DESIGN AND SIMULATION OF HYDRAULIC EXCAVATOR MANIPULATOR SYSTEM

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Abstract
The focus of this paper is hydraulic excavator and its manipulator. As part of introduction to this paper, basic functions of hydraulic excavator are given. Special attention is on manipulator system, its parts and their properties, as well as types of links and joints between them in terms of defining its kinematics. After kinematics, short review of manipulator dynamics properties is presented. The main part of this paper is focused on modelling of hydraulic excavator manipulator system and simulation of its movement. Software tool used for model creation and simulation is Matlab Simulink. Each manipulator part (boom, arm and bucket) is made to be in correlation with one another and connected with hydraulic cylinders via rotating joints. The results of the simulation are presented through series of line charts, each presenting work of specific part of the model.

Key words: hydraulic excavator, hydraulic manipulator system, simulation, optimization

1. INTRODUCTION

Machine is defined as an apparatus using mechanical power and having several parts, each with a definite function and together performing a particular task [I]. Hydraulic excavator is a large machine for digging and moving earth [II]. As title itself suggests, the focus of this paper is on design and simulation. According to Oxford Dictionary Design is plan or drawing produced to show the look and function or workings of a building, garment, or other object before it is made [III] while simulation itself is imitation of a situation or process [IV].

2. STRUCTURE OF FUNCTIONS

The structure of the functions (Table 1.) describes in detail and in abstract way the total transfer function of the machine. Total transfer function of the machine \( F \) represents the process or technology of the machine operation. The structure of the functions is determined in such a way that total function of the machine \( F \) is split into partial functions \( F_i \) and then partial functions are split into elementary functions \( F_{ij} \) of the machine. Total (primary) function \( F \) of hydraulic excavators is cyclical (interrupted) transport of land in a given work area. Regardless of size, primary function of any excavator consists of following partial functions \( F_i \): digging (excavating) land \( F_1 \), land transfer from digging position to unloading position \( F_2 \), unloading the land \( F_3 \), and selection of new digger position \( F_4 \).

<table>
<thead>
<tr>
<th>Primary function ( F )</th>
<th>Partial function ( F_i )</th>
<th>Elementary function ( F_{ij} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclical (interrupted) transport</td>
<td>Excavation</td>
<td>Excavation plane</td>
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<tr>
<td></td>
<td></td>
<td>Excavation position</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Digging</td>
</tr>
<tr>
<td></td>
<td>Transfer</td>
<td>Unloading plane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unloading position</td>
</tr>
<tr>
<td></td>
<td>Unloading</td>
<td>Unloading</td>
</tr>
<tr>
<td></td>
<td>Selection of new position</td>
<td>Working space</td>
</tr>
</tbody>
</table>

Elementary digger function \( F_{ij} \) can be achieved by using the excavating technique “towards itself” or “from itself”, which mainly depends of whether the working space is above or below the machine.
3. KINEMATIC CHAIN

Kinematic chain of the machine is an assembly of rigid bodies connected by joints (kinematic pairs) to provide constrained or desired motion with certain degree of freedom. Kinematic chain of excavator is consisted of the fifth class kinematic pairs, therefore joints have one rotational degree of freedom.

The base of the hydraulic excavator represents a zero (fixed) member of the kinematic chain \((L_0)\). Independently of the size of the hydraulic excavator, the kinematic chain is consisted of following members: support and movement mechanism \((L_1)\), rotating platform \((L_2)\), and the manipulator with boom \((L_3)\), arm \((L_4)\) and tool - bucket \((L_5)\) (Figure 1.) which represents the last member of kinematic chain.

The centre of joint \(O_2\) of the support member-rotation member kinematic pair \((L_1-L_2)\) is the point of perpendicular intersection of the vertical axis of the joint through the horizontal plane which contains the centres of rolling elements of the slewing bearing that connects support member and movement member to the rotation member of the chain.

The centres of the manipulator joints \(O_3, O_4,\) and \(O_5\) (Figure 1.) are the points of intersection of the axis of the joints through the plane of symmetry of the manipulator chain members \((L_3, L_4, \text{and} L_5)\).

![Figure 1. Kinematic chain of the hydraulic excavator [1]](image)

3.1 The Manipulator

Manipulators, whose elementary function is achieved by using the excavating technique “towards itself”, most often have four member in their kinematic chain: rotating platform \((L_3)\), and the planar configuration consisted of boom \((L_5)\), arm \((L_4)\) and tool - bucket \((L_5)\). The boom \((L_3)\), and with it, the entire device is lifted and lowered around the joint \(O_2\). The joint is moved by the \(C_3\) cylinder. At the top of the boom, there is the arm \((L_4)\) that oscillates by work of the \(C_4\) cylinder. The cylinder \(C_5\) moves the bucket \((L_5)\) indirectly via lever \(C_{5.1}\) and coupling \(C_{5.2}\) around the top of the arm \((L_4)\). Excavation of land with the bucket \((L_5)\) can be achieved by single or joint action of the \(C_4\) and \(C_5\) cylinder depending on the position of the manipulator. After that, the bucket \((L_5)\) is lifted by the \(C_3\) cylinder, with joint action of the boom \((L_3)\) and its accompanied cylinders \(C_3\) and \(C_5\). In order to get to the unloading position the rotating platform \((L_2)\), turns around fixed base of the excavator via joint \(O_2\). At the desired position, the bucket \((L_5)\) is emptied by the movement of \(C_5\) cylinder. Returning to the point of excavation is achieved by aligning the action of all three cylinders with the turning of the excavator platform around joint \(O_2\). (Figure 1.)

4. MODELLING AND SIMULATION

Analysis of complex systems requires the use of techniques consisted of modelling and simulation of that system. Modelling, as the word implies, consists of making a model, mostly mathematical rather than physical one. Mathematical model of complex system that has dynamic properties and uses numerical methods represents basic ground for simulation process. Simulation is the process of predicting the state of the real system by observing the model of that system in modelled conditions and working functions.

The process of simulation of excavator kinematic chain is consisted of defining [1]:
- the mathematical model of the excavator kinematic chain
- the mathematical model of the parameters of manipulator working movements, including trajectory of movement, partial and total time of movement, and correlation between kinematic chain and surface, as well as correlation between kinematic chain and working object

The assumptions of the mathematical model of the excavator kinematic chain are [1]:
- the support surface and kinematic chain members are modelled using rigid bodies
- during manipulation task the excavator is considered stable and not in movement in reference to the ground
- the kinematic chain of the excavator has an open configuration, bearing in mind that even though it has a closed configuration during digging operation it is still observed as an open configuration chain, whose final member – bucket is subjected to technological digging resistances
during manipulation task, the kinematic chain of the excavator is subjected to gravitational, innate and external (technological) forces – digging resistances
the position of the mass centre of hydraulic cylinder is in the middle of the current length of that hydraulic cylinder
the influence of friction resistances is neglected in the kinematic chain and excavator drive mechanism joints

4.1 Modelling in Matlab/Simulink

Software tool used for this paper is Matlab/Simulink. Using SimMechanics the model of hydraulic excavator with corresponding model of hydraulic components has been developed. Rigid bodies are presented as convex surfaces because of Simulink restriction, with boom consisting of two welded convex surfaces. Any influence of this welding is neglected in the simulation process.

Used mass for modelling manipulator members and its mass moment of inertia are presented in Table 2. Since boom (L3) is made of two rigid bodies (L3.1 and L3.2) and each of them has its mass and moment of inertia, they are presented separately in the table 2.

Table 2. The mass properties of the rigid bodies [2]

<table>
<thead>
<tr>
<th></th>
<th>L3.1</th>
<th>L3.2</th>
<th>L4</th>
<th>L5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>1190</td>
<td>1810</td>
<td>1500</td>
<td>1000</td>
</tr>
<tr>
<td>[kg]</td>
<td>3000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ixx</td>
<td>8040.526</td>
<td>12051.898</td>
<td>4183.35</td>
<td>348.1</td>
</tr>
<tr>
<td>Iyy</td>
<td>3853.743</td>
<td>27538.815</td>
<td>83253.75</td>
<td>94284.1</td>
</tr>
<tr>
<td>Izz</td>
<td>1189.27</td>
<td>39590.713</td>
<td>87437.1</td>
<td>94632.2</td>
</tr>
</tbody>
</table>

Simulink model of digging resistances to which bucket is subjected to is presented in Figure 2.

Figure 2. Simulink model of digging resistances [2]

Simulink model of hydraulic cylinders that move parts of the manipulator is presented in Figure 3.

Figure 3. Simulink model of hydraulic cylinders [2]

Hydraulic cylinder are regulated by hydraulic system, whose Simulink model is presented in Figure 4.

Figure 4. Simulink model of manipulator hydraulic system [2]

Simulink model of the manipulator kinematic chain of the hydraulic excavator is presented on Figure 5.

Figure 5. Simulink model of manipulator system of hydraulic excavator [2]
5. RESULTS OF SIMULATION

When simulation process is started, the simulation of manipulator movement is presented. Graphical chart of manipulator movement, presented via cutting edge point of the bucket, shows clear signs that the movement is two dimensional and that there is no movement in z-axis. (Figure 6.)

Data of hydraulic cylinders HC1 presented in Figure 7. indicate the force and movement data for joint O₃.

Data of hydraulic cylinders HC2 presented in Figure 8. indicate the force and movement data for joint O₄.

Data of hydraulic cylinders HC3 presented in Figure 9. indicate the force and movement data for joint O₅.

6. CONCLUSION

This paper shows the use of Matlab Simulink for modelling and simulation of kinematic chain of hydraulic excavator. The focus of modern science and engineering today is in optimisation and improving the effectiveness of any given system. Thus, the model of hydraulic excavator shown in this paper, although simple and idealistic in its nature, represents starting point for further modifications and optimising in order to achieve greater effectiveness of hydraulic excavators.

7. REFERENCES