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Dynamic analysis and control of jib crane in case of jib luffing motion using modelling and simulations

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Abstract: System studied in this work is Luffing jib Crane used for materials handling. Cycle of work is jib luffing upwards. Research focuses on control of oscillations using modeling and simulations. Dynamic parameters investigated are: acceleration, angular velocity, forces and torque in main parts of crane, and influence of load swinging. Diagrams are presented as the solution results of the tested system. The aim is to design block diagram that represents model of crane and motion, analyze dynamics, look for optimal motion control functions and get conclusions about behavior of crane. Analysis will be done with computer application MapleSim.

Keywords: Jib Crane, Jib Luffing, Dynamics, Oscillations, Control, Schematic, modeling, simulations

1. INTRODUCTION

Model of Jib Crane is designed and modelled with software Maple Sim 6.1, MapleSim User Guide, (2014). Model is created based on data from manufacturer Liebherr (Fig. 1), Liebherr TurmDrehKran, (2006). Technical data for the model of crane are: Length of Jib – 50.2 m, Mass of the Jib – 140 t, Height of Mast – 47 m, Height of upper mast – 8 m, Mass of mast – 160 t, Max carrying load: Working Load + Pulley system: Q_{max} = 10300 kg = 101 kN (Fig. 3). Jib Luffing can achieve motion between angles $\psi = 15° \div 85°$.

This work is based in the theory of crane dynamics and control, multibody dynamics, systems design and regulation. It is a contribution to these topics of Conference: Models & Simulation, Control and Automation to Improve Stability, as well as Sustainable Design and Control.

Fig. 1. Luffing Jib crane, Liebherr TurmDrehKran, (2006)

2. SCHEMATIC DESIGN OF CRANE MODEL

In Fig. 2 is presented schematic design and block diagram of Jib crane created with software that enables topological representation and interconnects related components, MapleSim User Guide, (2014). Schematic diagram is created in order to apply analysis, generate differential equations and apply simulations. Elements of diagram are chosen to best represent parts of crane and its motion through simulations.

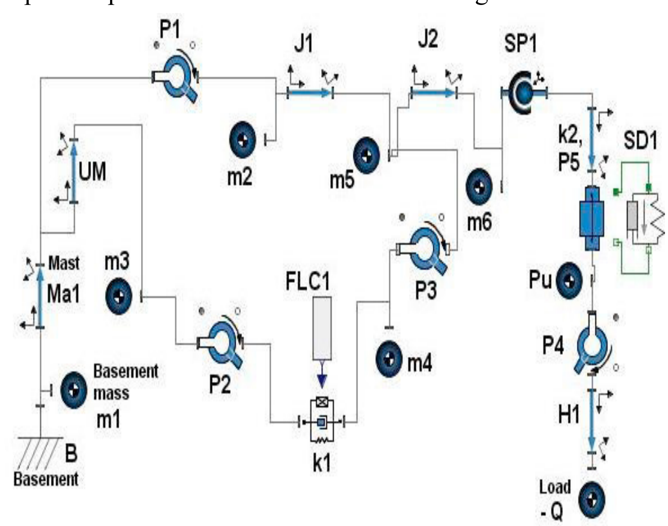

Fig. 2. Block Diagram of jib crane with jib luffing motion

Block diagram starts from left, with basement and mast of crane, and continues to the right until the end where Load Q is connected. All crane parts are designed with elements:

- *Rigid body frames* (bars): Mast-*Ma1*, Upper Mast-*UM*, Jib first part-*J,*; Jib second part-*J2. Concentrated masses: m1, m2, m3, m4, m5, m6, Pu*-Pulley system, *Q* –Load. *Fixed Frame* – Basement *B. Revolute joints*: Pulleys - *P1, P2, P3, P4. Spherical joint:* Pulley - *SP1*;

- *Luffing cables k1* - are created with *Translational Spring, Damper, Actuator block*. On this element is implemented element *FLC1* – Traction Force acting in luffing cables;

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- *Lifting cables- k2* with Pulley mass *Pu* - are created with Spring and dumping element *SD1*, and Joint *P5*. Together with Load *Q*, and carrying Cables with Hook – *H1* are modelled as double pendulum system. For the element SD1, Spring constant for lifting cables is $k = 350\ kN/m$ and Damping constant is $d = 7\ kNm/s$. Spak K., et al. (2014).

In Fig. 3. is presented discrete-continuous model of crane used for model view and simulation. This model is 3-D visualization created by software recurring from Block diagram on Fig. 2. On this model simulations will be performed in time frame of 0< t < 12 s. During this simulation time, crane will lift up Luffing Jib.

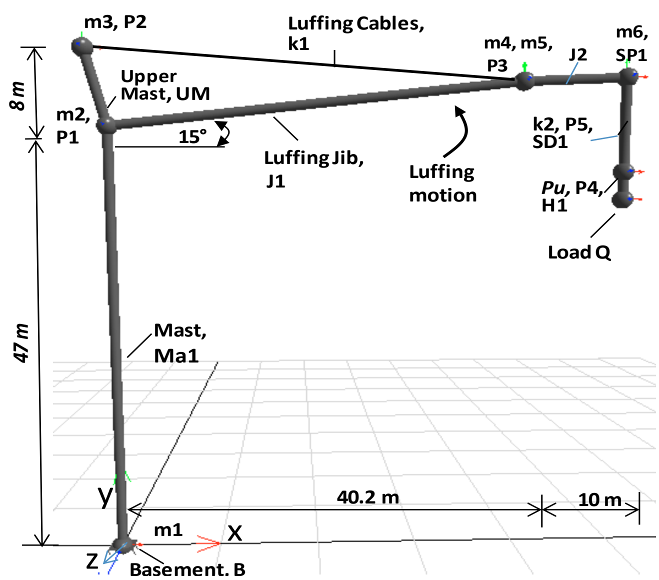

Fig. 3. Discrete-continuous model of Luffing Jib crane in form of 3-D visualization generated by software

3. DIFFERENTIAL EQUATIONS OF JIB CRANE FOR CASE OF JIB LUFFING MOTION

To formulate dynamics of this system, standard Euler-Lagrange methods are applied, by considering the crane as a multi-body system composed by links and joints. For a controlled system with several degrees of freedom (DOF), the Euler-Lagrange equations are given as:

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{q}_i}\right)+\frac{\partial E_p}{\partial q_i}=Q_i \qquad (i=1,2...n) \qquad (3.1)$$

Where: q_i - are generalized coordinates for system with n degrees of freedom, E_k is Kinetic Energy, E_p is Potential energy, Q is the n-vector of external forces acting at joints. Kinetic energy for mechanical systems is in the form:

$$E_k(q,\dot{q})=\frac{1}{2}\dot{q}^T\cdot M(q)\cdot\dot{q} \qquad (3.2)$$

$E_p(q)$ – is potential energy that is a function of systems position.

M(q) - is a symmetric and positive matrix of inertias. La Hera, et al., (2007).

Modern software calculates physical modelled systems through mathematical models, numeric methods and Finite Elements Method. These calculations are based on Euler-Lagrange Equation (3.1), and forces acting on crane applied for control. The modeling result is an *n*-degree-of-freedom crane model whose position is described by generalized coordinates $\mathbf{q} = [\,q_1 \ldots q_l\,]^T$, and which is enforced, in addition to the applied forces, by *m* actuator forces/moments $\mathbf{u} = [u_1 \ldots u_m]^T$, where m<n, Garcíaorden, et al. (2007). The crane dynamic equations can be written in the following second order differential equation:

$$M(q)\cdot\ddot{q}+C(q,\cdot\dot{q})\dot{q}+\frac{\partial E_p}{\partial q}=Q(q,\cdot\dot{q})-B^T u \qquad (3.3)$$

where **M** is the *nx n* generalized mass matrix, $C(q,\cdot\dot{q})$ is *nxn* matrix of Corriolis Forces, $\frac{\partial E_p}{\partial q}$ is the vector of gravity, **Q** is *n*-vector of generalized applied forces, and $\mathbf{B}^T$ is the *nxm* matrix of influence of control inputs **u** on the generalized actuating force vector $\mathbf{f_u} = -\mathbf{B}^T\mathbf{u}$, Garcíaorden, et al. (2007).

After completion and testing of model, Software Maplesim has powerful module for symbolic generation of differential equations. There are 9 DOF from crane model (Fig. 3), which gives 9 differential equations. Variables in differential equations are:

ζ(t) – Rotation of Pulley around *x* axis (Euler Angles)
η (t) – Rotation of Pulley around *y* axis
ξ(t) – Rotation of Pulley around *z* axis
P1_θ(t) – Rotation of Revolute joint P1around its axis
P2_θ(t) – Rotation of Revolute joint P2 around its axis
P3_θ(t) – Rotation of Revolute joint P3 around its axis
P4_θ(t) – Rotation of Revolute joint P4 around its axis
P5_F((t) – force in lifting cables, shown as translator joint with spring and damping,
P5_s(t) – Path of lifting cables.

3.1. Differential equations

9 Differential equations that represent jib luffing motion are very long, so we will present them in short form:

$$0.0001\cdot\frac{d}{dt}\left(\left(\frac{d}{dt}\mathrm{P1\_\theta(t)}\right)\right)+0.0001\cdot\frac{d}{dt}\left(\left(\frac{d}{dt}\mathrm{P3\_\theta(t)}\right)\right)=0 \quad ...(3.1.1)$$

$$\mathrm{Sin}(\eta(t))\cdot((3\cdot(\cos(\xi(t))\cdot\sin(\eta(t)\cdot\sin(\zeta(t))+\sin(\xi(t))\cdot\cos(\zeta(t))\cdot \sin(\mathrm{P4\_\theta(t)})-3\cdot(-\sin(\xi(t))\cdot\sin(\eta(t))\cdot\sin(\zeta(t))+ \ldots +0.0001\cdot \sin(\eta(t))\cdot\cos(\eta(t))\cdot\cos(\zeta(t)))\cdot(\cos(\eta(t))\cdot\cos(\zeta(t))\cdot\left(\frac{d}{dt}\mathrm{P4\_\theta(t)}\right) +\sin(\zeta(t))\cdot\left(\frac{d}{dt}(\eta(t)\right)+\cos(\eta(t))\cdot\cos(\zeta(t))\cdot\cdot\left(\frac{d}{dt}\xi(t)\right))))=0 \quad .(3.1.2)$$

$$-\mathrm{P5\_F(t)}-350000\cdot\mathrm{P5\_s(t)}-7000\cdot\left(\frac{d}{dt}\mathrm{P5\_s(t)}\right)=0 \quad ...(3.1.3)$$

$$\cos(\zeta(t))\cdot(-(3\cdot\cos(\xi(t))\cdot\cos(\eta(t))\cdot\sin(\mathrm{P4\_\theta(t)})+\ldots+0.0001\cdot \sin(\eta(t))\cdot\cos(\eta(t))\cdot\cos(\zeta(t)))\cdot\sin(\zeta(t))\cdot\left(\frac{d}{dt}\eta(t)\right)+\cos(\eta(t))\cdot \cdot\cos(\zeta(t))\cdot\left(\frac{d}{dt}\xi(t)\right)))\cdot\sin(\zeta(t))=0 \quad .....(3.1.4)$$