV) module, which can be used for modeling wheel- and crawler-type excavators. However, care should be taken using these modules; some parametric data for excavator tires, which are necessary for advanced tire models, are difficult to obtain, and the tracked excavator modeled in ATV is computationally inefficient for some purposes.

The ADAMS/Controls plug-in offers various simulation methods for use with MSC.EASY5, MatrixX, and MATLAB/Simulink. It provides three different simulation methods -continuous, discrete and control system import- for these dynamics simulation programs. As far as this research work is concerned, the discrete, i.e., the co-simulation method showed the most acceptable computational performance for use with MATLAB/Simulink.

Without loss of generality, some assumptions were made to simplify the mechanical system model of the excavator.

- 1) Inertial effects of moving parts, e.g., cylinders and pistons, of the hydraulic actuators are neglected. Masses and mass moments of inertia of the hydraulic actuators are much smaller than those of the boom, arm and bucket. Therefore, they can be reasonably neglected. Otherwise, they can be assumed to be constant and included in the masses and mass moments of inertia of the boom, arm and bucket, if needed.
- 2) Hydraulic cylinders can transmit axial forces only. There exist no radial force components.
- 3) Passive revolute joints have no friction. The major sources of friction are the stiction and viscous friction between the inner wall and the piston in the hydraulic cylinder assembly. These frictional forces can be treated in the hydraulic system model.

Fig. 2 shows an MSC.ADAMS dynamic model of the excavator for boom motion. The front manipulator consisting of a boom, an arm and a bucket is treated as a single rigid body. The SFORCE elements are used to model the axial boom cylinder forces that come from the hydraulic system model.

Two flexible bodies are used to take the vibrational modes of the traveling and swing body frames into account. Contact force elements are introduced to model the interaction between the tracks of the excavator and the ground. The simulation results obtained from this model will be shown in Section 4.

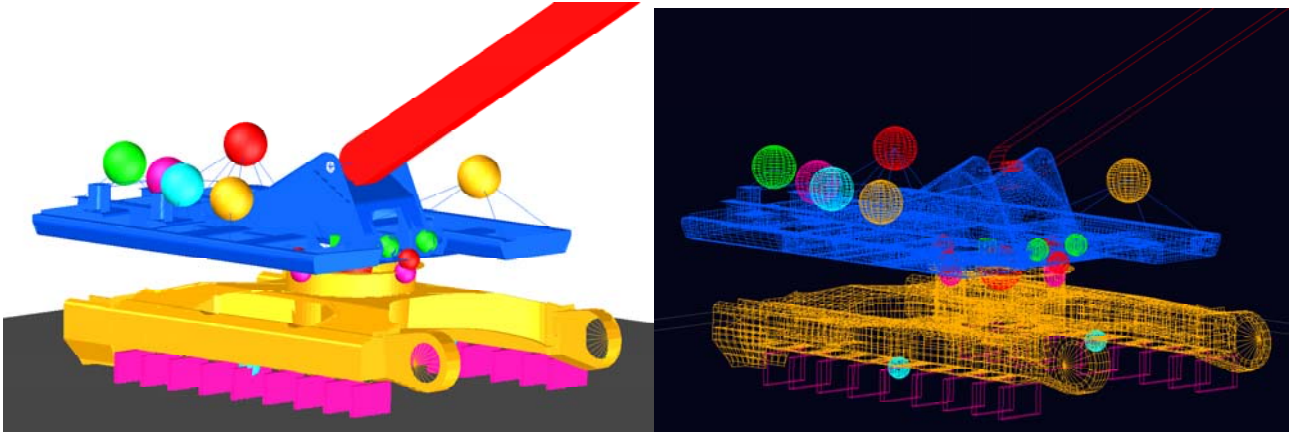


Fig. 2 An example of MSC.ADAMS excavator model

3. Simulink Hydraulic System Model

The hydraulic system of an excavator consists of various components such as pumps, control valves, auxiliary valves, motors and cylinders. Hydraulic pumps convert the mechanical energy supplied by the diesel engine to the fluid-power energy stored in hydraulic oil. The main role of control valves is to control the actuator velocities by properly metering the flows of hydraulic oil into and out of the actuators. The area characteristics of the control valves are very important since their profiles directly determine the actuator responses. Auxiliary valves are used to protect the hydraulic circuits and ensure safety during the excavating motion. A part of the hydraulic circuit diagram of an excavator is shown schematically in Fig.

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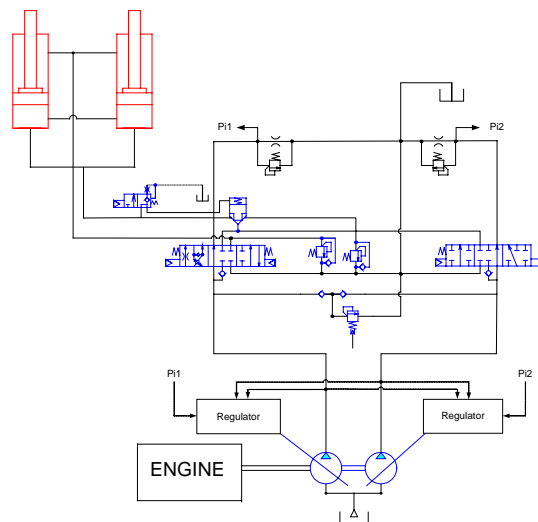
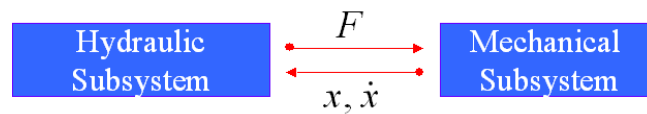


Fig. 3 A part of the hydraulic circuit of an excavator

Hydraulic motors and cylinders are used as the actuators. They generate torques and forces necessary for swing, boom, arm and bucket motion. These forces and torques are determined by the pressures of the chambers in each actuator, and these pressures, in turn, are determined by the velocity and displacement of the actuator which are calculated from the mechanical dynamics of the excavator. Therefore, it is in these actuators where the dynamic coupling between the mechanical and hydraulic system model of the excavator takes place. Fig. 4 shows this relationship schematically.



F : hydraulic cylinder force

x, \dot{x} : displacement and velocity of hydraulic cylinder

Fig. 4 Dynamic coupling between the mechanical and hydraulic system of an excavator

The differential equations of a hydraulic system are generally stiff in the numerical point of view. Moreover, the governing equations of a hydraulic system are mostly strongly nonlinear. Hence, solving the models of a hydraulic system is numerically challenging.

Hence, two important requirements for software for the hydraulic system of an excavator are to have stiff ODE solvers suited for the hydraulic system, and to have appropriate interfaces to as many multi-body dynamics programs as possible.

MATLAB/Simulink is one of the most widely used software tools in control engineers' society. Simulink provides relatively easy-to-use modeling tools for dynamic systems on the block diagram basis, and various numerical ordinary differential equation solvers including the stiff ODE ones.

Fig. 5 shows the performance of each ODE solver in MATLAB. A very simple hydraulic system model, consisting of a fluid-power source, a chamber and an orifice, was solved using each ODE solver. The abscissa denotes the given error tolerances and the ordinate denotes the number of steps required under the given error tolerances. This result shows that the stiff solvers are more efficient than the nonstiff solvers for error tolerances of 10^{-7} or larger, and ODE15S, based on the numerical differentiation formula, is the fastest method even for more stringent error tolerances.

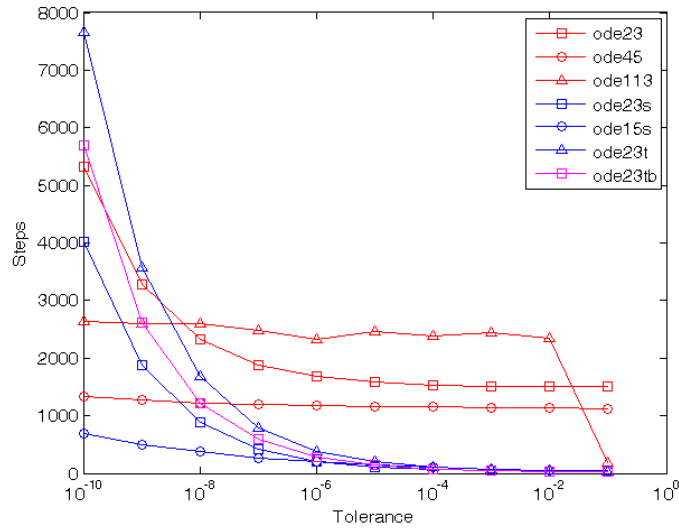


Fig. 5 Performance of ODE solvers in MATLAB

Most of dynamics-related programs provide interfaces to MATLAB/Simulink. MSC.ADAMS also has three different interfaces to Simulink, one of which is the co-simulation method used in this research work.

In this work, the hydraulic system model of the excavator was implemented in the form of a single Simulink S-function block. All the governing equations of the model were coded using C language and the template file provided by MATLAB. The produced MATLAB-executable DLL is called by the S-function block of the hydraulic system model and greatly shortens the simulation execution time. Fig. 6 shows the typical S-function routines that should be coded to make the S-function block of the hydraulic system model work properly.

The hydraulic system is modeled using three basic equations: flow equations, continuity equations, and equations of motion of moving parts such as spools, poppets, etc. A flow equation determines the flow rate of oil through an orifice.

$$Q = C_d A \sqrt{\frac{2}{\rho} \Delta p}$$

- where Q : flow rate through an orifice,
 C_d : discharge coefficient,
 A : opening area of the orifice,
 ρ : density of hydraulic oil,
 Δp : pressure drop across the orifice.

```

#define S_FUNCTION_LEVEL 2
#define S_FUNCTION_NAME BoomCtrl

static void mdlInitializeSizes(SimStruct *S)
{
    // The sizes information is used by Simulink to determine the S-function
    // block's characteristics (number of inputs, outputs, states, etc.)
    ...
}

static void mdlInitializeConditions(SimStruct *S)
{
    // Enter initialization statements
    ...
}

static void mdlOutputs(SimStruct *S, int_T tid)
{
    // Enter block outputs
    ...
}

static void mdlDerivatives(SimStruct *S)
{
    // Enter block state equations
    ...
}

#ifdef MATLAB_MEX_FILE
#include "simulink.c"
#else
#include "cg_sfun.h"
#endif

```

Fig. 6 Simulink S-function routines

Continuity equations originate from the mass conservation law and determine the pressure in a fluid chamber.

$$\frac{dV}{dt} + \frac{V}{\beta_e} \frac{dp}{dt} = Q_{in} - Q_{out}$$

where V : chamber volume,

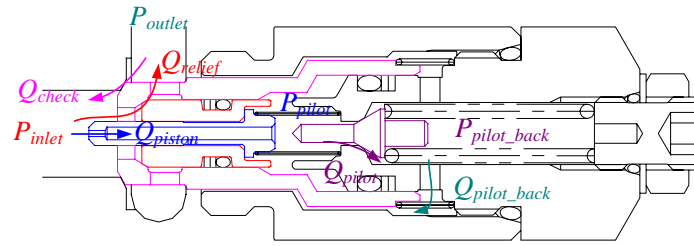
p : chamber pressure,

β_e : effective bulk modulus,

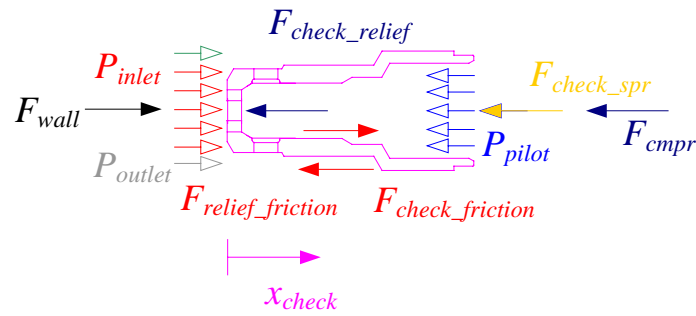
Q_{in} : flow rate into the chamber,

Q_{out} : flow rate out of the chamber.

Fig. 7 shows a modeling example. Fig. 7 (a) shows an auxiliary valve and the important variables defining the valve model, and (b) depicts the various force components exerted on the poppet of the valve. The detailed equations for the hydraulic system model are omitted.



(a) An auxiliary valve



(b) Forces exerted on the poppet

Fig. 7 A model for an auxiliary valve

4. Boom Motion Simulation

As a first step to the simulation of full excavating motion, a mechanical and hydraulic system model for boom motion was developed.

The mechanical system model for boom motion is the one described at the bottom of Section 2 and shown in Fig. 2. It contains two flexible bodies to model the traveling and swing body frames. The front manipulator is modeled as a single rigid body because arm and bucket motions can be ignored during the boom motion only. It also has two arrays of contact force elements in order to model the interaction between the tracks of the excavator and the ground.

The hydraulic circuit for boom motion consists of piston pumps, boom control valves, cylinders, and pipes and hoses connecting the major hydraulic components. Many auxiliary valves are also used to protect the hydraulic circuit and ensure safe motions. These auxiliary valves include relief valves, check valves, anti-drift valves, overload protecting valves, and so on.

The static characteristic curves replaced the dynamic model of the pumps and their regulators because the dynamic model of the pump system of the excavator is very complex. The measured displacements of spools in the boom control valves were used as the simulation inputs in order to compare the simulation results with the experiment ones. The dynamic characteristics of other valves and cylinders were modeled using the equations described in Section 3.

The boom hydraulic system, modeled in this way, consists of more than 60 first order ordinary

differential equations and is contained in a single Simulink S-function block as described in Section 3.

Fig. 8 shows the Simulink simulation model for MSC.ADAMS co-simulation. Notice the Simulink S-function block for the hydraulic system dynamics and the ADAMS co-simulation block.

Two different experiments were conducted. The first experiment was performed while moving the boom slowly in order to use the experiment data for tuning the hydraulic model parameters. The second one was to move the boom fast and then stop suddenly so as to excite the excavator as much as possible. The data from this experiment contain information on the overall transient behavior of the excavator.

The simulation results obtained with the tuned model parameters are plotted in Fig. 9. The related data from the first experiment are also displayed. Fig. 9 (a) and (b) are the plots of pressures associated with the pump control. Fig. 9 (c) displays the chamber pressures of the boom cylinder. Fig. 9 (d) shows the boom cylinder velocity and displacement.

The dynamic behavior after the boom stops should be obtained from the co-simulation of MSC.ADAMS and Simulink, where the dynamic interactions between the boom and the other bodies can be taken into account.

Fig. 10 plots the co-simulation results and the data from the second experiment. Comparison of the co-simulation results with the experiment data shows that the simulation results from this simulation environment have reasonable accuracy and that the simulation technique can be applied to solve the dynamics-related real world problems such as hydraulic system design, structural design, and ride quality.

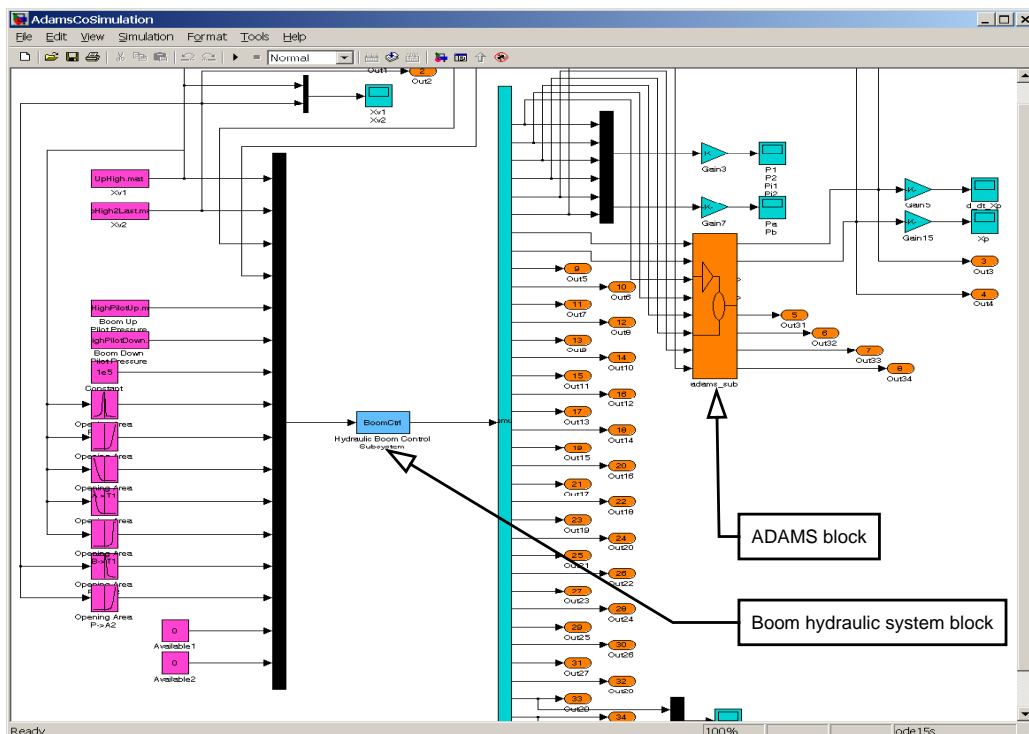
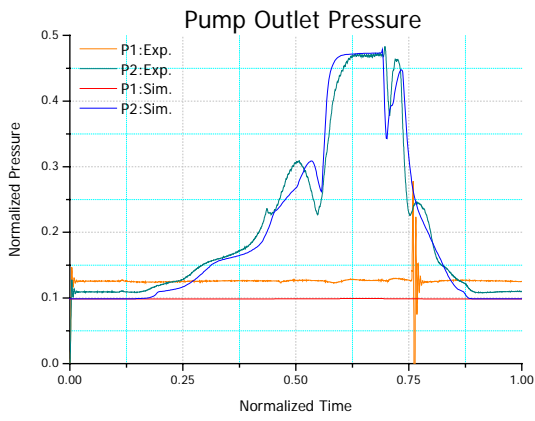
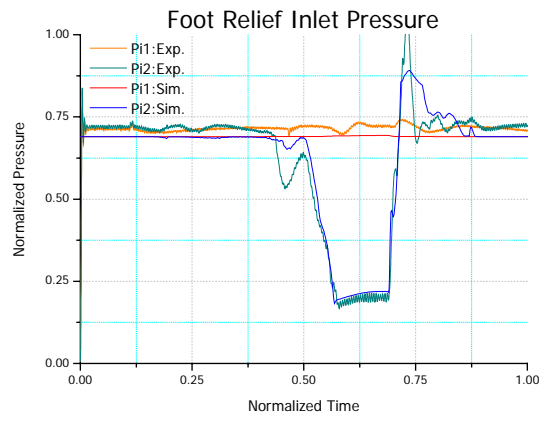


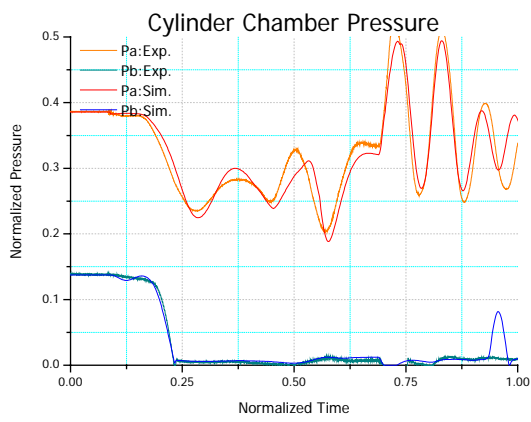
Fig. 9 Simulink simulation model for MSC.ADAMS co-simulation



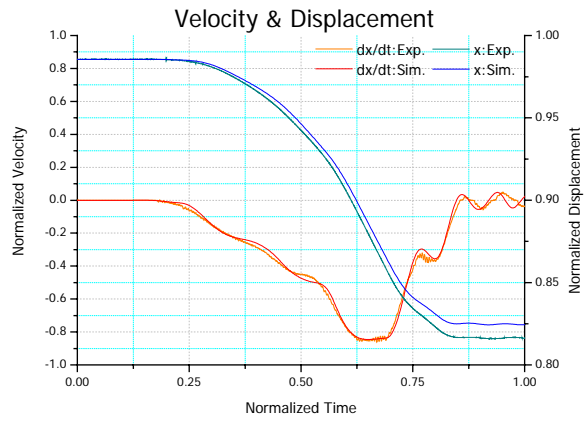
(a) Pump pressure



(b) Relief Pressure

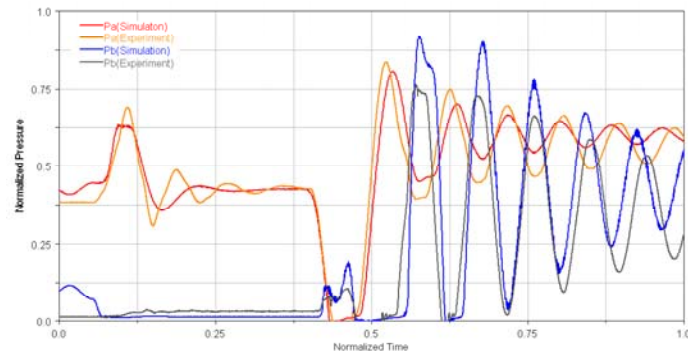


(c) Cylinder Pressure

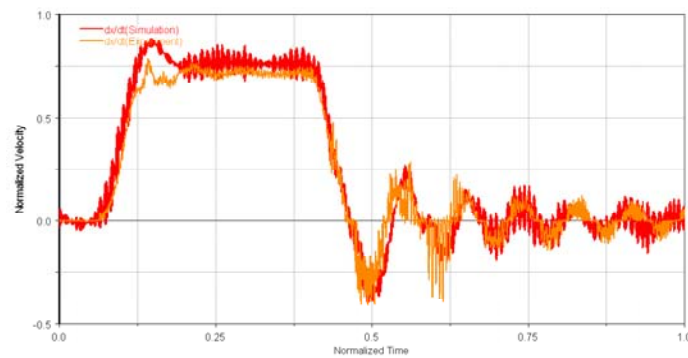


(d) Cylinder velocity and displacement

Fig. 9 Simulation results from the tuned hydraulic system model



(a) Cylinder pressure



(b) Cylinder velocity

Fig. 10 Simulation results from MSC.ADAMS and Simulink co-simulation

5. Conclusions

A simulation environment for excavator dynamics is presented. The mechanical dynamic model of an excavator is implemented on MSC.ADAMS and the hydraulic system model on Simulink. Comparison of the co-simulation results with the experiment data shows that the simulation results from this simulation environment have reasonable accuracy and that the simulation technique can be applied to solve the dynamics-related real world problems.

The dynamic model of the mechanical and hydraulic system of the excavator is being extended to simulate simultaneous motion of the swing, boom, arm and bucket, and finally realize the full excavating motion.

Reference

- (1) Getting Started Using ADAMS/Controls, MSC.Software Corporation, 2003
- (2) Writing S-Functions, The MathWorks Inc., 2003
- (3) L. Shampine and M. Reichelt, "The MATLAB ODE Suite," The MathWorks, Inc.
- (4) H. E. Merritt, Hydraulic Control Systems, John Wiley & Sons, 1967
- (5) P. K. Vähä and M. J. Skibniewski, "Dynamic Model of Excavator," Journal of Aerospace Engineering, Vol. 6, No. 2, pp. 148-158, 1993
- (6) A. J. Koivo, M. Thomas, E. Kocaoglan, and J. Andrade-Cetto, "Modeling and Control of Excavator Dynamics during Digging Operation," J. of Aerospace Engineering, Vol. 9, No. 1, pp. 10-18, 1996
- (7) M. Krishna and J. Bares, "Hydraulic System Modeling through Memory-based Learning," IEEE Intelligent Robot Systems Conference, 1998