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Review of the Dynamic and Mathematical Models of Portal Slewing Cranes

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This paper presents an overview of previous research in the field of slewing crane dynamics. Emphasis is placed on the gantry slewing cranes but due to the lack of literature in this field into consideration were taken types of cranes whose dynamic and mathematical models can be applied to the aforementioned type of crane. The plan of further research is given at the end of the paper.

Keywords: Portal slewing crane, Dynamic model, Mathematical model

1. INTRODUCTION

The rapid development of water transport (sea and river), as well as the increased traffic of goods, caused the development of new solutions of crane machines for manipulation in ports and docks. The most commonly used type of cranes for operations of loading and unloading in ports and harbours is portal cranes (slewing and non-slewing). Slewing portal cranes represents crane machine composed of revolving platform with boom which can rotate for 360 degrees and carrying structure that can move in a straight line along the rails. Slewing portal crane is also composed of appropriate mechanisms: mechanism for crane movement, mechanism for raising and lowering the load associated with corresponding rope system, mechanism for changing the reach of the boom and mechanism for the rotation of platform [1-3].

One of the general classification of portal slewing cranes is shown in Fig.1. This type of cranes is used for transport of piece and bulk cargo. Detailed characteristics of a slewing portal crane (Load capacity, dimensions, speed and acceleration) are shown in the paper [4]. During the operation with crane, acceleration and deceleration (braking) mechanisms occurs frequently what causes different dynamic effects [5]. During the design and performances and construction of this cranes, in addition to static loads, dynamic loads also appear which are manifest in the form of changes of speed of the mechanism for lifting and lowering, inertial forces due to the movement of load from the state of immobility, the occurrence of oscillation (swinging) of the payload due to the rotary motion of platform and the impact of the wind force. Listed dynamic effects significantly influencing on the crane carrying structure and the crane operator, and represent essential factors for an adequate calculation and optimization of cross-sections of the carrying structure elements.

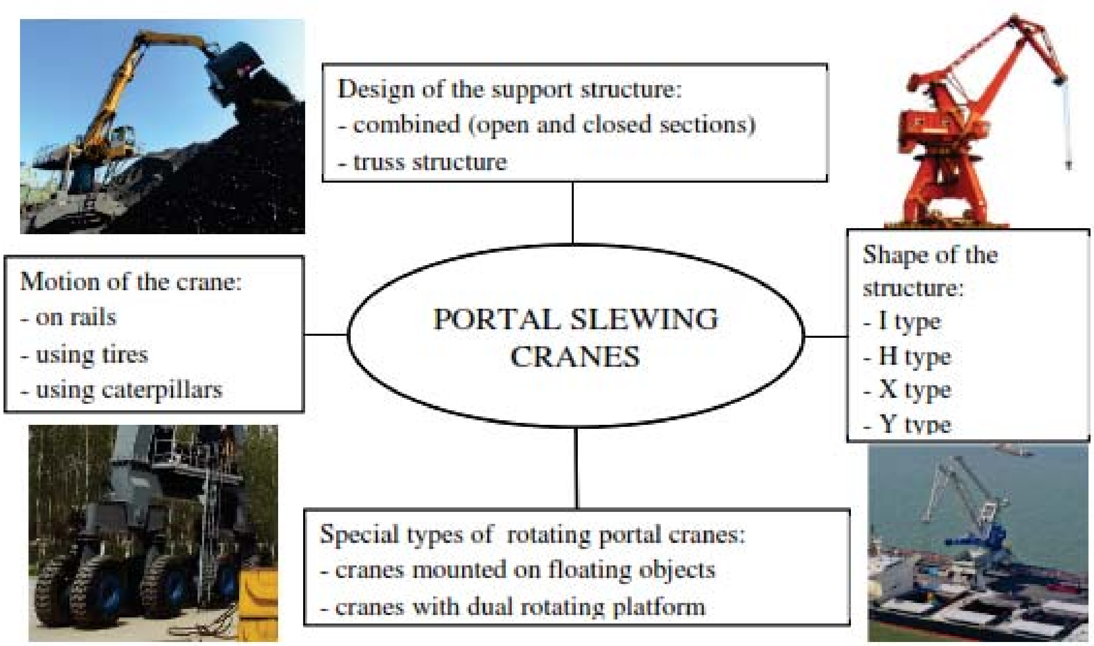

Figure 1: General classification slewing portal cranes

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2. THE DYNAMIC AND MATHEMATICAL MODELS OF SLEWING CRANES

In this chapter the dynamic and mathematical models of portal slewing cranes will be presented and described. In the lacking of literature in the aforementioned field, in consideration will be taken cranes of similar construction whose mathematical and dynamical models can be applied or adjusted to concrete solutions of crane structures.

In papers [6,7] are studied the parameters that influence the dynamic behavior of the structure of slewing portal cranes of large capacity during movement as well for the occurrence of swaying load. Spatial dynamical model on Fig.2 that allows the determination of the parameters mentioned above is formed. Using the finite element method and also modal analysis, the dynamic behavior of the spatial structure of the crane that depends on changing the angle of rotation of the crane boom is determined.

The equations that describe the movement of the crane are presented in the form of:

$$\ddot{\theta}(t)+\omega_l^2\sin\theta(t)=-\frac{1}{L_r}\ddot{x}(t)\cos\phi, \quad (1)$$

$$\ddot{\psi}(t)+\omega^2\sin\psi(t)=-\frac{1}{L_r}\ddot{x}(t)\sin\phi, \quad (2)$$

$$J\ddot{\phi}(t)=T \quad (3)$$

where: θ is angle of oscillation of payload in the longitudinal direction, ψ is angle of oscillation of payload in the transverse direction, φ angle of the boom rotation, x rectilinear motion of the boom and ω circular frequency of oscillation of the load.

Using Laplace transformation and Heaviside functions with linear polynomial, the laws of changes of payload oscillation are determined. These laws are of great importance because uncontrolled oscillations of payload can cause the breakdown of the crane structure. Also, the maximal displacements of characteristic 4 points of the support structure are determined. By determining the large number of parameters that influence on the dynamic behavior of the crane, the possibility to optimize the elements of the support structure of the crane, is created.

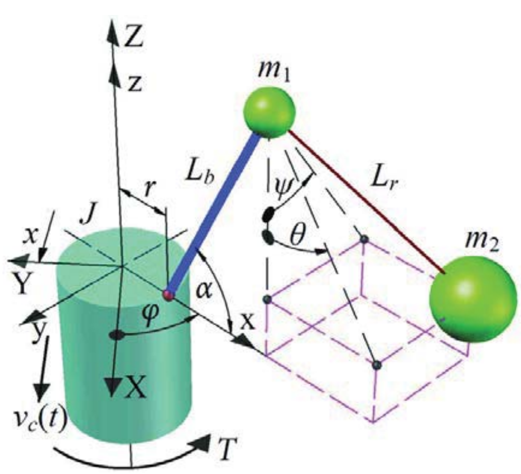

Figure 2: Dynamic model of the crane [6]

In the paper [8] the dynamic stability of portal slewing cranes is studied. The finite-element (plane) model of the crane is formed Fig.3, by which the dynamic behavior of the crane was analyzed with the aim of determining the sensitivity of the crane parts for large amplitudes of oscillations and a long period of deceleration. Elastic supports of the crane are modeled as springs, to represent the elasticity of the base. The influence of inertial forces during movement of structural elements and the influence of oscillations (swinging) of the payload are considered in this paper.

The equations that represent the theoretical basis and describe discrete dynamical structure are written in the form:

$$[\boldsymbol{M}]\cdot\{\ddot{\boldsymbol{q}}\}+[\boldsymbol{B}]\cdot\{\dot{\boldsymbol{q}}\}+[\boldsymbol{K}]\cdot\{\boldsymbol{q}\}=\{\boldsymbol{R}(\boldsymbol{t})\} \quad (4)$$

where: $[\boldsymbol{M}]$ is the inertia coefficients matrix, $[\boldsymbol{B}]$ is the dumping matrix, $[\boldsymbol{K}]$ is the structure stiffness matrix, $\{\boldsymbol{R}\}$ is the generalized loads vector and $\{\boldsymbol{q}\}$ are generalized coordinated in the structure nodes.

By obtaining the dynamically sensitive positions of the crane elements solving the problem of selection of the design material is enabled, knowing the speed of during operation and geometric characteristics of the crane. Comparative analysis of the results obtained by the finite element method and results obtained by the experiment is presented.

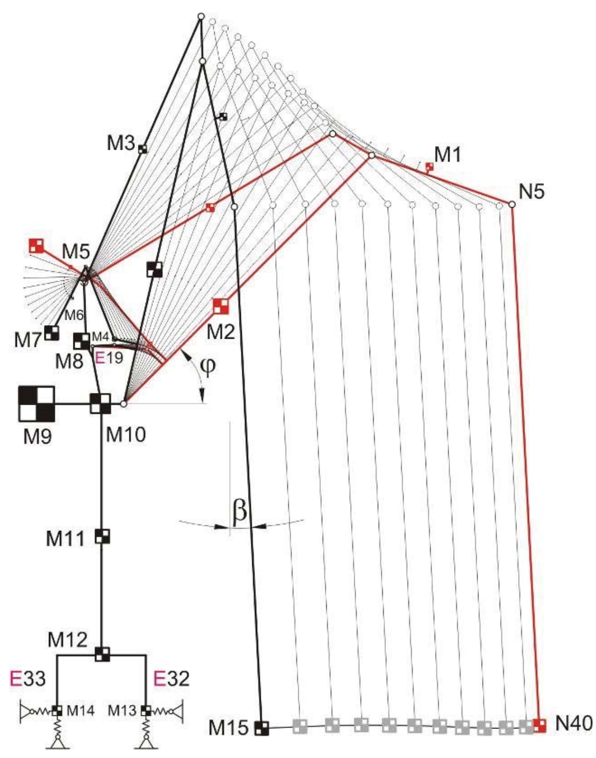

Figure 3: Dynamic model of the crane for finite element analysis with 12 characteristic positions [8]

In the paper [9] the multi-mass model of the slewing crane is presented, by which the rotary motion of the crane is considered and which produce as well spatial oscillations of the payload.

The following impacts are considered in this paper: air resistance, friction in the main bearing, damping and elasticity of the support structure of the slewing crane.

The mathematical model of the crane is presented with the Lagrange equations of the second kind in which figure 10 independent generalized coordinates in the following form:

$$\frac{d}{dt}\left[\frac{\partial T}{\partial \dot{q}_j}\right]-\frac{\partial T}{\partial q_j}+\frac{\partial V}{\partial q_j}=Q_j^{'},\quad j=1,....s. \qquad (5)$$

where: T is the total kinetic energy of the system, $Q_j^{'}$ are generalized non-conservative forces, V is the potential energy of the system and q_j are independent generalized coordinates.

This mathematical model also takes into account the non-linear movement of the payload for higher angles of inclination and there is no limit for small swinging angles of the payload. For the verification of obtained numerical results scaled laboratory model of slewing crane is used where the regulation of the input speed of rotation is controlled by a frequency converter. The simulations were carried out using a weight ranges of the payload $\left(m_Q = 20 \div 50\,kg\right)$, radius of load pivot point $\left(R_o = 1 \div 2\,m\right)$ and as well different lengths of rope that hanging the payload $\left(L_0 = 0,5 \div 2\,m\right)$.

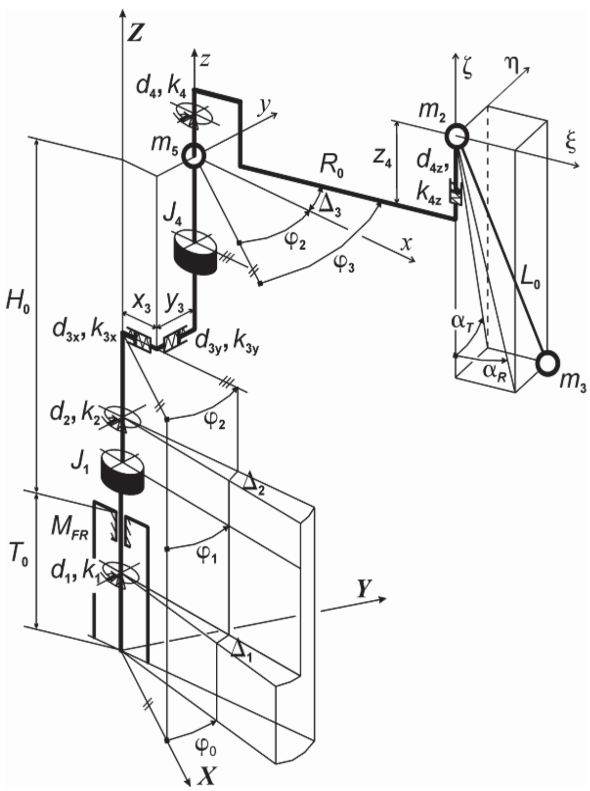

Figure 4: Multi-mass model of the slewing crane [9]

Graphically, using 16 diagrams comparison of results of numerical simulation based on a mathematical model and measurement results on a laboratory model of the crane is given. Based on the given diagrams it can be concluded that there is a good overlap of the simulation results and the results obtained by experiment.

In the paper [10] dynamical modeling ans control of slewing crane rotation using only horizontal movement of crane boom is presented. From the aspect of energy efficiency (energy savings) of the crane, it is more useful to use only horizontal movement of boom, where except where in addition to energy savings also reduce the costs of installing different sensors and controllers for measuring the swinging load. Dynamic model shown on Fig.5 includes only significant terms of the centrifugal and Coriolis force. This simple dynamic model of the rotating crane provides analytical solving of differential equations derived for the presented model written in the following form:

$$\begin{aligned} & l\left(1+\theta_1^2\right)\ddot{\theta}_1 + l\theta_1\theta_2\ddot{\theta}_2 - l\theta_2\ddot{\theta}_4 + l\theta_1\dot{\theta}_1^2 + l\theta_1\dot{\theta}_2^2 - \\ & \quad - 2l\dot{\theta}_2\dot{\theta}_4 - \left(l\theta_1 + L\sin\theta_3\right)\dot{\theta}_4^2 + g\theta_1 = 0 \end{aligned} \qquad (6)$$

$$\begin{aligned} & l\theta_1\theta_2\ddot{\theta}_1 + l\left(1+\theta_2^2\right)\ddot{\theta}_2 - l\theta_2\dot{\theta}_4^2 + l\theta_2\dot{\theta}_1^2 + l\theta_2\dot{\theta}_2^2 + \\ & \quad + 2l\dot{\theta}_1\dot{\theta}_4 + \left(l\theta_1 + L\sin\theta_3\right)\ddot{\theta}_4 + g\theta_2 = 0 \end{aligned} \qquad (7)$$

where: θ_1 and θ_2 are angles of swinging of the payload in the plane of vertical motion of the boom and the tangential direction of the horizontal movement of the boom, θ_3 and θ_4 indicate the horizontal and vertical angles of boom, respectively, and a L and l represent the lengths of boom and rope.

Using numerical solving of algebraic equations trajectory of S-curve can be obtained, which includes the elimination of residual vibrations without measuring them, using only the horizontal movement of the crane boom. Using a laboratory model of the crane, the verification of results obtained by numerical simulation an experimental results from scaled model of the crane was carried out.

Good agreement between the results is observed and found that with the same laboratory model except obtaining trajectories can obtain time of deceleration of the crane in the real time, which is one of the ideas for future research.

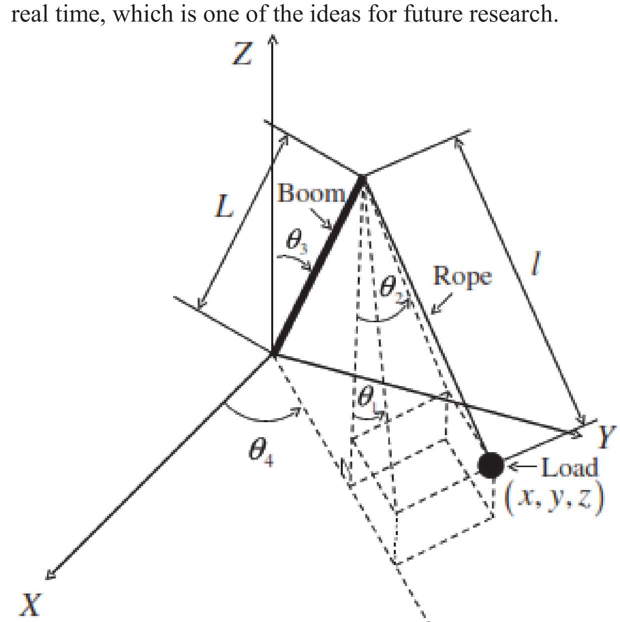

Figure 5: Schematic of slewing crane model [10]

In the paper [11], a dynamic model tower (construction) crane Fig.6 is presented, where along the rotating crane boom, trolley wit hanged payload is moving.

The crane can be modeled as a system consisting of cantilever beam attached to the rigid rotating pillar and trolley on which id hanged the payload in the form of a pendulum and which are moving along the console. Cantilever beam is modeled using Euler-Bernoulli theory assuming that the revolving inertial and shear deformations can be discarded. The payload is modeled as pendulum Fig.7, on which end is located a concentrated mass and which is hung at one end to the massless inextensible cable and the second attached on trolley which are moving frictionless along the rotating boom and also are represented as concentrated mass.

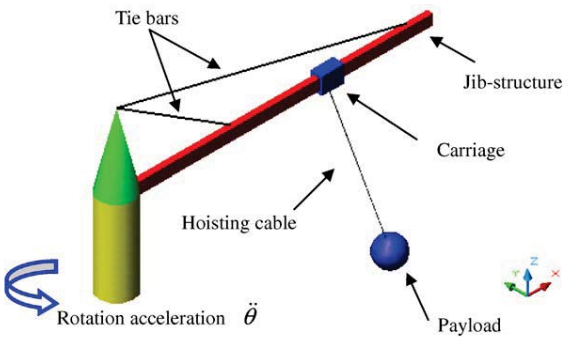

Figure 6: Configuration of the elastic boom with moving load [11]

Movement of rotating boom is described with the help of coupled equations in plane and out of the console plane, while the equations of motion of the payload are derived from the Hamilton's principle. In the paper are given notes in the form of of guidelines for solving equations.

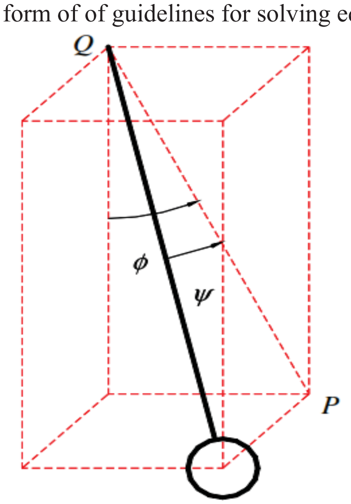

Figure 7: The angles of the payload oscillations [11]

The paper [12] deals with research of dynamic behavior of hydraulic slewing crane with free hanging load which is oscillating during rotation and raising and lowering the crane boom Fig.8. For the purpose of simplification of the mentioned procedure two movements are discussed individually. Crane represents the kinematic chain of 3 members with rotating joints. With two degrees of freedom raising and lowering of the load is described while with an additional degree the rotation of the crane is described.

For the formation of mathematical model of the crane, the Newton-Euler algorithm on the basis of which formed the second order differential equation problem for forward dynamics is used.

$$-M(q)\ddot{q} - H(q,\dot{q}) + G(q) + \tau(t) = 0 \qquad (8)$$

where: q, $\dot{q}$, $\ddot{q}$ are vectors of position, speed and angular acceleration of joints, $M(q)$ is mass matrix composed of elements which describe acceleration $\ddot{q}$ for every element, $G(q)$ weight terms and $\tau(t)$ is vector of torque for every joint.

Based on the simulation, which is based on the aforementioned equations, angles of raising and lowering of the boom are determined, hydraulic system pressure and also forces in the joints, a good match between the results obtained by the simulation and the results obtained by experiment is achieved.

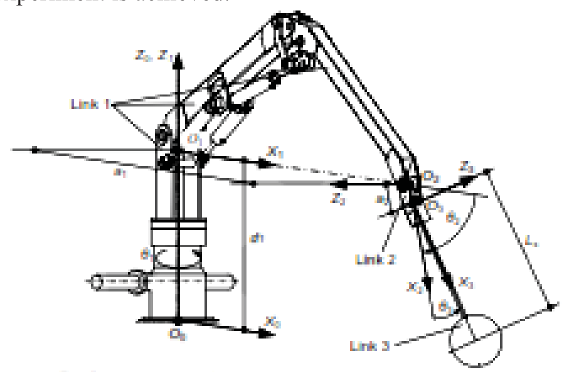

Figure 8: Denavit- Hartenberg parameters in case of oscillation of the load [12]

The paper [13] considers the movement of the payload represented by the pendulum and the dynamic response of the structure of construction tower crane on Fig.9. Crane is modeled using finite element method while equations of the payload movement are described using Lagrange equations of second kinds, including the dissipative function.

The analysis of dynamics of the real crane model using the proposed approach and the numerical methods for solving the equations of motion of the system is performed. It was found that the dynamic amplification factors increase with increasing initial angle of oscillation of the payload whose changes when moving in the plane are non-linear.

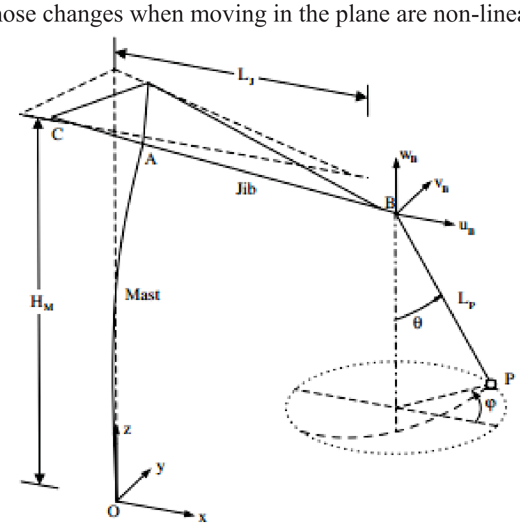

Figure 9: Scheme geometry construction of the tower cranes with a load in the form of a pendulum [13]

The paper [14] deals with the dynamic behavior of mobile construction crane not only from the aspect of the support structure and external loads, also in terms of the drive and control system Fig.10. A new method for dynamic analysis of mobile cranes, which is based on a system with more rigid bodies which is coupled to a drive system is developed. In this way, on the basis of the integrated model dynamic behavior of the crane, motion of the crane construction and dynamic behavior of the drive system can be determined.

The movement of the entire system is described with using the Lagrange equation of second kind. Numerical simulation of the system was carried out with the assistance of input parameters, the required speed of rotation and the control parameters. Using the new method various parameters of the system can be considered, and some of them are: oil pressure, output torque of the engine, the oil flow, stability control, and many other parameters which are important for the design of the crane.

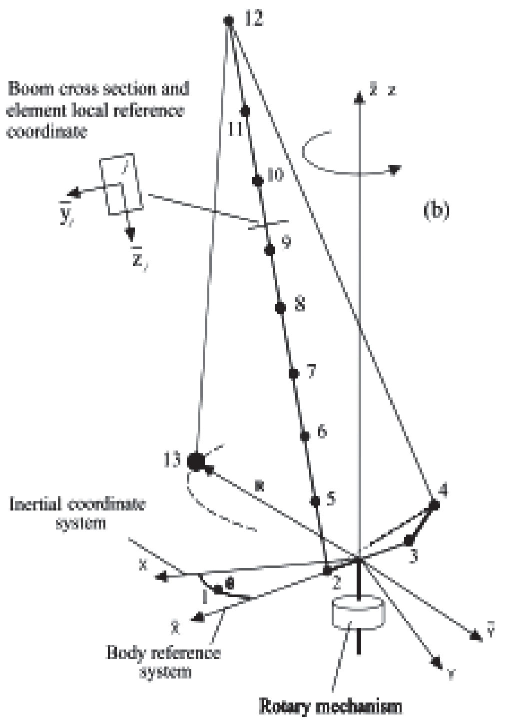

Figure 10: Dynamic model of the crane with coordinate system [14]

The paper [15] examined the effect of supports elasticity of slewing crane dynamics Fig.11. The mathematical model that consists of four rigid bodies is constructed using Lagrange equations of the second order which are numerically solved using the Newmark integration method. In order to obtain the required trajectory and the stabilization of the final positions of the payload, at the end of the motion dynamic optimization method is applied.

The results of numerical simulations were compared with the results from the software package MSC.ADAMS, and also with the results obtained by experiment. The results of dynamic optimization can be used in order to form a neural network which allows that the crane drive functions are defined in real time.

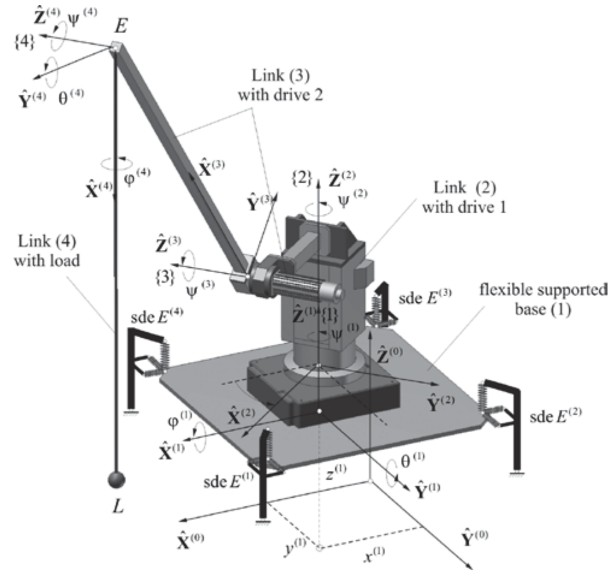

Figure 11: Dynamic model of the crane [15]

The paper [16] presents a method of reducing the payload oscillations by using of winding and unwinding of cable for lifting. The payload is modeled as a concentrated mass, the rope is modeled as a rigid connection and assembly represents the spherical pendulum hanging on the tip of the boom. Using two-dimensional and three-dimensional models, the movement of the payload is described. The results of numerical simulations show that with change of rope, length swinging (oscillation) of the payload can be reduced because of the near resonant excitation.

Lagrangian function which represents the total energy of the system can be written in the following form:

$$L = T - V = \\ = \frac{1}{2} m \left(\left(\dot{x}_a + \dot{\xi} \right)^2 + \left(\dot{y}_a + \dot{\zeta} \right)^2 + \dot{z}^2 \right) - mgz \tag{9}$$

where: T is kinetic energy of the system, V potential energy of the system, while (ξ, η, ζ) are the coordinates of the load position in the coordinate system attached to the boom tip, shown on Fig.12. It was found that the appropriate selection of the winding and unwinding speed of the cable, a significant reduction in the oscillation of the payload can be achieved.

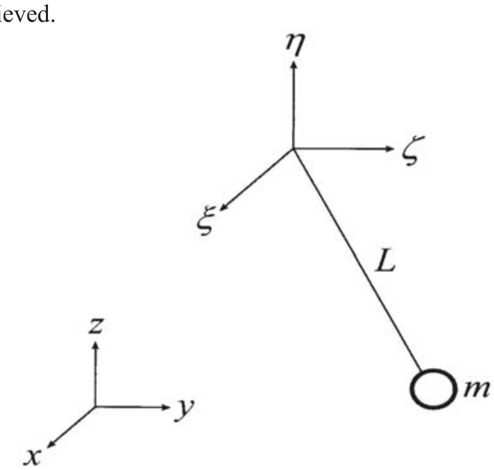

Figure 12: Coordinate system of the crane [16]

3. CONCLUSION

The paper presents the mathematical and dynamic models of slewing cranes with a focus on craft portal cranes. Through the analysis of existing research, slewing portal cranes, construction tower cranes, mobile construction cranes and hydraulic telescopic cranes are discussed in this paper.

All aforementioned papers represent a good basis for further research in the field of crane dynamics, which should focus on describing a system using precise dynamic model that takes into account the larger number of concentrated masses. Apart from that, in future researches should be taken into account the elasticity of the segments of the construction which affects the future budget and the results obtained. In addition, in future researches the elasticity of the segments of the structure that affects the further calculation and obtained results, should be taken in to the account.

Also, further studies should be directed towards the use of modern optimization algorithms that can be used to reach optimal values of structural parameters of cranes.

4. ACKNOWLEDGEMENT

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