THE CRANE ROBUST CONTROL

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Abstrakt Článok sa zaoberá návrhom riadenia pre kompletnú štruktúru žeriava t.j. mačky, mostu a zdvihu žeriava. Najdôležitejšími neznámymi parametrami pre simulácie sú hmotnosť bremena a dĺžka závesného lana. Bude použité robustné riadenie pohonu mačky a mosta, ktorým zabezpečíme adaptivitu na hmotnosť bremena a dĺžku lana. Robustné riadenie bude navrhnuté pre prúdovú reguláciu mačky a mosta, k tomu je nutné vedieť pásmo neurčitých parametrov. Celkové robustné pásmo bude rozdelené na subintervaly a po správnej identifikácii neurčitých parametrov budú zvolené najvhodnejšie robustné regulátory. Najdôležitejšou požiadavkou pri pohybe mačky a mosta je zakázané kývanie bremena v koncovej polohe. Asynchrónnymi motormi napájanými z frekvenčných meničov je navrhnutý pohon mačky i mostu žeriava. Zdvih žeriava s pozorovateľom hmotnosti bremena použijeme pre kombináciu zdvih, pohon mačky a mosta so vzájomným odovzdávaním si parametrov: hmotnosť bremena, dĺžka lana a poloha mačky a mostu. Regulátory sú navrhnuté metódami stavového riadenia. Výhodne zavedieme pozorovateľ poruchy, ktorý bude mať za úlohu identifikovať hmotnosť bremena ako poruchu. Systém bude pracovať v oboch režimoch pri prázdnom háku ako aj pri maximálnej zát'aži: zdvíhanie a spúšťanie bremena. Pre pohon zdvihu použijeme trojfázový asynchrónny motor nakrátko napájaný z frekvenčného meniča. Simulácie sú navrhnuté tak, že najskôr realizujeme zdvih a potom prepínací blok uskutočňuje súčasný pohyb mačky a mosta. Pri simuláciách je možné voliť ľubovoľnú hmotnosť bremena, dĺžku lana, polohy a rýchlosti pohybov mačky a mosta.

Summary The article is about a control design for complete structure of the crane: crab, bridge and crane uplift. The most important unknown parameters for simulations are burden weight and length of hanging rope. We will use robust control for crab and bridge control to ensure adaptivity for burden weight and rope length. Robust control will be designed for current control of the crab and bridge, necessary is to know the range of unknown parameters. Whole robust will be split to subintervals and after correct identification of unknown parameters the most suitable robust controllers will be chosen. The most important condition at the crab and bridge motion is avoiding from burden swinging in the final position. Crab and bridge drive is designed by asynchronous motor fed from frequency converter. We will use crane uplift with burden weight observer in combination for uplift, crab and bridge drive with cooperation of their parameters: burden weight, rope length and crab and bridge position. Controllers are designed by state control method. We will use preferably a disturbance observer which will identify burden weight as a disturbance. The system will be working in both modes at empty hook as well as at maximum load: burden uplifting and dropping down. For uplift drive we will use an asynchronous motor fed from frequency converter. Simulations are proposed for situation that firstly we do uplift and then switching block realize simultaneous crab and bridge motion. At simulations it is possible to choose different burden weight, rope length, crab and bridge positions and speeds.

1. INTRODUCTION

Robust control has to ensure correct controlling for crane crab, bridge and uplift. Before the whole design it is good to specify which parameters will have to transfer influence between subsystems. The first important, but unknown parameter is burden weight m_G, which we will identify by observer in the uplift model. This parameter is transferred for the crab and bridge to know which subinterval of robustness will be necessary for controllers switching to ensure correct position control with zero swinging in the final position. Control system was designed by classical state control primary control structure of all subsystems and their upgrade will be robust design by Ackermann. Ackermann method of calculation needed controllers we will observe the width of the robust area for burden weight at individual lengths of hanging rope. Designing of robust intervals for crab and bridge motion we will ensure covering crane loading limit and so total crane control for burden transport at performing two conditions: robustness against burden weight variations and forbidden burden swinging in the final position of crab and bridge. The uplift drive is a part of the crane crab which moves in perpendicular motion to the crane bridge motion [6, 7].

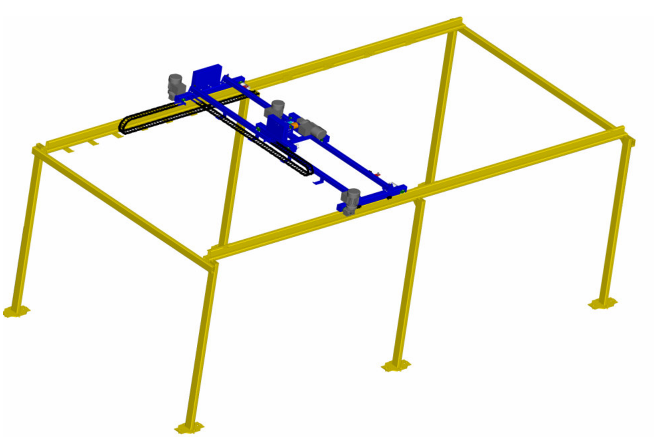


Fig.1 Model of double cross-beam bridge crane

2. SYSTEM FORMULAS

We choose followed state parameters: $w_1 = i_{2m}$ [A], speed $x_3 = \dot{x}_K = \omega$ [rads^{-1}], torque current $x_4 = i_{1y}$ [A], position $x_5 = x_K$ [m], arc circumscribed by burden $x_6 = \beta$ [m] and burden speed in the arc $x_7 = \dot{\beta}$ [ms^{-1}] [5].

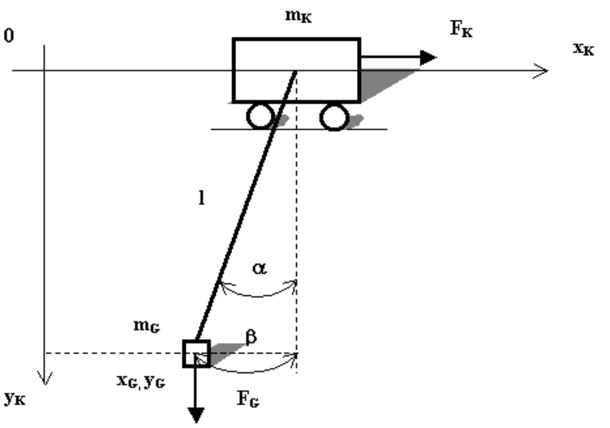


Fig.2 Mechanical part of the crane crab and bridge

Mechanical crab and bridge model is on the figure 2 where by power from motor F_K is driven crane crab (bridge) with own weight m_K (for bridge m_{KM}), whereas burden weight is m_G. Index G refers to burden, F_G is gravitation power from burden weight. Crab and bridge motion we can describe by formulas [3, 4]:

$$m_K \ddot{x}_K - m_G \, g \frac{\beta}{d} = F_K , \qquad (1)$$

$$m_K \ddot{\beta} + (m_K + m_G)\, g \frac{\beta}{d} = -F_K . \qquad (2)$$

After modification of formulas (1, 2) and using motion formula (3) of asynchronous motor we can write:

$$\frac{J_c}{p}\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{3p}{2}\frac{L_h}{1+\sigma_2} i_{2m} i_{1y} - m_z , \qquad (3)$$

$$\ddot{x}_K = a_{31} c_2 c_1 i_{2m} i_{1y} + \frac{a_{11}}{n} c_1 \beta , \qquad (4)$$

$$\ddot{\beta} = -a_{31} c_2 i_{2m} i_{1y} + c_3 \ddot{x}_K - \frac{a_{12}}{n} \beta . \qquad (5)$$

For formulas (4, 5) were set up symbols for creation of system for crane crab and bridge:

$$c_1 = \frac{1}{\frac{J_c}{p}\frac{j^2}{r^2}\frac{1}{m_K} + 1} , \quad c_2 = \frac{j}{m_K r} ,$$

$$c_3 = \frac{J_c}{p}\frac{j^2}{r^2 m_K} , \qquad a_{11} = \frac{m_G}{m_K} , \qquad (6)$$

where l is length of hanging rope, J_c total torque of inertia, p number of motor poles, L_h main motor induction, coefficient $\sigma_2 = \frac{L'_{2\sigma}}{L_h}$, m_z load torque, r radius of driving wheel and j transmission.

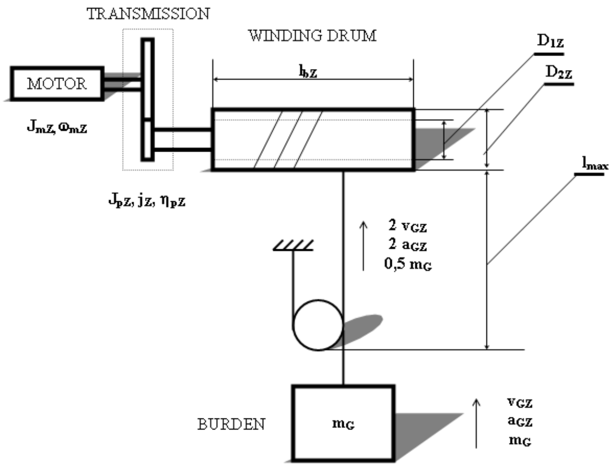


Fig.3 Mechanical part of the crane uplift

Design for uplift drive is by figure 3:
Torque equation for conditions of torque situations for crane uplift is [5]:

$$M_{mZ} - M_{GZ} = J_{CZ} \frac{d\omega_{mZ}}{dt} , \qquad (7)$$

where M_{mZ} - motor torque, M_{GZ} - burden torque and J_{CZ} - total inertia torque. Firstly we calculate sliding burden speed v_{GZ} to angle motor speed ω_{mZ}:

$$v_{GZ} = \frac{\omega_{mZ}}{j_Z}\frac{D_{2Z}}{4} . \qquad (8)$$

Recalculated burden inertia torque comes from the basic formula $J_{CGZ} = \frac{m_G}{2} r_{2Z}^2$ where $r_{2Z} = \frac{2 v_{GZ}}{\omega_{mZ}}$. Potential burden torque at uplift when $M_{1Z} = \frac{m_G}{2} g r_{2Z}$, then:

$$M_{1GZ} = \frac{m_G g D_{2Z}}{4 j_Z \eta_{pZ}} \text{ so burden dropping down:} \qquad (9)$$

$$M_{2GZ} = \frac{m_G g D_{2Z}}{4 j_Z} \eta_{pZ} . \qquad (10)$$

The final formula for total inertia torque for uplift:

$$J_{CZ} = \frac{J_{mZ}}{\eta_{mZ}} + J_{CbZ} + J_{CGZ}, \qquad (11)$$

where J_{mZ} - motor inertia torque, J_{CbZ} - drum inertia torque, J_{CGZ} - burden inertia torque.

Company KPK Martin offered us real parameters of double cross-beam bridge crane for checking our design control for the crane, bridge and uplift at real crane by figure 4. And more, in cooperation with Department of constructing, transport and logistics, headed by Mr. Juraj Ritók we prepare examination on smaller model by figure 1.

Fig.4 Crane of company KPK Martin

3. CONTROL METHOD

We decide control system which includes: converter, asynchronous motor and mechanical part. State control describes system with unknown parameters by [1, 2]:

$$\dot{\mathbf{x}} = \mathbf{A}(\mathbf{p})\mathbf{x} + \mathbf{b}(\mathbf{p})u + \mathbf{e}(\mathbf{p})z,$$
$$y = \mathbf{c}^T\mathbf{x}. \qquad (12)$$

Feedback parameters r_i are calculated by ensuring of poles movement of characteristic polynom of the crane crab and bridge in defined Γ - region by figure 4 with characteristic stability and required damping. Poles region method allows designating control of feedback circuits:

$$u = -\mathbf{r}^T\mathbf{x}, \qquad (13)$$

Condition of Γ - stability describes formulas system 14 where unknown parameters are included in polynom $a(p)$. We get by solving formulas system feedback parameters valid for unknown system parameters and so required robustness of the system [1, 2]:

$$\begin{bmatrix} d_o(\alpha) & d_1(\alpha) & \dots & d_n(\alpha) \\ 0 & d_o(\alpha) & \dots & d_{n-1}(\alpha) \end{bmatrix} \mathbf{a}(\mathbf{p}) = \begin{bmatrix} 0 \\ 0 \end{bmatrix},$$

where: $d_o(\alpha) = 1,\ d_1(\alpha) = 2\sigma(\alpha)$,

$$d_{i+1} = 2\sigma(\alpha)d_i(\alpha) - \left[\sigma^2(\alpha) + \omega^2(\alpha)\right]d_{i-1}(\alpha)$$

for i = 1, 2, ... n-1. (14)

If all poles of characteristic polynom are located in the left part of Γ- region in length ($-a$) from imaginary axis and in sector assigned by damping values $d = \sin\gamma$ is established stability and necessary damping (Fig.5). Robust design needs to know $n-2$ feedback parameters. Graphic-calculation method will designate values of the rest two controllers r_1, r_2. Then rounds for minimum and maximum variable parameters are calculated and their borders of the intersection show possible area A of choosing robust controllers.

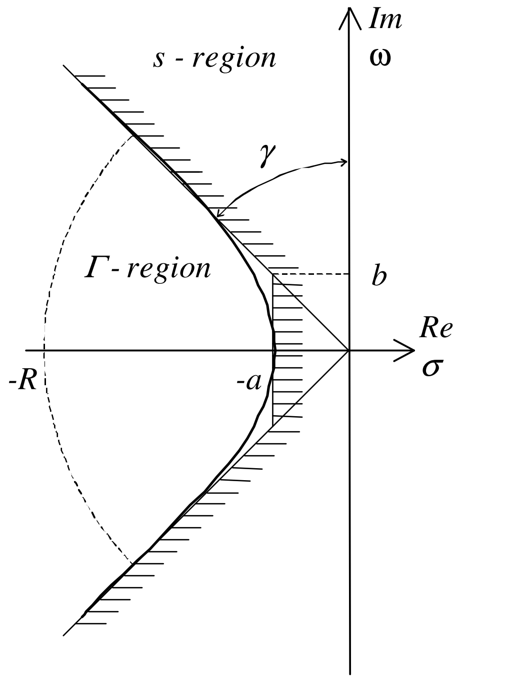


Fig. 5 Γ - region definition

Robust design of crab and bridge by system 14 determined three subintervals of robust area. Covering areas of minimum and maximum burden weight determines area for choosing controllers. Each area presents covering of total crane loading from 342 kg to 20342 kg of burden weight. We define real burden weight by burden weight identification and switching needed robust controllers. We choose one pair of r_{36}, r_{37} controllers from robust area A for each subinterval (Fig.6). We observe for crane bridge robust control design whole area A which is located into only one area (Fig.7). Choosing of controllers r_{36M}, r_{37M} ensures covering the whole crane loading at bridge control with different burden weight.

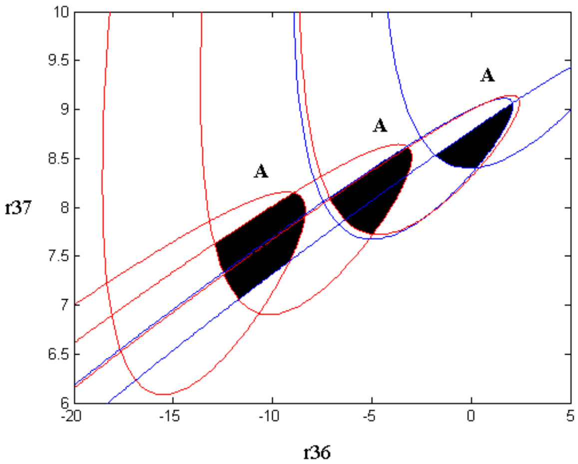


Fig.6 Choosing controllers for three subintervals of the crane crab at varying of burden weight

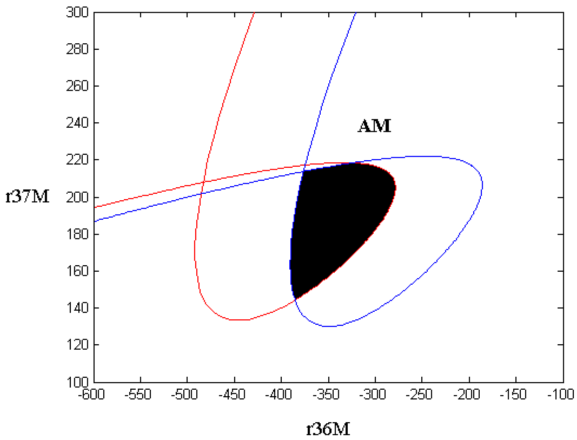


Fig.7 Choosing controllers for one subinterval of the crane bridge at varying of burden weight

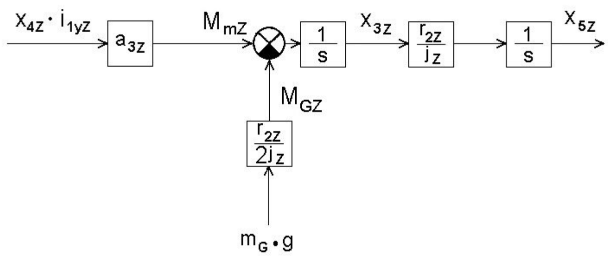
We design by state control crane uplift. We choose PI controllers for current, speed and position control. Preferable disturbance observer will be set which will identify burden weight as a disturbance. By practise reasons designed from KPK Martin we think over for two values of hanging rope: l = 4 or 8 m. At l = 8 m is in progress loading and unloading, burden transport begins after uplifting to l = 4 m. Control is designed by figure 8 and for speed control we can write:

$$\begin{bmatrix} \dot{x}_{3Z} \\ \dot{x}_{4Z} \\ \dot{v}_{4Z} \\ \dot{v}_{3Z} \end{bmatrix} = \begin{bmatrix} 0 & a_{3Z} & 0 & 0 \\ 0 & -r_{4Z} & 1 & 0 \\ -K_{4Z}r_{33Z} & -K_{4Z}(1+r_{34Z}) & -K_{4Z}d_{34Z} & K_{4Z} \\ -K_{3Z} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_{3Z} \\ x_{4Z} \\ v_{4Z} \\ v_{3Z} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ K_{3Z} \end{bmatrix} w_{3Z} \tag{15}$$

State formula for position PI controller will be:

$$\begin{bmatrix} \dot{x}_{5Z} \\ \dot{v}_{5Z} \\ \dot{v}_{3Z} \\ \dot{v}_{4Z} \\ \dot{x}_{3Z} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{r_{2Z}}{j_Z} \\ -K_{5Z} & 0 & a_{3Z} & 0 & 0 \\ -K_{3Z}r_{55Z} & K_{3Z} & -K_{3Z}d_{53Z} & -K_{3Z}d_{54Z} & -K_{3Z}(1+r_{53Z}) \\ 0 & 0 & K_{4Z} & -K_{4Z}d_{34Z} & -K_{4Z}r_{33Z} \\ 0 & 0 & 0 & a_{3Z} & 0 \end{bmatrix} \begin{bmatrix} x_{5Z} \\ v_{5Z} \\ v_{3Z} \\ v_{4Z} \\ x_{3Z} \end{bmatrix} + \begin{bmatrix} 0 \\ K_{5Z} \\ 0 \\ 0 \\ 0 \end{bmatrix} w_{4Z} \tag{16}$$

Fig.8 Torque formula for crane uplift



Observer:

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{b}u + \mathbf{h}\left(y - \hat{y}\right) + e\,\hat{z}_{pm},$$

$$\hat{y} = \mathbf{c}^T\hat{\mathbf{x}}, \quad \dot{\hat{z}}_{pm} = -K_i\left(y - \hat{y}\right). \tag{16}$$

Total state formula at implementation of difference $\Delta x = x - \hat{x}$ will be:

$$\begin{bmatrix} \Delta\dot{x}_{3Z} \\ \dot{\overset{\Delta}{z}}_Z \end{bmatrix} = \begin{bmatrix} -h_{1Z} & e_Z\dfrac{r_{2Z}}{2j_Z} \\ -K_{iZ} & 0 \end{bmatrix} \begin{bmatrix} \Delta x_{3Z} \\ \hat{z}_{pmZ} \end{bmatrix} + \begin{bmatrix} -e_Z\dfrac{r_{2Z}}{2j_Z} \\ 0 \end{bmatrix} z_{pmZ} \tag{17}$$

Simulation scheme on the figure 9 represents complete structure of the crane. Switching structure is included in crane control, ensures correct reciprocity of each crane subsystems and does not allows wrong service. Simulation enables from service side to set follows parameters: burden weight at forward and backward motion, rope length during transport and for positioning, reference crab and bridge position at forward and backward motion. Switching structure realizes correct reciprocity of the motions. And more, to the simulation scheme belongs uplift with identified weight and rope length out, crab block and bridge block.

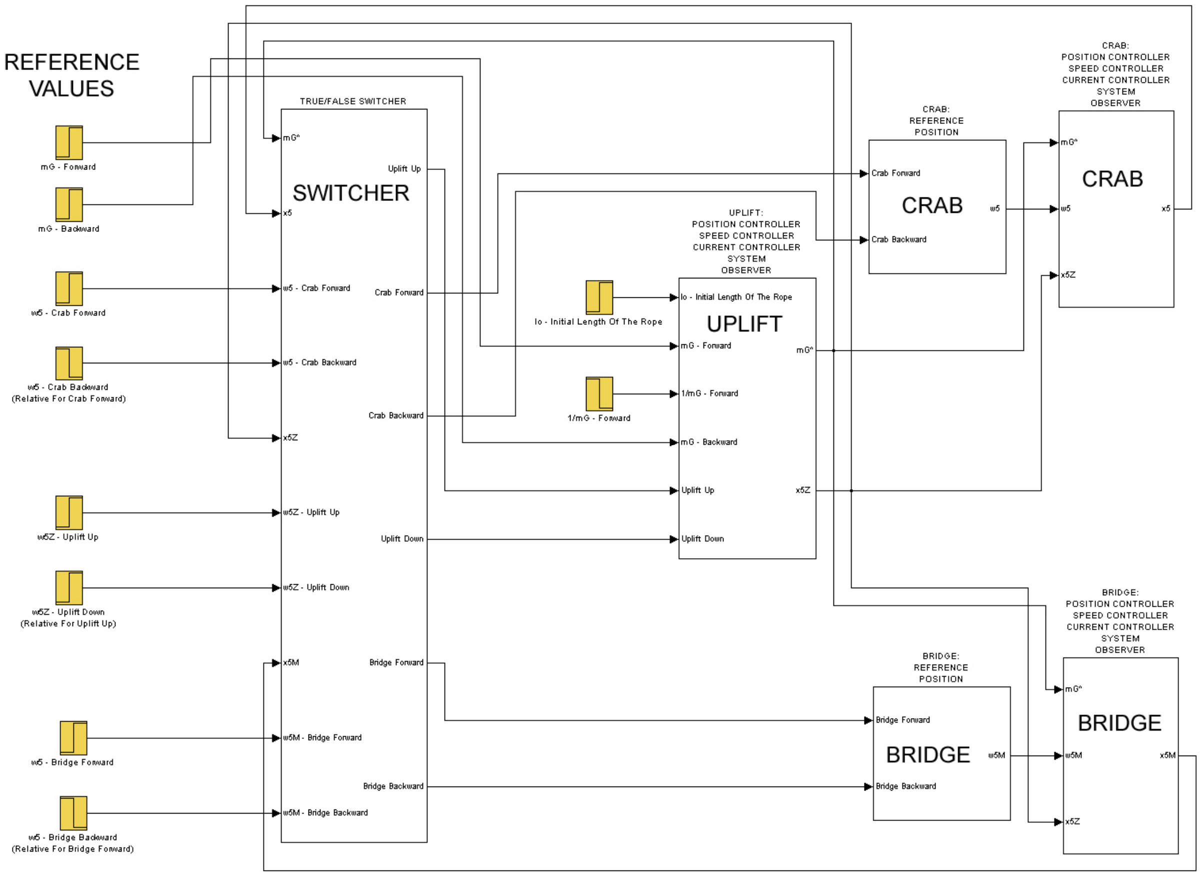


Fig.9 Simulation scheme of crane from MATLAB Simulink

4. SIMULATION RESULTS

Running the simulation immediately starts burden uplift to the reference uplift position (Fig.10, 1'-1, l = 4 m) with burden weight m_G = 20342 kg. Simulation allows after finished uplift synchronous crane crab and bridge motion (obr.10, 2'-2). We transfer burden in principle in the position up or down, because controllers were calculated for switching robust area for length of hanging rope l = 4 m and 8 m. However, this complete allows transferring burden in range of rope length from 4 m to 8 m, because system is robust against to variation of rope length in permited tolerance. We consider rope length 4 m for safety because on the other hand problems can become on the trajectory of drives where the burden moves. When crab and bridge are located in reference position with the burden, the burden begins dropping down (Fig.10, 3'-3) and the system waits for burden weight change m_G which represents service staff by status change on the hook. If become burden weight change follows uplift (Fig.10, 4'-4). After finished uplift of new weight, crab and bridge move backward or to the specific other position (Fig.10, 5'-5). Again crab and bridge move synchronous and after finishing of their movements follows the burden dropping down (Fig.10, 6'-6), [6, 7].

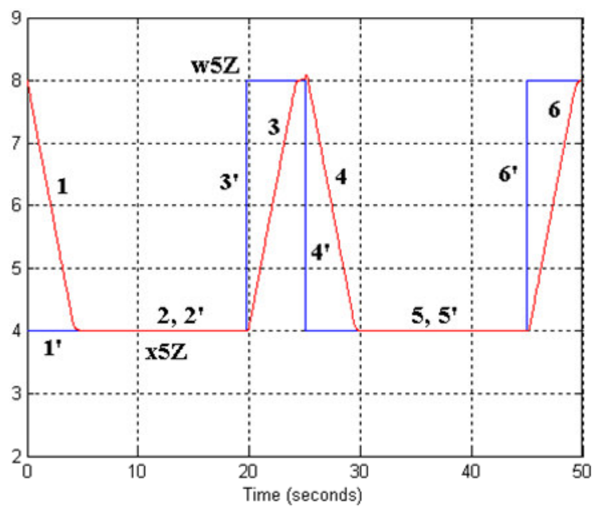


Fig.10 Reference w_{5Z} [m] and real x_{5Z} [m] crane uplift at burden transport

We can observe on the figures 11 and 12 time sequence with figure 10. In the time about t = 5 s after finishing of uplift begins synchronous crab and bridge motion (at different speed, (Fig.11, 12, 1'-1)). In the crab and bridge reference position (Fig.11, 12, 2'-2) followed burden dropping down and service staff changed burden weight for backward motion (342 kg what means empty hook). Crab and bridge moved to the backward position $w_5 = w_{5M} = 0$ (Fig.11, 12, 3'-3) and in the reference backward position started dropping down of empty hook and system is ready for next uploading by burden for transport.

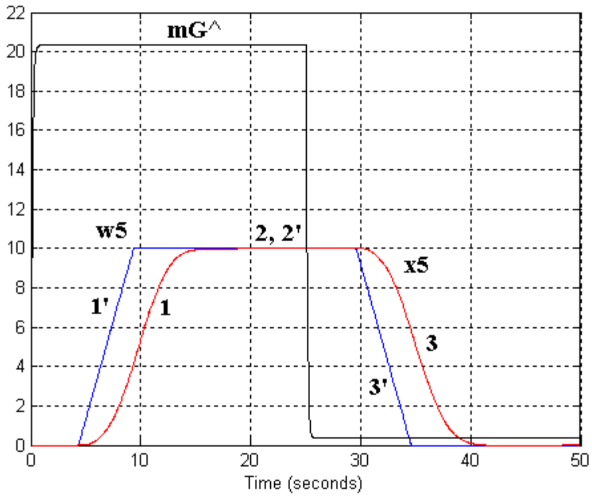


Fig.11 Reference w_5 [m] and real x_5 [m] crane crab position

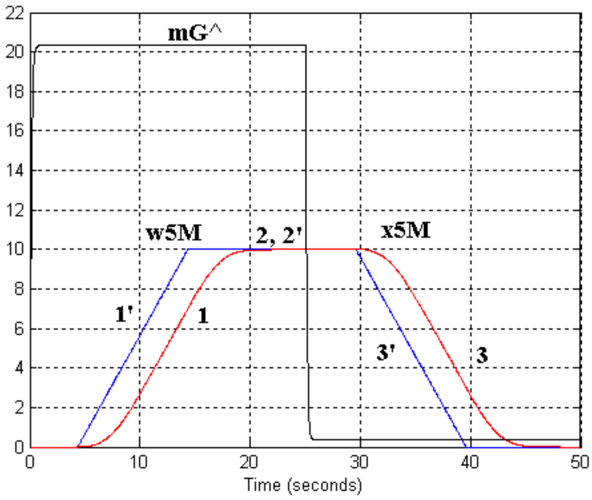


Fig.12 Reference w_{5M} [m] and real x_{5M} [m] crane bridge position

On the figure 13 is sharp identification of real burden weight. Firstly, uplift drive works with maximum burden weight m_G = 20342 kg and after unloading system again in minimum time identified empty hook m_G = 342 kg.

Keeping condition of forbidden swinging in the final position at forward motion and at backward motion is illustrated by figure 14. Burden deviation by crab x_6 [m] and bridge x_{6M} [m] have zero value at finishing crab and bridge motions. Their maximum overswingings during crab and bridge motions are different because speed of crab and bridge is different.

Rope length has influence also to the maximum overswinging.

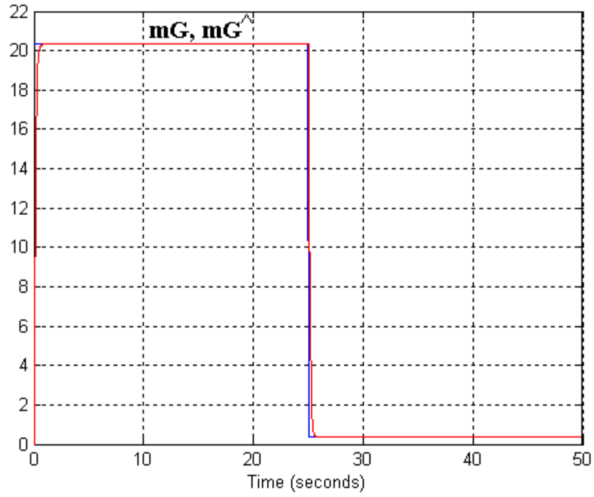


Fig.13 Real m_G [t] and observed $\hat{m}_G$ [t] burden weight

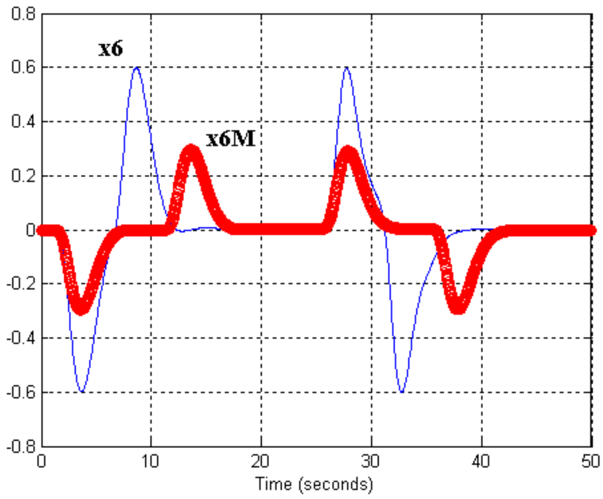


Fig.14 Burden deviation at crane crab x_6 [m] and bridge x_{6M} [m] motion

5. CONCLUSION

Robust control design ensures sharp burden positioning with different weight at zero swinging in the final position. System is steady resistant against variation of rope length and speed of crane crab and bridge motions. At design of less known, variable systems or systems with variable parameters is very profitably to ensure control by robust design by Ackermann. By identification of burden weight we should in very short time to get information about real burden weight and rope length and these were used for simulations in models of crane crab and bridge. It is good to set up from emergency reasons signalization by press-button STOP, pushing by can service staff to disconnect control from object and so disallow state, when service staff after finishing whole cycle in turned on mode would like to manipulate with empty hook. Then system can find out about burden deviation and so will start control for zero deviation what can occur accident to service staff because they are close to the burden and rope in this moment.

Article is included in project G-985.

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