ELECTRO-MECHANICAL DYANAMIC SIMULATION OF OVERHEAD CREANS DURING THE OPERATION OF LIFTING MECHANISM

Congmin Niu*, Huajiang Ouyang** & Hongwu Zhang*a)

*State Key Laboratory of Structure Analysis for Industrial Equipment, Department of Engineering Mechanics, Dalian University of Technology, Dalian 116023, China

**School of Engineering, University of Liverpool, Liverpool L69 3GH, U.K.

Summary A dynamic model of electric overhead cranes during operations of the lifting mechanism are derived based on a modified Lagrangian. In the model, the interaction between the trolley, the payload, the lifting mechanism (including the wire rope), the steel structure and the driving motor governed by a control system is considered. The dynamic responses of an overhead crane controlled by a control system through changing rotor resistances are simulated numerically for a normal lowering process of half a rated load.

INTRODUCTION

Electric cranes are special handling equipments used extensively in steel works, manufacturing workshops, power stations and freight yards etc. They require a high level of safety. However, the dynamic effect when they operate is considered crudely in the form of an amplification factor in the current design standard which cannot provide the sufficient information for fatigue analysis of the components of cranes when designing cranes for frequent operations. Therefore, it is very important to determine more accurately the time histories of loads acting on the mechanisms, the steel structure and the electrical system during all kinds of crane operations from a global standpoint in the design stage because electric cranes are essentially electro-mechanical systems, and hence it is the focus of this paper.

MATHEMATIC MODELLING OF ELECTRIC OVERHEAD CRANES

Main assumptions

For simplicity, the following fundamental assumptions are made: 1) The clearance between mechanical driving elements, and the bending of driving shafts are neglected; 2) The stators, rotors and enclosures of motors, couplings, brake drums (or discs), the rope drum, gears and reducers' cases, sheaves, the trolley frame, wheels, end carriages, the load handling device and the payload are considered rigid bodies; 3) The wire rope is a massless elastic body with a constant modulus of elasticity and viscous damping and can withstand only axial tension. Two girders are modeled as Euler beams with the same small curvature, viscous damping, uniform mass, and the elastic property; 4) The rated braking capacity of the mechanical brake stays constant; 5) For motors, the iron loss, electromagnetic radiation and parameter variation due to temperature changes are neglected. The gap between stator and rotor is uniform and the coupling magnetic field is linear in the 3-phase AC symmetrical induction motor. Under these assumptions, the physical model of an electric overhead crane during lifting or lowering is shown in Fig.1.The lifting mechanism is represented as a subsystem with two degrees of freedom.

Equations of motion

Only equations of motion for the process in which the payload is not supported by its support are presented due to lack of space. The reference frame *OXYZ* is defined as shown Fig.1. Suppose the elastic deformation of the girders due to vertical loads relative to their equilibrium position under the dead weight is $w(y,t)=\mathbf{N}(y)\,\mathbf{a}(t)$, $\mathbf{N}(y)=(\sin(i\pi y/L))$, $\mathbf{a}=(a_i)$ (i=1, 2, …, n), here, $\mathbf{a}$ and y are the generalized coordinate vector describing elastic deformation of the girder and Y-coordinate of any section of the girder in the *OXYZ* frame respectively. The potential energy V consists of the elastic potential energy of the driving shafts, the wire rope and two girders, and the gravitational potential energy of the trolley (including the lifting mechanism) and the payload. The kinetic energy T is composed of the kinetic energy of two girders and the trolley (including the lifting mechanism) due to the vibration of the girders, the payload, and the lifting mechanism due to the rotation movement. Because the total length of the undeformed wire rope keeps constant during crane operations, $\boldsymbol{\theta}$, l and ε are constrained by the constraint $\varphi=\mathbf{R}^{\mathrm{T}}\boldsymbol{\theta}-2l_{\mathrm{d}}\varepsilon+l-l_{00}=0$ and thus interdependent. Therefore a modified Lagrangian $\mathcal{L}=T+V_{\mathrm{c}}-V+\xi\varphi$ is defined [1, 2]. Here, $\mathbf{R}^{\mathrm{T}}=(2\mu l_{\mathrm{d}},0)$; $\boldsymbol{\theta}^{\mathrm{T}}$ is the angular displacement vector $(\theta_{\mathrm{d}},\theta_{\mathrm{r}})$ of the components with the moment of inertia J_{d} and J_{r}; l and ε are the free length and tensile strain of the falling wire rope respectively; l_{d} is a constant. l_{00} is the length of the falling rope when both θ_{d} and ε equal to zero. V_{c} is the magnetic co-energy of the motor which is the function of θ_{r}, $\mathbf{i}_{\mathrm{s}}$ and $\mathbf{i}_{\mathrm{r}}$ of the driving motor; ξ is a Lagrange multiplier. Through Hamilton's principle $\int_{t_1}^{t_2}(\delta\mathcal{L}+\delta W)\mathrm{d}t=0$ (δW is the virtual work of non-conservative forces which include the braking torque $M_{\mathrm{b}i}(i=1,2)$ of the mechanical brake, the resisting torque M_{f} in the lifting mechanism, the damping

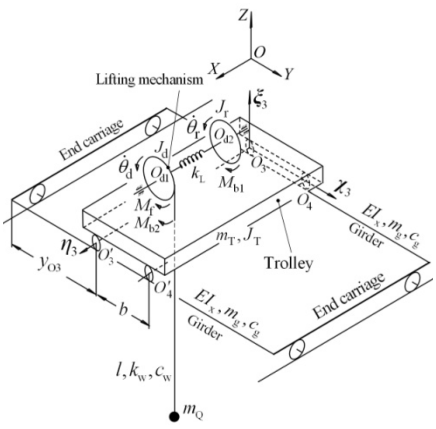

Fig.1 physical model of electric overhead crane

a) Corresponding author. Email: zhanghw@dlut.edu.cn.

forces relating to the elastic components, and the friction force between the drum and the wire rope wrapping around the drum) and integrating with the voltage equation of the induction motor, the electro-mechanical equations of motion for electric overhead cranes are derived:

$$\mathbf{M}_{\mathrm{aa}}\ddot{\mathbf{a}} + c_{\mathrm{g}}\mathbf{N}_{\mathrm{v1}}\dot{\mathbf{a}} + \mathbf{N}_{\mathrm{v1}}\mathbf{a} = m_{\mathrm{Q}}l\ddot{\varepsilon}\mathbf{N}_{\mathrm{d}}^{\mathrm{T}} + m_{\mathrm{Q}}\ddot{l}(1+\varepsilon)\mathbf{N}_{\mathrm{d}}^{\mathrm{T}} + \left(2\dot{l}\dot{\varepsilon} - \mathrm{g}\right)m_{\mathrm{Q}}\mathbf{N}_{\mathrm{d}}^{\mathrm{T}} - m_{\mathrm{T}}\mathrm{g}\mathbf{N}_{\mathrm{T}}^{\mathrm{T}} \tag{1}$$

$$\mathbf{J}_{\mathrm{L}}\ddot{\boldsymbol{\theta}} + c_{\mathrm{s}}\mathbf{H}_{\mathrm{L}}\dot{\boldsymbol{\theta}} + \mathbf{K}_{\mathrm{L}}\boldsymbol{\theta} = \xi\mathbf{R} + \mathbf{T}_{\mathrm{m}} - \mathbf{Q}_{\mathrm{b}}^{\mathrm{T}} - \mathbf{Q}_{\mathrm{f}}^{\mathrm{T}} \tag{2}$$

$$m_{\mathrm{Q}}\ddot{l}(1+\varepsilon) + 2m_{\mathrm{Q}}\dot{\varepsilon}\dot{l} + m_{\mathrm{Q}}\ddot{\varepsilon}l = m_{\mathrm{Q}}\mathbf{N}_{\mathrm{d}}\ddot{\mathbf{a}} - k_{\mathrm{w}}\varepsilon^2/2 + m_{\mathrm{Q}}\mathrm{g} + \xi(1-\varepsilon) \tag{3}$$

$$m_{\mathrm{Q}}l\ddot{\varepsilon} + \left[c_{\mathrm{w}}(1+2l_{\mathrm{d}}/l) + 2m_{\mathrm{Q}}\dot{l}\right]\dot{\varepsilon} + \left[m_{\mathrm{Q}}\ddot{l} + k_{\mathrm{w}}(1+2l_{\mathrm{d}}/l)\right]\varepsilon = m_{\mathrm{Q}}\mathbf{N}_{\mathrm{d}}\ddot{\mathbf{a}} - m_{\mathrm{Q}}\ddot{l} - 2l_{\mathrm{d}}\xi/l + m_{\mathrm{Q}}\mathrm{g} \tag{4}$$

$$L_{\mathrm{s}}\dot{\mathbf{i}}_{\mathrm{s}} + M\dot{\mathbf{i}}_{\mathrm{r}} + r_{\mathrm{s}}\mathbf{i}_{\mathrm{s}} = \mathbf{v}_{\mathrm{s}}\,, \quad M\dot{\mathbf{i}}_{\mathrm{s}} + L_{\mathrm{r}}\dot{\mathbf{i}}_{\mathrm{r}} + p_{\mathrm{p}}i_{\mathrm{L}}\dot{\theta}_{\mathrm{r}}M\mathbf{H}_{\mathrm{m}}\mathbf{i}_{\mathrm{s}} + (p_{\mathrm{p}}i_{\mathrm{L}}\dot{\theta}_{\mathrm{r}}L_{\mathrm{r}}\mathbf{H}_{\mathrm{m}} + r_{\mathrm{r}}\mathbf{I}_{2\times2})\mathbf{i}_{\mathrm{r}} = \mathbf{0} \tag{5}$$

where, $\mathbf{M}_{\mathrm{aa}} = m_{\mathrm{g}}\mathbf{I}_{\mathrm{n\times n}} + m_{\mathrm{T}}\mathbf{N}_{\mathrm{T}}^{\mathrm{T}}\mathbf{N}_{\mathrm{T}} + m_{\mathrm{Q}}\mathbf{N}_{\mathrm{d}}^{\mathrm{T}}\mathbf{N}_{\mathrm{d}} + J_{\mathrm{T}}\mathbf{N}_{\Phi}^{\mathrm{T}}\mathbf{N}_{\Phi}$, $\mathbf{N}_i = [\chi_i\mathbf{N}(y_{\mathrm{o3}}+b) + (b-\chi_i)\mathbf{N}(y_{\mathrm{o3}})]/b\ (i = \mathrm{T},\mathrm{d})$, $\mathbf{N}_{\mathrm{v1}} = \pi^4 EI_{\mathrm{x}}\mathrm{diag}(1, 2^4, \cdots, n^4)/L^3$, $\mathbf{J}_{\mathrm{L}} = \mathrm{diag}(J_{\mathrm{d}}, J_{\mathrm{r}})$, $\mathbf{H}_{\mathrm{L}} = (\mathbf{h}_1, -\mathbf{h}_1), \mathbf{h}_1 = (1,-1)^{\mathrm{T}}$, $\mathbf{K}_{\mathrm{L}} = k_{\mathrm{L}}\mathbf{H}_{\mathrm{L}}$, $\mathbf{T}_{\mathrm{m}}^{\mathrm{T}} = \left(0, 3i_{\mathrm{L}}p_{\mathrm{p}}M\mathbf{i}_{\mathrm{s}}^{\mathrm{T}}\mathbf{H}_{\mathrm{m}}^{\mathrm{T}}\mathbf{i}_{\mathrm{r}}/2\right), \mathbf{Q}_{\mathrm{b}} = (M_{\mathrm{b2}}, M_{\mathrm{b1}})$, $\mathbf{Q}_{\mathrm{f}} = (M_{\mathrm{f}}, 0)$, $\mathbf{H}_{\mathrm{m}} = (\mathbf{h}_{\mathrm{m1}}, \mathbf{h}_{\mathrm{m2}})$, $\mathbf{h}_{\mathrm{m1}} = (0,1)^{\mathrm{T}}$, $\mathbf{h}_{\mathrm{m2}} = (-1,0)^{\mathrm{T}}$, χ_{d} and χ_{T} are the χ_3 coordinates of the drum axis and the centre of gravity of trolley in the coordinate frame $O_3\eta_3\chi_3\xi_3$, respectively. $L_{\mathrm{s}}, L_{\mathrm{r}}, M, r_{\mathrm{r}}, r_{\mathrm{s}}$ and p_{p} are stator inductance, rotor induction, magnetizing inductance, rotor and stator resistance per phase, and the number of pairs of poles of the motor in the lifting mechanism, respectively; $\mathbf{i}_{\mathrm{s}}$, $\mathbf{i}_{\mathrm{r}}$ and $\mathbf{v}_{\mathrm{s}}$ are the vectors whose entries are the coordinates of the stator current, rotor current and stator voltage space vectors in the stationary reference frame, respectively; i_{L} is the speed ratio of the gear reducer in the lifting mechanism.

Because the brake is released after energizing the motor in the control for the lifting mechanism, stick-slip motion between the brake drum and friction linings of the brake may happen during both starting and braking. Equation (2) must be reduced properly when the stick state happens. There are Coulomb friction forces in equation (2), which is nonlinear and non-smooth. Moreover, the mass, damping and stiffness matrices vary with time. Therefore the dynamic simulation is very complicated.

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NUMERICAL EXAMPLE AND CONCLUSIONS

For illustrating the effectiveness of the model, a process for lowering half a rated payload by a 32-tonne electric overhead crane controlled by the motor control system through changing rotor resistances is simulated (Fig.2). The parameters are from [3] except for the some parameters in the rotor resistance function and the braking capacity function of the brake. The braking is implemented by the single-phase braking first and then plug braking of the 3-phase induction motor, and the motor may be out of control over very short periods in which the stator voltage is switched during braking. It can be seen from Fig.2 that the electromagnetic torque, and stator and rotor currents of large amplitude and high frequency persist throughout the single-phase braking period of the motor; in the high-speed shaft, high frequency elastic vibration exists at the start and during braking of the lowering process and the peak torque is much greater than that during normal lifting for a full rated payload [3]; the maximum internal forces acting in the rope and girders occur after application of the mechanical brake during plug braking of motor.

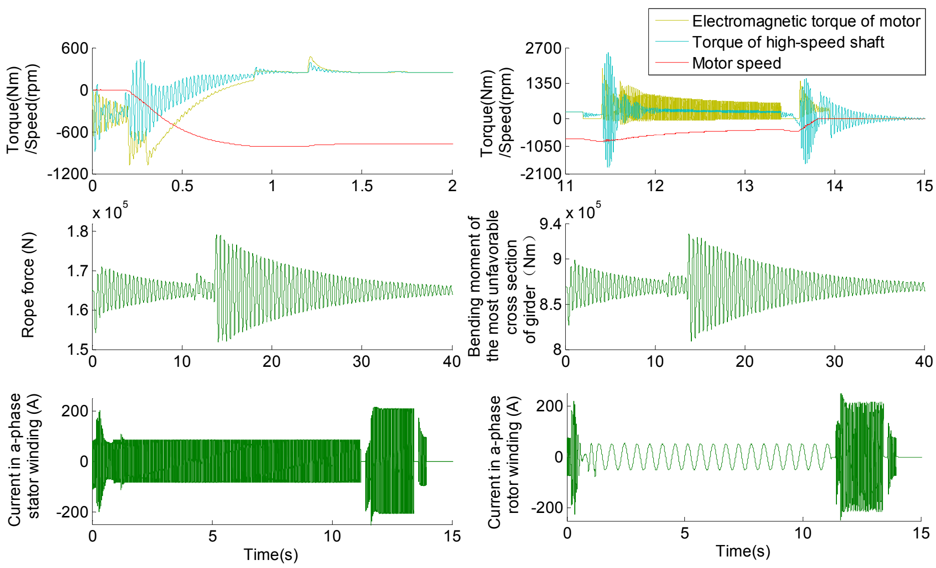

Fig.2 Some simulation results during a normal lowering process of half a rated load

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