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Onesmus Muvengei[α], John Kihiu[Ω]

Abstract - In this paper the interaction of hydraulic and mechanical dynamics, the inter-actuator and inter-link interactions in an excavator are modeled using bond graphs, and then simulated on a MATLAB/SIMULINK environment. Bond graph method was chosen as the modeling method because, firstly, it is a domain-independent graphical method of representing the dynamics of physical systems. Therefore, systems from different engineering disciplines can be described in the same way. Secondly, the available literature shows that the method being relatively new has not been thoroughly applied to model the dynamics of nonlinear systems such as excavators. A complete bond graph dynamic model of the excavator was obtained by coupling the mechanical and hydraulic models using appropriate Manipulator Jacobians which were treated as Modulated Transformer Elements. The causal bond graph model of the excavator was expanded into block diagrams and simulated on MATLAB/SIMULINK to determine the transient and steady state responses of the system. From the responses obtained, the model developed was found to capture the inter-component interactions and also the interaction between the hydraulic and mechanical dynamics. Therefore, the model developed can be used to design control laws necessary for controlling the dynamics and motions of the excavating manipulator.

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I. Introduction

Most of research work on excavator dynamics has primarily considered the manipulator dynamics (Koivo, et. al, 1996, Vaha and Skibiniewski, 1993, Cannon, 1999). Only a few researchers have considered the interactive hydraulics and mechanical dynamics of excavators (Beater and Otter, 2003, Cheol-Gyu and Kwang-Ho, 2004, Nguyen, 2000). The complication of coupled dynamics and the computational difficulty have prevented the progress of research in this field (Zangh and Duqiang, 1999)

3-dimensional mechanical systems consisting of hydraulic components like excavators are difficult to simulate. Usually two different modeling techniques, one for mechanical dynamics and the other for the hydraulic dynamics, have been used and then coupled to a complete model which is then simulated using a single (Beater and Otter, 2003, Cheol-Gyu and Kwang-Ho,2004, Nguyen, 2000). Cheol-Gyu and Kwang-Ho (Cheol-Gyu and Kwang-Ho, 2004) presented a simulation environment of excavator dynamics by coupling the MSC.ADAMS mechanical dynamic model of the excavator and the Ordinary Differential Equation's hydraulic system model, and then simulating the overall model on SIMULINK. Beater and Otter (Beater and Otter, 2003) demonstrated how to model the dynamics of an excavator by modeling the mechanical part using Modelica language, and modeling the dynamics of the hydraulic system using HYLIB language, then integrating the two models and simulating the output model using DYMOLA 2003 simulation software. Nguyen (Nguyen, 2000) modeled the mechanical dynamics of the excavator using Newton-Euler method and the hydraulic dynamics using ordinary differential method.

The integration of models from different domains have proved to be a complex and time consuming task, because, although powerful simulation libraries exist, they are generally based on different modeling languages, almost invariably not compatible (Ferreira et. al 2000). Also, the integration of two modeling techniques leads to unnecessary numerical problems and the resulting model may contain fragile interfaces which affect the simulation results.

The bond graph method was established as a new approach to model, analyze and control various dynamical systems by Professor Henry Paynter (Paynter, 1961). Through bond graph modeling technique, the problem of coupling several models from different engineering systems has been solved, and now a model representing several sub-models from various engineering disciplines can be simulated using one simulation environment such as MATLAB/SIMULINK, 20-SIM, CAMP-G, et cetera. Since Prof. Paynter introduced the basic concept of bond graph modeling, bond graphs have been a topic of research or are being used in research on modeling and simulation of dynamic behavior of physical systems.

Margolis and Karnopp (Margolis and Karnopp, 1979) contributed to the field of bond graphs by carrying out a comprehensive research, the outcomes of which

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are applicable to areas of robotics, cranes, excavators, wheel loaders, and space vehicles. The study investigated the dynamics of two arms, with articulated joints and actuated on the joint considering actuation unit dynamics, rigid body dynamics and bending vibrations all together. Margolis and Shim, (Margolis and Shim, 2003) used bond graph method to develop a complete pitch/plane model of a backhoe considering the boom dynamics, the hydraulic dynamics of the boom cylinder and valve, the chassis/cab mountings and the control stick dynamics. Using the parameters of a medium size back hoe in simulating the bond graph model, the authors demonstrated the instability of the backhoe in consideration. Also Krishnaswamy (Krishnaswamy, 2004) modeled the boom motion of an excavator to study the passivity of hydraulic systems. The authors only considered the boom motion, but in this research work, three excavator motions, i.e, boom, arm, bucket motions will be considered.

The available literature shows that a lot of emphasis on modeling the dynamics of excavators has been focused on the mechanical dynamics of the manipulator, with less attention to the interactive hydraulic and mechanical dynamics. This has been attributed to the computational difficulty and the complication of coupled dynamics which result when models from different modeling techniques one for mechanical and the other for hydraulic dynamics are integrated together for simulation. In this paper, models of the hydraulic and mechanical dynamics of an excavator are developed using one modeling technique, that is, bond graphs, hence eliminating the problem of coupling models from different techniques.

II. Dynamic Coupling of Mechanical and Hydraulic Bond Graph Models of the Excavator

The bond graph models of mechanical and hydraulic dynamics of the excavating mechanism shown in Fig. 1 have been developed in previous research works (Muvengei and Kihiu, 2009a, Muvengei and Kihiu, 2009b). The objective of modeling the excavating mechanism is to predict its dynamic behavior by combining actuator and manipulator dynamics. Hydraulic cylinders are used to actuate the manipulator joints by generating forces necessary for boom, arm and bucket motion. These forces 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 (Beater and Otter, 2003). Therefore, it is in these actuators where the dynamic coupling between the mechanical and hydraulic system model of the excavator takes place. Figure 2 shows this relationship schematically. From the knowledge of manipulator dynamics, we have the following well known relations.

$$\dot{X} = J\dot{q} \qquad \tau = J^{T}F \tag{2.1}$$

Where X is the vector of piston displacements, is the vector of piston velocities, q is the vector of manipulator joint angles, F includes the forces generated by actuators, and τ is the vector of corresponding torques at the manipulator joints.

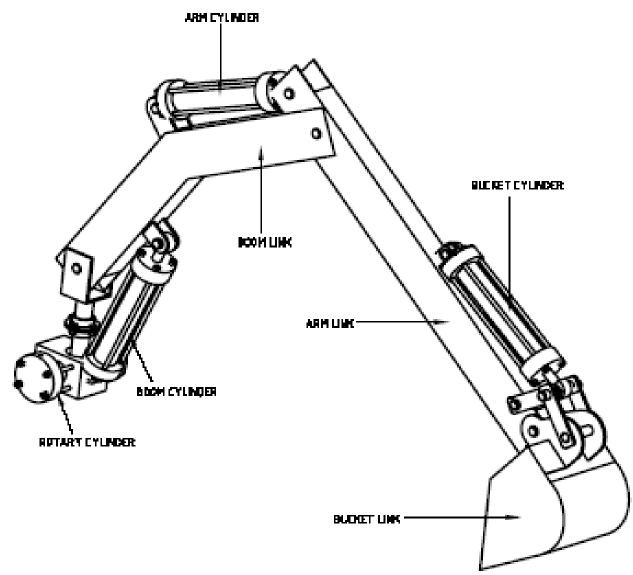
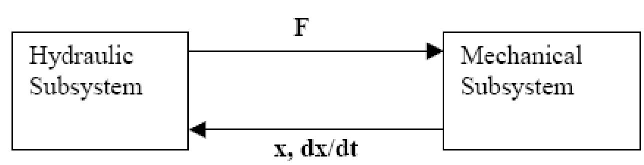


Fig. 1 : Schematic drawing for part of the assembled excavator.



F: Hydraulic cylinder force.
x, dx/dy: Displacement and velocity of the cylinder.

Fig. 2 : Dynamic coupling between the mechanical and hydraulic systems of an excavator.

Since boom, arm, and the bucket links are independently actuated, the jacobian matrix J is a diagonal matrix, and hence equation (2.1) can be written as;

$$\begin{pmatrix} \dot{x}_{bo} \\ \dot{x}_{a} \\ \dot{x}_{bu} \end{pmatrix} = \begin{pmatrix} r_{19} & 0 & 0 \\ 0 & r_{20} & 0 \\ 0 & 0 & r_{21} \end{pmatrix} \begin{pmatrix} \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{pmatrix} \tag{2.2}$$

Where $\dot{x}_{bo}$, $\dot{x}_{a}$ and $\dot{x}_{bu}$ are the velocities of the pistons of the boom, arm, and bucket cylinders respectively.

a) Deriving the Jacobi Expressions for the Manipulator

The diagonal elements of the Jacobi matrix in equation (2.2) can be treated as modulated transformer elements in bond graph method since they relate the input and output flow variables in a junction, that is, they transform the angular velocities of the links to the linear velocities of the pistons, and their magnitudes depend on the angular positions of the links. The length of a hydraulic actuator can be specified by a line segment between the attachment points as shown in Fig. 3.

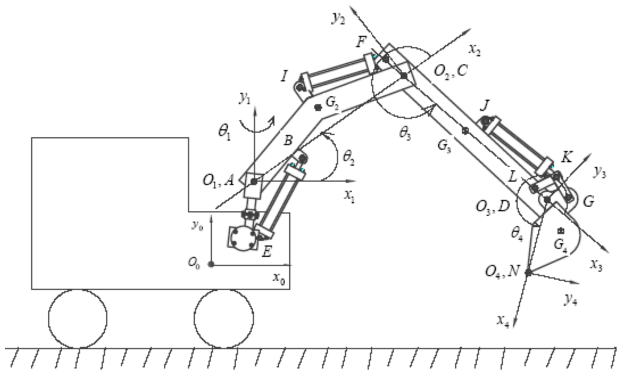


Fig. 3 : Coordinate System assignment for the excavator.

i. *Boom Link*

This is actuated by the boom cylinder which moves joint 2. Consider Fig. 4 which is obtained from Fig. 3.

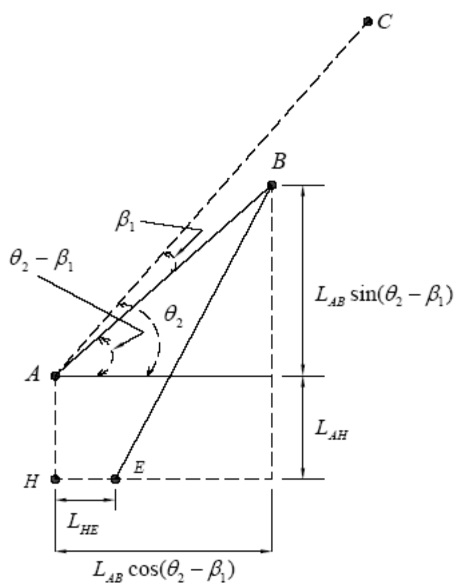


Fig. 4 : Boom cylinder length

Since the rate in which the boom cylinder is changing L_{BE} is technically equal to the piston velocity of the boom cylinder , it can be shown that;

$$\dot{x}_{bu} = r_{19}\,\dot{\theta}_2 \tag{2.3}$$

Where

$$r_{19} = \frac{L_{AB}L_{AH}\cos(\theta_2 - \beta_1) + L_{AB}L_{HE}\sin(\theta_2 - \beta_1)}{\sqrt{[L_{AB}\sin(\theta_2 - \beta_1) + L_{AH}]^2 + [L_{AB}\cos(\theta_2 - \beta_1) - L_{HE}]^2}}$$

β_1 is constant angle <BAC, and L_{AB} , L_{AH} and L_{HE} have constant values obtained from the manipulator's geometry. Equation (2.3) can be represented in bond graphic form as shown in Fig. 5.

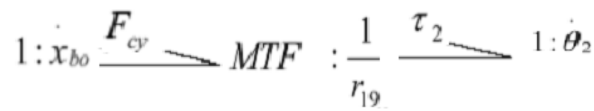


Fig. 5 : Coupling the hydro-mechanical dynamics of the boom link

ii . *Arm Link*

This is actuated by the arm cylinder which moves joint 3. Consider Fig. 6 which is obtained from Fig. 3.

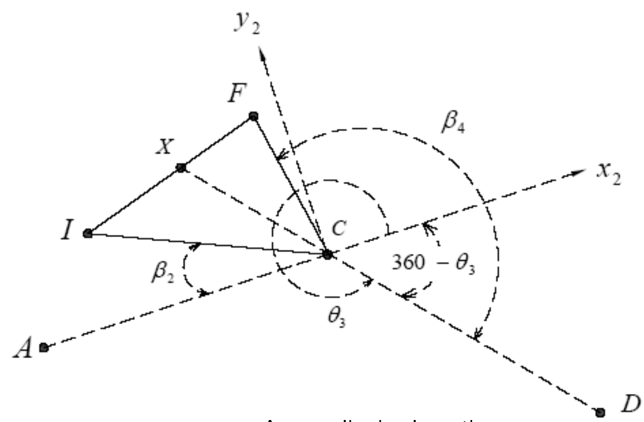


Fig . 6 : Arm cylinder length

Since the rate in which the arm cylinder is changing L_{FI} is technically equal to the piston velocity of the arm cylinder $\dot{x}_a$,it can be shown that;

$$\dot{x}_a = r_{20}\,\dot{\theta}_3 \tag{2.4}$$

Where

$$r_{20} = \frac{-L_{CI}\sin(540 - \beta_2 - \beta_4 - \theta_3)}{\sqrt{1 + \frac{L_{CI}^2}{L_{FC}^2} - 2\frac{L_{CI}}{L_{FC}}\cos(540 - \beta_2 - \beta_4 - \theta_3)}}$$

$<ACI = \beta_2$ and, $< FCD = \beta_4$. Equation (4) can be represented in bond graph form as shown in Fig. 7.

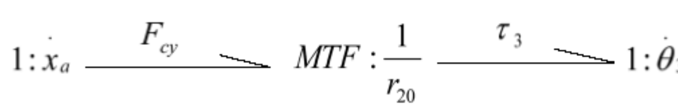


Fig. 7 : Coupling the hydro-mechanical dynamics of the arm link

iii. *Bucket Link*

This is actuated by the bucket cylinder which moves joint 4. Consider Fig. 8 which is obtained from Fig. 3. Since the rate in which the bucket cylinder is changing $\dot{L}_{JK}$ is technically equal to the piston velocity of the bucket cylinder , it can be shown that;

Global Journal of Researches in Engineering (A) Volume XI Issue VI Version I November 2011

$$\dot{x}_{bu} = r_{21}\,\dot{\theta}_4 \qquad (2.5)$$

Where

$$r_{21} = \frac{-L_{KL}\sin[\nu_1 - (\theta_4 + \pi + \nu_2 + \nu_3 - \varepsilon_2 - \varepsilon_3)]}{\sqrt{1 + \frac{L_{KL}^2}{L_{JL}^2} - 2\frac{L_{KL}}{L_{JL}}\cos[\nu_1 - (\theta_4 + \pi + \nu_2 + \nu_3 - \varepsilon_2 - \varepsilon_3)]}}$$

$\nu_1 =< JLD$, $\varepsilon_1 =< KLD$, $\varepsilon_2 =< KDG$, and $\varepsilon_3 =< LKG$

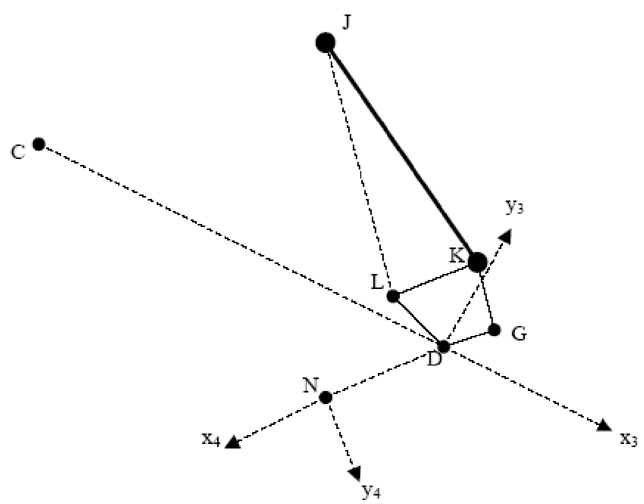


Fig. 8 : Bucket cylinder length

Equation (2.5) can be represented in bond graphic form as shown in Fig. 9.

$$1:\dot{x}_{bu} \xrightarrow{\;F_{cy}\;} MTF:\frac{1}{r_{21}} \xrightarrow{\;\tau_4\;} 1:\dot{\theta}_4$$

Fig. 9 : Coupling the hydro-mechanical dynamics of the bucket link .

b) Overall Bond Graph Model of the Hydraulic and Mechanical Dynamics

Figure 10 shows the overall causal bond graph model representing the interaction of mechanical and hydraulic dynamics of the excavator. Derivative causality was observed at both the vertical and horizontal momenta of the boom, arm and bucket links. This means that the assumptions made in constructing this model have led to a model that will not compute easily with a computer. To fix this derivative causality problem easily, the Karnopp-Margolis method (Karnopp et. al, 2000) of appending very stiff springs and dampers at the pin joints of the manipulator links was used. These are pointed out in the figure. This allowed a causal bond graph to result with straight-forward simulation properties, that is, integral causality in all the capacitive and inertial elements of the bond graph model. In practice, these additional elements are selected to produce frequencies well outside the range of interest. In this case, elements were chosen to produce 200Hz frequencies since we are interested in frequencies no higher than 20Hz and no modal dynamics have been included for any of the mechanical or fluid parts of the system.

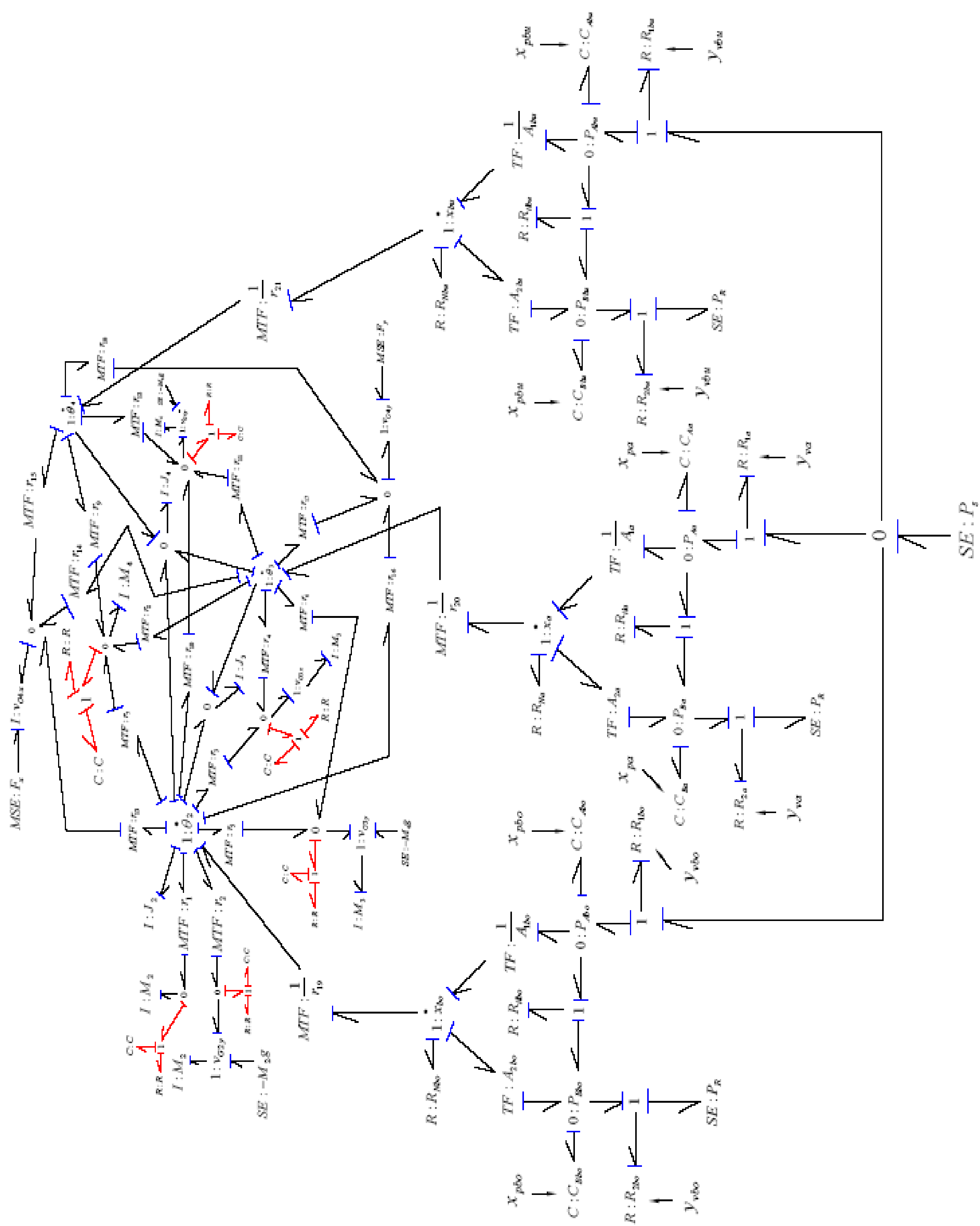


Fig. 10 : Causal bond graph model of the excavating mechanism

III. Results: System Response Using Forward Dynamics

One of the main purposes of modeling a dynamic system is to design appropriate control laws for the system. For a system to be controlled, its model should capture the essential dynamic aspects of the system which include but not limited to, the interaction of the domains involved and also the inter-component interactions. The transient and steady state responses of for the displacements, velocities of the cylinder pistons and manipulator links, flow rates to the cylinders and chamber pressures of the cylinders when all the cylinders are extending simultaneously were simulated to show the dynamic interactions involved in the system. During simulations, one of the links, that is the bucket, was stopped suddenly so as to excite the other links as much as possible, and observed if this excitation was felt in the responses of the other links and the hydraulic system.

a) Link Angular Velocity and Displacement Responses

Figure 11 shows the simulated responses for the angular displacements and velocities plotted in one axis with two y axes for the three links.

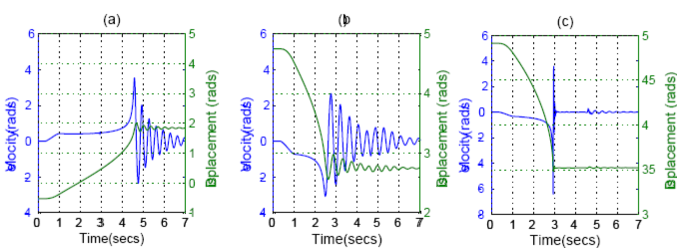


Fig. 11 : The simulated angular velocity and displacement responses for; (a) Boom link (b) Arm link (c) Bucket link.

As clearly seen in Figs. 11 and 12, each manipulator link reaches its final angular position after the piston of the corresponding cylinder completes its stroke (for the case of boom and arm) or is stopped (for the case of bucket). Also, after the final angular position is reached, the velocity response curve of the given cylinder drops and settles to zero value as it is expected practically. The effect of stopping the bucket link suddenly is felt at the velocity response curve of the boom link as an excitement at time 3 seconds as shown in Fig. 11 (a).

b) Piston Velocity and Displacement Responses

Figure 12 shows the simulated responses for the piston displacements and velocities plotted in one axis with two y axes for the three hydraulic cylinders.

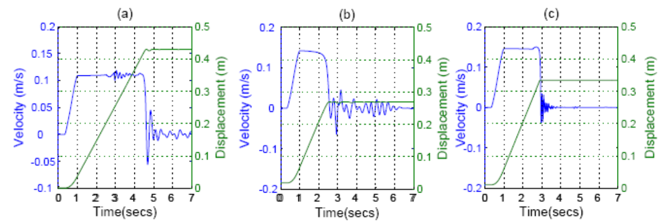


Fig. 12 : The simulated piston velocity and displacement responses for; (a) Boom cylinder (b) Arm cylinder (c) Bucket cylinder

The response curves show clearly that at that time when the piston completes its stroke or stops, the velocity of the piston drops and settles to zero as it is expected practically. The effect of stopping the bucket link suddenly is felt at the velocity response curve of the boom cylinder piston as an excitement in form of damped oscillations at times 3-4 seconds as shown in Fig. 12(a).

c) Flow Rate Responses

Figure 13(a) shows the simulated responses for the flow rates of the three hydraulic cylinders plotted in one axis, while Fig. 16(b) shows the simulated response for the total flow rate.

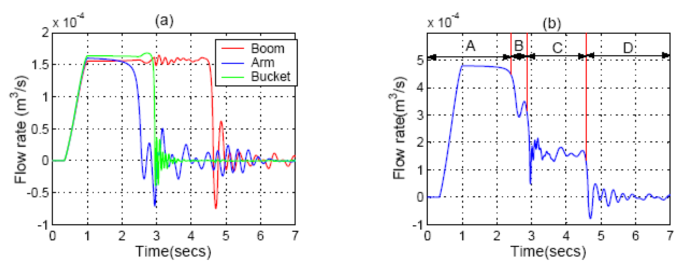


Fig. 13 : The simulated flow rate response; (a) Flow rate responses to individual cylinders (b) Total flow rate.

The flow rate responses for all the cylinders reach the steady state value after 1 second, that is, when the spool valve orifices are completely open. The response curve for the boom cylinder which controls the heaviest link has a lowest steady state value, due to the fact that the cylinder moving the heaviest load offers greater resistance to fluid flow, hence the inter-actuator interaction is captured by the model. The flow rate response curve for the arm cylinder which finishes its stroke first drops to zero value first, then followed by the bucket cylinder which is stopped rapidly after 3 seconds. The excitement caused by stopping the bucket link rapidly is significantly felt at the flow rate response of the boom cylinder at times 3-4 seconds as shown in Fig. 13(a). Since all the manipulator links are extending simultaneously, the total flow rate response which is the summation of the flows to the actuators is simulated and plotted in Fig. 13(b). This curve can be divided into four regions, namely A, B, C and D. In region A the three cylinders are supplied with fluid flow since they are all moving. This is the region of maximum flow requirement. In region B only the boom and bucket cylinders require fluid flow since already the arm cylinder has completed its stroke. In region C only the boom cylinder requires fluid flow since the bucket cylinder has been stopped. In region D no fluid flow is required since all the links have stopped moving after the boom cylinder has completed its stroke.

d) Pressure Responses at the Cylinder Chambers

Figure 14 shows the simulated pressures in the two chambers of the boom, arm and bucket cylinders plotted in the same axis. It is clearly seen that at the region of ramp input (between 0 and 1 second), the pressures at the two sides of each cylinder increase at the same rate until when the orifices of the valves are completely open. After the cylinder finishes its stroke or is stopped from moving, the pressure at the head side chamber which receives pressurized fluid increases rapidly to the supply pressure of . This is because the control action of a constant pressure hydraulic system which ensures that the pressure supplied to the cylinder drops or increases to an appropriate value rather than to the pump supply pressure when the cylinder stroke is finished, was not included in the model. The effect of this is seen in the rod side chamber pressure responses for all the cylinders in form of significant pressure fluctuations. The effect of stopping the bucket link suddenly is felt at the pressure response curves of the boom and arm links as an excitement at time 3 seconds as shown in Fig. 14 (a) and (b).

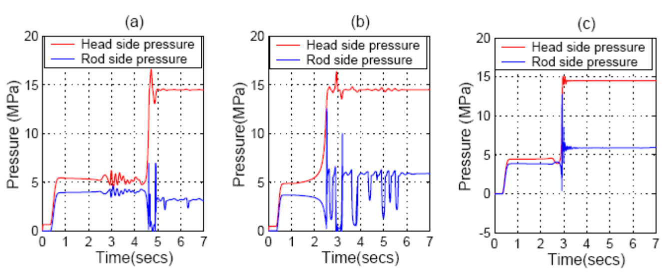


Fig. 14 : The simulated head and rod side pressure responses for; (a) Boom cylinder (b) Arm cylinder (c) Bucket cylinder

From the responses plotted, it is seen that the bond graph model developed captures the interactive dynamics, that is, inter-actuator interactions, inter-link interactions and interaction of the hydraulic and mechanical dynamics.

- Inter-actuator interaction is captured since the cylinder actuating the heavier link receives less fluid flow, and the cylinder actuating the lightest link receives more fluid flow.
- Inter-link interaction is captured since the excitation caused by stopping the bucket link suddenly is witnessed at the response curves of the other links.
- The interaction of the mechanical and hydraulic dynamics is captured since the excitation caused by stopping the bucket link is witnessed at the response curves of the hydraulic system. Also the cylinder actuating the heavier link receives less fluid flow, and the cylinder actuating the lightest link receives more fluid flow.

IV. Conclusion

Dynamic bond graph models representing the mechanical and hydraulic dynamics have been coupled together using appropriate Manipulator Jacobians which were treated as Modulated Transformer. Forward dynamic simulations were then run to determine the open loop transient and steady state responses of the excavator. The bond graph model developed was found to capture the interactive dynamics, that is, inter-actuator interactions, inter-link interactions and interaction of the hydraulic and mechanical dynamics. This is due to the fact that the excitation caused by suddenly stopping the bucket link during simulation, was felt in the response curves of the other links and also of the hydraulic system. Therefore, it can also be concluded that the dynamic model developed in this work can be applied in designing appropriate control laws for the manipulator motions.

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