

Dynamic Analysis of an Excavator During Digging Operation

Tatsuya Yoshida, Takayuki Koizumi, Nobutaka Tsujiuchi, and ZhongMou Jiang
Doshisha University

Yozo Nakamoto
Caterpillar Japan Ltd.

ABSTRACT

Researches for automation of hydraulic excavators have been conducted for laborsaving, improved efficiency of operations and increased worker's safety improvement. Authors' final goal is to develop automatic digging system which can realize the high efficiency. Therefore, it is thought that appropriate digging control algorithm is important for the automation. For this goal, this paper shows a dynamics model of the backhoe excavator and simulations using such models. Detailed dynamic models are needed from the point of view of the control engineering. Authors evaluate effectiveness of automatic digging algorithm by simulation models. In this research, the linkage mechanism which contains the closed loops is modeled based on the Newton-Euler formulation, where motion equation is derived. Moreover, we apply a soil model for simulation, based on the two dimensional distinct element method (DEM), in order to reproduce reaction force from grounds. This paper presents two example of dynamics simulation, integrating the linkage model and the soil model. The inverse dynamic analysis shows that cylinder generative forces, varying depending on digging reaction force, significantly influence the cylinder force during digging operations. By the forward dynamics simulation, a controller for tracking control, which consists of a PID controller and a gravity compensator, is designed and adjusted each PID gain.

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INTRODUCTION

Although hydraulic excavators are used in wide range of fields such as a field of construction and resources development, the number of operators is not necessarily enough. Moreover, the operating efficiency is often limited by operator's skills. Operation of a hydraulic excavator calls for a high degree of skill. There is large difference in productivity between an unskilled operator and a skilled operator. Automatic excavators will help to improve not only unskilled operator's productivity but also safety and economic efficiency. However, the level of automation in the construction machinery industry is relatively low compared to those in other fields of industries (e.g. assembly line in the automobile industry). Although various research projects [1], [2], [3], [4] have been conducted for development of automatic hydraulic excavators, few applications are yet in practical use.

Skilled operators can operate excavators depending on conditions and/or features of grounds. Apparently, appropriate digging control algorithm is one of the critical factors for automatic hydraulic excavators. The final goal of authors is to develop automatic digging control system. Toward achieving this goal, authors evaluate effectiveness of automatic digging algorithm by simulation models that are critical in this authors' research. In past studies[5][6], dynamic models of backhoe type excavators, considering an excavator's front linkage as 3 links open chain manipulator, were presented. As the size of excavators modeled in this way increases, impacts of components (composing the closed loop) on such modeling increase due to the disregarded inertia.

In order to develop a detailed dynamic simulation model, our study uses dynamics model of an excavator having closed loops that consist of the three hydraulic cylinders. This paper discusses kinematics and dynamics of link mechanism in digging operation analysis of a hydraulic excavator. Motion

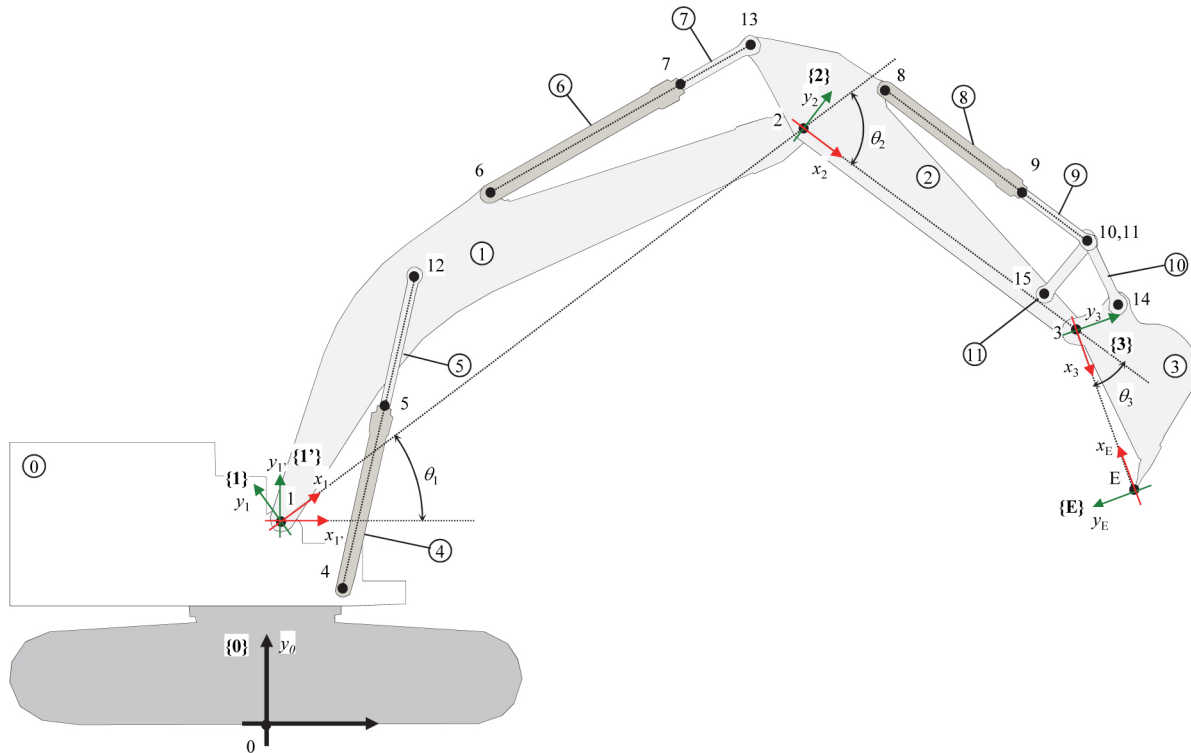


Figure 1. Definition of coordinate system at main link

equations for an excavator are derived as a closed loop manipulator based on Newton-Euler method. In addition, we apply soil model for simulation, based on two dimensional distinct element method (DEM), which had been developed in authors' past study [7], in order to reproduce reaction force from ground. A coupled simulation involving dynamic model and soil model helps to analyze actual digging operation of a hydraulic excavator.

We show dynamic simulation results obtained using our developed simulation models. In inverse dynamic simulation, when digging motions are given, cylinder driving force which realizes the given motions of the excavator is calculated. In forward dynamics simulation, we design a controller that enables a simulation for a hydraulic excavator to track a given digging trajectory.

DYNAMICS MODEL OF EXCAVATOR

Definition of Coordinates

Backhoe type excavator has three closed loop mechanisms consisting of three hydraulic cylinders. Here, we define a serial link consisting of a boom link, an arm link and a bucket as the main link system. Moreover, the boom closed loop is defined as a serial link of an upper structure, a boom and a boom cylinder. The arm cylinder loop is defined as a serial link of a boom, an arm and an arm cylinder. The bucket cylinder loop is defined as a serial link of an arm, a bucket, a power link, an idle link and a bucket cylinder.

In this model, a coordinate is located at each linkage part, as shown in [figure 1](#), [2](#), [3](#), [4](#). In these figures, circled numbers show call-out numbers of parts. $\{i\}$ shows coordinate system of part number i . In order to describe motions of an excavator, a coordinate is located at each linkage based on Denavite- Hartenberg method[8]. [Table 1](#) shows call-out number of coordinate system and joint number of the origin on each part. The intersection of the ground and the pivot at the swing center of the upper body is defined as the origin of coordinate $\{0\}$. The swing motion of upper body is not considered in this model because this study mainly focuses on digging motion.

By Denavite-Hartenberg method, dynamic problems mentioned later are recursively solved, where motion equations can be derived easily. Denavite-Hartenberg parameters of a hydraulic excavator shown in [table-2](#) are defined as follow.

$a_{(i-1) i}$: Distance from axis z_{i-1} to z_i along axis x_i

α_{i-1} : Angle about axis x_{i-1} , formed by axis z_{i-1} and z_i

d_i : Distance from axis x_{-1} to x_i along axis z_i

θ_{i-1} : Angle about axis z_{i-1} , formed by axis x_{i-1} and x_i

In the case of the excavator, α_{i-1} becomes either value of $-90, 0$ or 90 [deg]. d_i shows cylinder length.

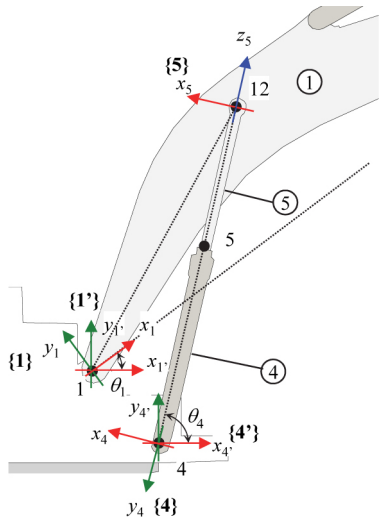


Figure 2. Definition of coordinate system at boom cylinder loop

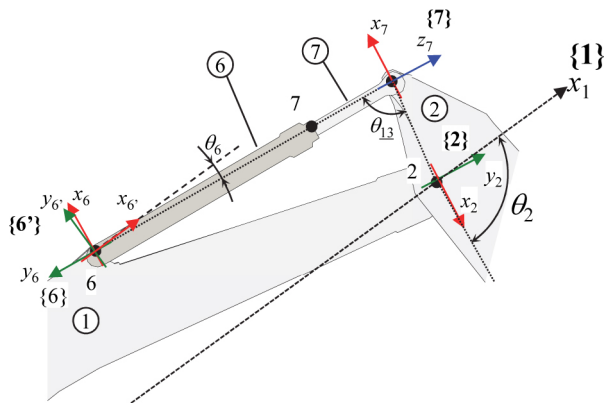
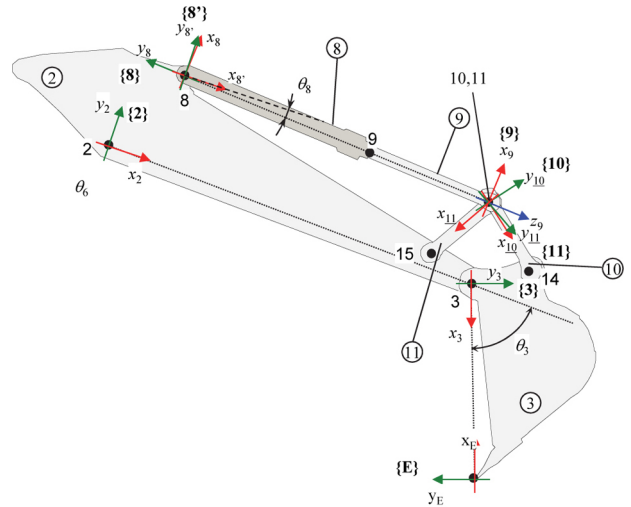
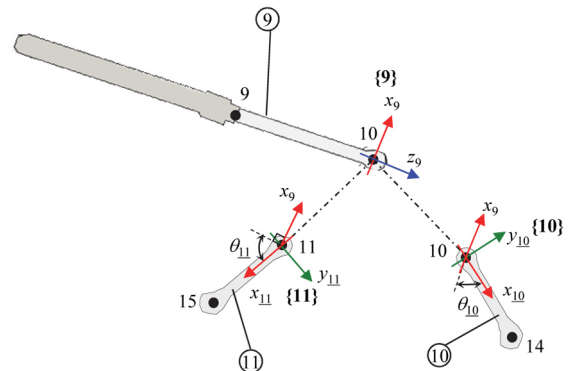


Figure 3. Definition of coordinate system at arm cylinder loop



(a) General view of bucket cylinder loop



(b) Detail of bucket cylinder end

Figure 4. Definition of coordinate system at bucket cylinder loop

Table 1. Arrangement of coordinate system

Parts	Parts No.	Coordinate No.	Joint number of coordinate origin
Upper body and crawler	0	0	0
Boom	1	1	1
Arm	2	2	2
Bucket	3	3	3
Boom cylinder tube	4	4	4
Boom cylinder rod	5	5	12
Arm cylinder tube	6	6	6
Arm cylinder rod	7	7	13
Bucket cylinder tube	8	8	8
Bucket cylinder rod	9	9	10
Power link	10	10	10
Idle link	11	11	11
Bucket tip	3	E	E

Table 2. Denavit-Hartenberg Parameter

	Frame		Denavit-Hartenberg parameter			
	$i-1$	i	a_{i-1}	α_{i-1}	d_i	θ_i
Main Link	0	1'	a_{01}	0	0	0
	1'	1	0	0	0	θ_1
	1	2	a_{12}	0	0	θ_2
	2	3	a_{23}	0	0	θ_3
	3	E	a_{3E}	0	0	180°
Boom loop	0	4'	a_{04}	0	0	0
	4'	4	0	0	0	$\theta_4 + 90^\circ$
	4	5	0	90°	d_5	0
Stick loop	1	6'	a_{16}	0	0	0
	6'	6	0	0	0	$\theta_6 + 90^\circ$
	6	7	0	90°	d_7	0
Bucket loop	2	8'	a_{28}	0	0	0
	8'	8	0	0	0	$\theta_8 + 90^\circ$
	8	9	0	90°	d_9	0
	9	10	0	-90°	0	$\theta_{10} + 180^\circ$
	9	11	0	-90°	0	$\theta_{11} + 90^\circ$