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BEHAVIOR OF TOWER CRANES UNDER SEISMIC ACTIONS

Mircea ALĂMOREANU[1], Andrei VASILESCU[2]

Comportarea macaralelor turn ancorate de clădiri supuse acțiunilor seismice a fost prezentată în două comunicări, considerându-se cazul simplu al orientării brațului macaralei pe direcția de propagare a undei seismice. Au rezultat două modele dinamice: cu un grad de libertate - pentru macaralele aflate în afara serviciului (fără sarcină) şi respectiv, cu două grade de libertate pentru cele aflate în serviciu (cu sarcină). Cu toate acestea, brațul macaralei poate fi orientat arbitrar față de direcția undei seismice; de aceea lucrarea de față consideră acest caz şi analizează modelul dinamic general având trei grade de libertate.

The behavior of tower cranes fixed on the buildings was studied in two previous papers considering the simplified hypothesis that the saddle jib has the direction of seismic wave propagation. Two dynamical models were considered with one degree of freedom for the "out of service" cranes (without load) and respectively, with two degrees of freedom for the case of "in service" cranes (with load). However, the jib may be arbitrary oriented in front of the seismic wave direction. This paper takes into account this hypothesis and a dynamic model with three degrees of freedom was developed and analyzed.

Keywords: tower cranes, seismic action, interaction tower crane-building,

1. Introduction

The European norms do not provide specific regulations for control of lifting cranes to seismic actions. Although dynamics of in service lifting machines as well as cranes under the wind loading are considered usually [3] [4], their behavior under the seismic actions and the dynamics of tower cranes anchored to buildings, it seems to not appear in the available databases.

However, two dynamic models of tower cranes fixed on the buildings and submitted to seismic actions along the crane jib, were studied in two recent papers [1] and [2], taking into account the tower crane with load, and the tower crane without load. The present paper is concerned with analytical equations of the dynamic model with three degrees of freedom, considering the jib arbitrary

[1] Prof., Dept. of Constructions Equipments, Technical University of Civil Engineering of Bucharest, Romania, e-mail: alamor@utcb.ro

[2] Prof., Dept. of Mechanics, Statics and Dynamics of Structures, Technical University of Civil Engineering of Bucharest, Romania

oriented in front of the seismic wave direction. The canonic form of the system of differential equations of motion is obtained and practical conclusions are presented.

2. Hypothesis and the dynamic model

We will consider the following hypotheses in the present approach:

1) The tower crane has the behavior of an elastic beam with fixed end;
2) The tower crane is connected to the building with *n* rigid anchors that are considered simple supports for torsion loading;
3) The total mass of the crane tower is concentrated by equivalence to the jib hinge;
4) The rotational inertia of the rotating part of the crane is considered the moment of inertia of masses calculated with respect to the rotation axes (the same with the tower axes), and the rotating substructure (jib and counter jib) is considered stiff in the plane of rotation;
5) The seismic action is applied directly on the base of the crane, and is applied indirectly by the building and anchors;

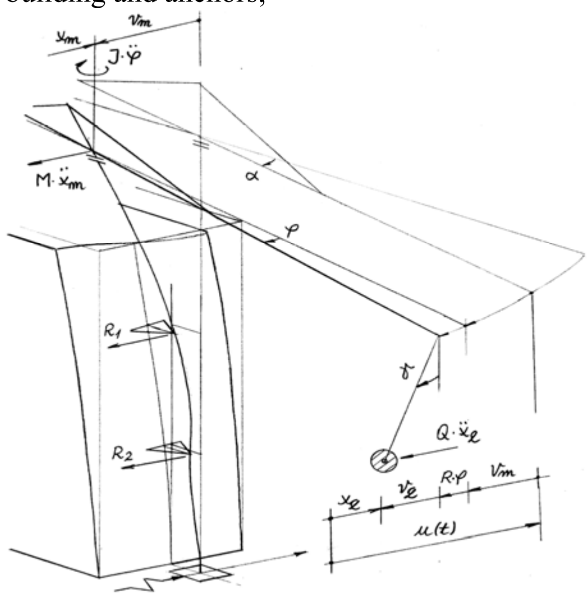

Fig. 1. Dynamic model of the crane

6) Under the seismic motion, the crane has small elastic bending and torsion non-damped oscillations, and the load has a pendulum motion;
7) The effect of the crane over the building is neglected.

The last hypothesis is one of practical use to have a simplified theoretical approach, because the mass and the stiffness of the building are greater than the ones of the cranes. Figure 1 presents the dynamic model considering the above hypotheses. The generalized displacements for the three degrees of freedom are:

x_m - absolute displacement of the equivalent crane mass, *M*,

φ - torsion rotation of the tower crane,

x_q - absolute displacement of the loading.

3. Differential equations of motions

According to the representation from Fig. 2, the relations between the absolute displacements x_j, x_q, the seismic displacement *u*, and the relative displacements v_j, v_q are:

$$\begin{cases} x_j = u - v_j = u - \left(v_m + r_j \cos\alpha \cdot \varphi\right) = u - v_m - y_j \cdot \varphi \\ x_q = u - \left(v_m + R\cos\alpha \cdot \varphi + v_q\right) = u - v_m - y_q \cdot \varphi - v_q \end{cases} \quad (1)$$

The subscript *j* denotes a current point of the rotating part of the crane, where the mass m_j is considered; v_m is the elastic bending displacement of the tower to the level of the jib.

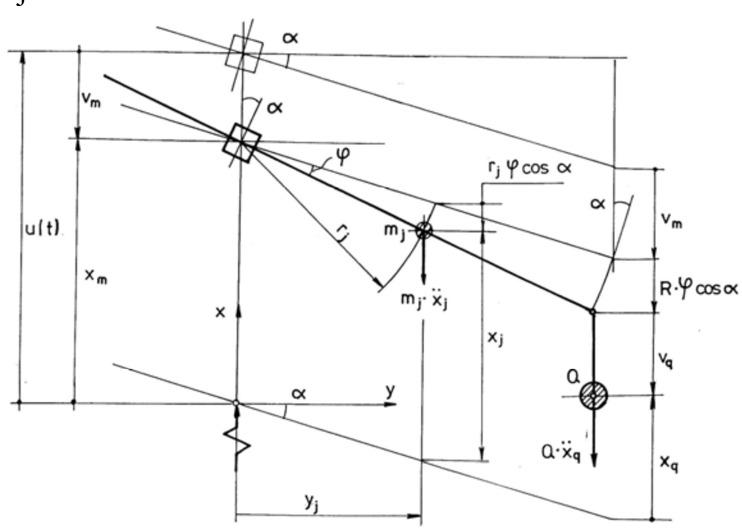

Fig. 2. Absolute and relative displacements

The inertia forces and their corresponding moments calculated with respect to the tower crane axes are:

$$\begin{cases} F_j = m_j \cdot \ddot{x}_j \\ M_j = F_j \cdot r_j \cos\alpha = m_j \cdot \ddot{x}_j \cdot y_j \\ F_q = Q \cdot \ddot{x}_q \\ M_q = F_q \cdot r_q \cos\alpha = Q \cdot \ddot{x}_q \cdot y_q \end{cases} \qquad (2)$$

We consider as unknowns the relative displacements (elongations) v_m and v_q, as also the rotation φ. Considering the specific methods of Statics, their expressions are established by means of the influence coefficients δ and θ:

$$\begin{cases} v_q = \dfrac{h}{g} \cdot \ddot{x}_q \\ v_m = \sum_j F_j \cdot \delta_{mj} + F_q \cdot \delta_{mq} + \sum_i R_i \cdot \delta_{mi} \\ \varphi = \sum_j M_j \cdot \theta_{m1} + M_q \cdot \theta_{m1} \end{cases} \qquad (3)$$

where R_i are the forces transmitted by the building through the anchors of the tower. The meaning of the influence coefficients can be viewed in Fig. 3. Evidently

$$\delta_{mj} = \delta_{mq} = \delta_{mm}$$

We can underline that equation 3 implies that the torsion moment is totally taken by the first anchorage (the upper one).

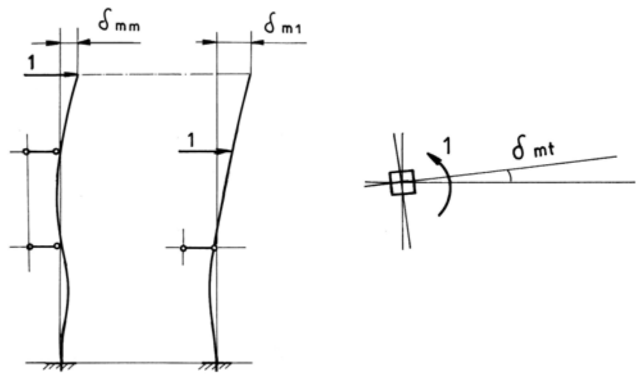

Fig. 3. Influence coefficients

By substituting equation (1) of displacement x_j into equations (2), along with the use of equations (3), we obtain the following form of the differential equations of motion:

$$\begin{cases} v_q = \dfrac{h}{g}\left(\ddot{u} - \ddot{v}_m - y_q \cdot \varphi - \ddot{v}_q\right) \\ v_m = \left[\left(\sum_j m_j + Q\right)(\ddot{u} - \ddot{v}_m) - \left(\sum_j m_j y_j + Q y_q\right) \cdot \ddot{\varphi} - Q \ddot{v}_q\right] \cdot \delta_{mm} + \sum_i R_i \delta_{mi} \\ \varphi = \left[\left(\sum_j m_j y_j + Q y_q\right)(\ddot{u} - \ddot{v}_m) - \left(\sum_j m_j y_j^2 + Q y_q^2\right) \cdot \ddot{\varphi} - Q y_q \cdot \ddot{v}_q\right] \cdot \theta_{m1} \end{cases}$$

We consider the following notations:

$$\begin{cases} \sum_j m_j + Q = M \\ \sum_j m_j y_j + Q y_q = M y_G \\ \sum_j m_j y_j^2 + Q y_q^2 = J\cos^2\alpha = M\left(i\cos\alpha\right)^2 = M i_y^2 \end{cases} \tag{4}$$

where: M is the total mass of the rotating part of the crane, including the load and partially the tower mass, $y_G = r_G \cos\alpha$, r_G - radius of the mass center, $J = \sum_j m_j r_j^2 + Q r_q^2$ - total moment of inertia of masses, and i - radius of inertia.

We introduce the following notations:

$$\omega_q^2 = \frac{g}{h}, \quad \omega_m^2 = \frac{1}{M \cdot \delta_{mm}}, \quad \omega_\varphi^2 = \frac{1}{M i_y^2 \cdot \theta_{m1}} \tag{5}$$

Since ω_q, ω_m and ω_φ have the meaning of circular eigenfrequencies, the equations system becomes

$$\begin{cases} \ddot{v}_m + \ddot{v}_q + y_q \cdot \ddot{\varphi} + \omega_q^2 \cdot v_q = \ddot{u} \\ \ddot{v}_m + \omega_m^2 \cdot v_m + \dfrac{Q}{M} \cdot \ddot{v}_q + y_G \cdot \ddot{\varphi} = \ddot{u} + \omega_m^2 \sum_i R_i \delta_{mi} \\ \dfrac{y_G}{i_y^2} \cdot \ddot{v}_m + \dfrac{Q y_G}{M i_y^2} \cdot \ddot{v}_q + \ddot{\varphi} + \omega_\varphi^2 \cdot \varphi = \dfrac{y_G}{i_y^2} \cdot \ddot{u} \end{cases} \tag{6}$$

4. Contribution of anchors

The second term from the right side of the second equation (6) has the explicit contribution of the anchors by the unknown forces R_i. The tower receives indirect excitations through anchors, i.e. the building displacements induced by the seismic motion. The relations between these displacements (v_i), and anchors, forces (R_i) are:

$$v_i = \sum_k R_k \cdot \delta_{ik}, \qquad i = 1...n, \;\; k = 1...n \tag{7}$$

where δ_{ik} are the influence coefficients of the tower.

Assuming that the displacement v_i are known, the forces of the anchors are obtained from the system of equations (7), solved by Krammer method

$$R_i = \frac{\Delta_{Ri}}{\Delta} \tag{8}$$

where Δ is the determinant of the influence coefficients, and Δ_{Ri} is the determinant obtained substituting the *i* column from Δ with the column of displacement v_i. Returning to the second equation from (6), we get:

$$\ddot{v}_m + \omega_m^2 \cdot v_m + \frac{Q}{M} \cdot \ddot{v}_q + y_G \cdot \ddot{\varphi} = \ddot{u} + \frac{\omega_m^2}{\Delta} \sum_i \Delta_{Ri} \cdot \delta_{mi} \tag{9}$$

The displacements v_i can be estabilshed studying the building behavior under the seismic motion.

5. Simplified approach; canonic form of differential equations of motion

Major simplifications can be obtained if we observe that the stiffness of the building is grater then the stiffness of the crane (see the hypothesis 7, second part). Consequently, only the elastic oscillations of the building are considered, according to the fundamental frequency. In this way, this approach considers the dynamic model of the building with a single concentrated mass M_c, and one degree of freedom. The relative displacement v_c of the building to the level of the mass M_c can be easy established. We have the relative displacements v_i to the level of each anchor:

$$v_i = \frac{\delta_{ih}}{\delta_{hh}} \cdot v_c \tag{10}$$

The influence coefficients involved are specific to the building (see figure 4). Considering v_i from equation (10), the determinant Δ_{Ri} from (8) and (9) will be

$$\Delta_{Ri} = \frac{v_c}{\delta_{hh}} \cdot \begin{vmatrix} \delta_{11} & \delta_{12} & \cdot & \cdot & \delta_{1h} & \cdot & \cdot & \delta_{1n} \\ \cdot & & & & & & & \\ \cdot & & & & & & & \\ \delta_{n1} & \delta_{n2} & \cdot & \cdot & \delta_{nh} & \cdot & \cdot & \delta_{nn} \end{vmatrix} = \frac{v_c}{\delta_{hh}} \cdot \Delta_i \tag{11}$$

↑ col *i*

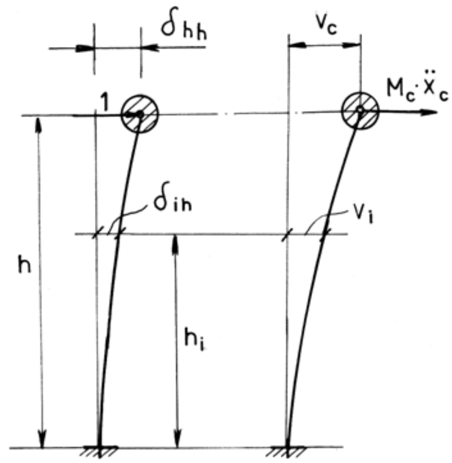

Fig.4. Simplified model of the building

At this point we should consider (11) to obtain the second term from right side of equation (9)

$$\omega_m^2 \cdot \frac{\sum_i \Delta_i \cdot \delta_{mi}}{\Delta \cdot \delta_{hh}} \cdot v_c$$

It is more customary to denote the non-dimensional factor

$$\sqrt{\frac{\sum \Delta_i \cdot \delta_{mi}}{\Delta \cdot \delta_{hh}}} = k \qquad (12)$$

to obtain the canonic form of the system of the differential equations of motion:

$$\begin{cases} \ddot{v}_m + \ddot{v}_q + y_q \cdot \ddot{\varphi} + \omega_q^2 \cdot v_q = \ddot{u} \\ \ddot{v}_m + \omega_m^2 \cdot v_m + \dfrac{Q}{M} \cdot \ddot{v}_q + y_G \cdot \ddot{\varphi} = \ddot{u} + (k\omega_m)^2 \cdot v_c \\ \dfrac{y_G}{i_y^2} \cdot \ddot{v}_m + \dfrac{Qy_G}{Mi_y^2} \cdot \ddot{v}_q + \ddot{\varphi} + \omega_\varphi^2 \cdot \varphi = \dfrac{y_G}{i_y^2} \cdot \ddot{u} \end{cases} \qquad (13)$$

where we take: $\ddot{u}$ the linear acceleration of direct action (acceleration of horizontal seismic motion); $(k \cdot \omega_m)^2 \cdot v_c$ the acceleration of indirect action transmitted from the building by anchors; $(y_G / i_y^2) \cdot \ddot{u}$ the angular acceleration induced by the seismic motion, as a result of the particular distribution of mass of the rotating part of the crane $(r_G \neq 0)$, producing torsion oscillations of the tower.

6. Initial conditions

Assuming that the seismic wave finds the crane not moving, all displacements and absolute speeds are zero in the initial moment. Thus

$$x_m(0)=0,\;\; x_q(0)=0,\;\; \varphi(0)=0 \qquad \dot{x}_m(0)=0,\;\; \dot{x}_q(0)=0,\;\; \dot{\varphi}(0)=0 \tag{14}$$

According to (1), the initial conditions expressed in relative displacements are:

$$v_m(0)=u(0),\;\; v_q(0)=0,\;\; \varphi(0)=0 \qquad \dot{v}_m(0)=\dot{u}(0),\;\; \dot{v}_q(0)=0,\;\; \dot{\varphi}(0)=0 \tag{15}$$

7. Particular cases

7.1. Harmonic seismic action

If the seismic action has the expression:

$$u(t)=U\sin\Omega t\,, \tag{16}$$

then, the elongation of the equivalent mass of the building v_c is obtained

$$v_c(t)=\frac{\Omega^2}{\Omega^2-\omega_c^2}\cdot U\left(\frac{\omega_c}{\Omega}\sin\omega_c t+\sin\Omega t\right) \tag{17}$$

where ω_c is the fundamental circular frequency of the building.

7.2. The crane is anchored

In this case, for the right hand side of the second differential equation (13), the second term is zero.

7.3. The case $r_G=0$

If the center of mass of the rotating part of the crane is in the axes of the tower, then $y_G=0$, and the system of differential equations of motion becomes:

$$\begin{cases} \ddot{v}_m+\ddot{v}_q+y_q\cdot\ddot{\varphi}+\omega_q^2\cdot v_q=\ddot{u} \\ \ddot{v}_m+\omega_m^2\cdot v_m+\dfrac{Q}{M}\cdot\ddot{v}_q=\ddot{u}+(k\omega_m)^2\cdot v_c \\ \ddot{\varphi}+\omega_\varphi^2\cdot\varphi=0 \end{cases} \tag{18}$$

The last equations can be separated, and if $\varphi(0)=0$, then $\varphi(t)=0$ showing the fact that the seismic action does not produce torsion oscillations. This observation leads to a practical conclusion for the tower cranes with saddle jib and trolley. These types of cranes have the rotating part with important mass and elevated moment of inertia of mass, therefore at the end of working program, it is safety to fix the trolley in the position for a minimum value of r_G; that means the position of maximum crane radius.

7.4. The jib is oriented along the propagation direction of seismic wave ($\alpha = \pm\pi/2$)

In this case, the resulting moments of forces is zero, then the third equation (3) gives $\varphi(t) = 0$ and no torsion oscillations are produced. We have only the first two equations from (18).

7.5. The jib is normal to the propagation direction of seismic wave ($\alpha = 0$)

In the system of differential equations (13) we have to consider:

$$y_G \to r_G, \quad y_q \to r_q, \quad i_y \to i$$

7.6. The crane without load

In (13) we consider $Q = 0$, and thus two equations remain:

$$\begin{cases} \ddot{v}_m + \omega_m^2 \cdot v_m + y_G \cdot \ddot{\varphi} = \ddot{u} + (k\omega_m)^2 \cdot v_c \\ \dfrac{y_G}{i_y^2} \cdot \ddot{v}_m + \ddot{\varphi} + \omega_\varphi^2 \cdot \varphi = \dfrac{y_G}{i_y^2} \cdot \ddot{u} \end{cases} \tag{19}$$

with the initial conditions for v_m and φ.

8. Equivalent loads of the seismic actions

The equivalent loads of the seismic actions are generalized forces. Their actions on the dynamic model have the result of elastic displacements equal with maximum calculate elongations. Thus:

a) the horizontal force acting in the reduction point of the crane mass has the expression $F_m^{ech} = \dfrac{v_m^{\max}}{\delta_{mm}}$

b) the torsion moment is given by $M_t^{ech} = \dfrac{\varphi^{\max}}{\delta_{m1}}$

9. Coments and conclusions

The tower cranes with saddle jib without load could be in one of the two following situations:

a) **in service**, between two cycles of working, when the slewing mechanism of the crane is braked;

b) **out of service** when usually, the slewing part of the crane is weathervaning (the slewing part of the crane is free to be oriented by the wind).

In the first case the torsion moment transmitted to the fixed tower is limited to the value

$$M_t = \frac{M_F \cdot i_t}{\eta_t} + M_w$$

where: M_F is the braking torque, produced by the brake of the slewing mechanism, i_t and η_t are the transmitting ratio, respectively the total efficiency value of slewing mechanism, and M_w is the resisting rotation moment.

In the case of the above point *b)*, the torsion moment transmitted to the fixed tower, cannot be greater than M_w, because $M_F = 0$.

Note, for example, the most disadvantageous case concerning the seismic actions, is the one shown at point *a)*.

As a postscript, we would like to draw attention to the remark made at SIMEC 2008, 28 March 2008, by Professor Panaite Mazilu, Honorary member of the Romanian Academy, when the communication [1] was presented. He observed that, in his view it's great importance to introduce the tasks of dynamic modelling and subsequent mathematical approach in the European as well as in national norms, because the safety problem of cranes to seismic actions is not at all present in the actually regulations frame. For these reasons, the analytical approach and an experimental study is necessary before a synthesis to a methodology and prescriptions of regulations types.

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