UDC 621.87

Design of general LQR-ANN-controller of „crane-load" system. Part 1

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Received: 30.10.2024; Accepted: 14.11.2024
https://doi.org/10.32347/gbdmm.2024.104.0201

Abstract. The first part of the article describes the research concept and presents the results, which in the future allow the development of a LQR-neurocontroller of the movement of the dynamic "crane-load" system. For this purpose, the the problem of optimal control was stated. It uses a mathematical model in which the control function is considered as the rate of driving force change. This increases the order of the system by one. For individual components of the integral criterion, the weight coefficients were chosen and the values of the initial conditions were substantiated. The original problem of the synthesis of a LQR-controller is reduced to the Riccati equation. For one case, a solution to the Riccati equation was obtained and graphic dependencies corresponding to the obtained optimal control were built. The analysis of graphical dependencies made it possible to establish the disadvantages and advantages of the obtained optimal control. Among the advantages are the smoothness of the movement of the system and the provision of a zero value of the driving force at the beginning of the movement. This makes it possible to reduce the dynamic forces of the drive of the crane movement mechanism and its metal structure. Among the disadvantages of optimal control is a significant rate of increase of the driving force at the beginning of the movement, which can cause difficulties in the implementation of optimal control in practice, as well as an overshoot of the crane velocity.

Multiple solutions of the Riccati equation made it possible to obtain datasets for training, validation, and testing of an artificial neural network, which is considered as a universal approximator of Riccati equation solutions. The process of data normalization and formation of training pairs is described.

All data regarding the optimal values of the controller coefficients were obtained for load masses that varied within 60...25,000 kg and lengths of flexible suspension that varied within 1.2...12 m. In addition, the power of the weight coefficient varied within -5...-30, which corresponds to the minimization of the driving force rate.

Keywords: crane, linear-quadratic criterion, controller, artificial neural network.

INTRODUCTION

Cranes are widely used in many areas of production. Their effective exploitation plays an important role in increasing quality and quantity indicators of production, whether it is construction, light, or heavy industry. One of the most influencing factors, which obstructs the high crane productivity is pendulum load oscillations. They may be eliminated in many ways. However, optimal control in this regard appears the most reasonable. That is why there is a huge amount of scientific works, that copes with this issue [1-5]. Among them, one may note a class of optimal LQR-controls, i.e. strategies, which minimize a linear-quadratic cost function. The latter is an integral functional, which reflects „costs" on system movement quality as well as „costs" on control. For instance, in the work [6] LQR-criterion was used in the problem of double pendulum „crane-load" system control. The elements of weight matrices *Q* and *R* in criterion structure were obtained by application of PSO method. A similar approach is used in the study [7]. Here PSO, SA, and GA methods were involved to fit the values of matrices *Q* and *R* elements. However, to control the system movement PID-controller is used.

LQR- and LQG-controls for two masses system „crane-load” were developed in the work [8]. A comparison of controls quality allowed to conclude, that LQR is better than LQG, however, there is the opposite situation in the sense of practical implementation. This fact is connected with a lower number of sensors for LQG, which provide system state measurements.

Tuning of matrices *R* and *Q* was carried out in the article [9]. Beside the LQR-criterion authors added to the objective function overshoot, rise time, and settling time. SA metaheuristic method was used to solve the problem.

In the paper [10] authors considered a gantry crane and described it with the partial differential equation model. The designed control allows to suppress of the load pendulum oscillations. Experimental results have verified the performance of the developed control on the lab crane installation.

LQR-criteria might be used for different purposes. For instance, in the study [11] polynomial-based trajectories of crane trolley were designed. To track them and minimize the possible errors (deviations from the trajectories) LQR-controller was applied.

Almost all mentioned works provided calculations with parameters of laboratory crane installations. These are located far from the parameters of real cranes, which to some extent decreases the practical value of the obtained results.

In the current study, we used real parameters of the crane. Thus, the obtained results may be applied in practice.

PURPOSE OF THE PAPER

The paper’s purpose is to design a general controller of the system „crane-load”, that is optimal in the sense of LQR-criterion minimization. The first part of the study is dedicated to obtaining and preparing a data set, which is multiple solutions of LQR-problem for various dynamical system parameters and a parameter, which influences the intensity of movement mode.

RESEARCH RESULTS

First of all, the authors will briefly describe the concept of the study. In the investigation, LQR-problem is considered. Indeed, such problems are commonly accepted and well-studied. The problem itself may be relatively simply solved by its reducing to Riccati equation solution (Fig. 1).

Multiple Riccati equation solutions with different values of system and movement mode parameters allow obtaining some set of numerical data. Its preprocessing brings all the needed data for artificial neural network (ANN) training. The latter is considered as a powerful approximator of the LQR-problem dataset solutions.

In order to prove ANN high prediction features ANN testing is mandatory. Thus, one may access the developed ANN (fed it with some input data: mass of the load and length of the load suspension) and obtain values of optimal coefficients of LQR-controller. These calculations may be carried out online, i.e. when the length of load suspension is varied during the crane movement.

In the current research, a dynamical model of the „crane-load” system (Fig. 2) is used [1, 2, 5, 7].

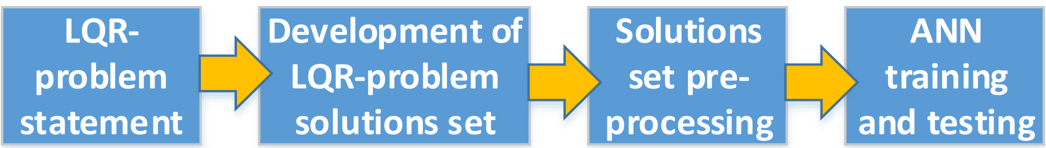

Fig. 1. Scheme which describes the development stage of general LQR-ANN-controller

ISSN(online)2709-6149. Mining, constructional, road and melioration machines, 104, 2024, 15-27

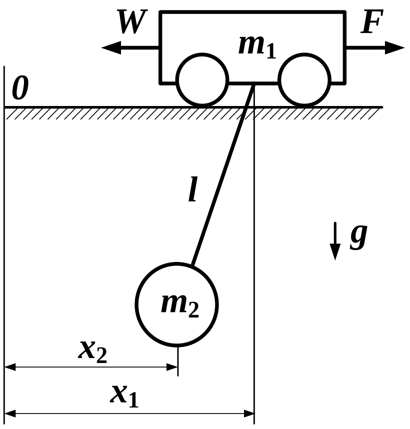

Fig. 2. Dynamical model of the „crane-load" system

In the study, to take into account the drive force rate, we consider a control function, which is a first derivative of the drive force by time. Thus, the mathematical model of the system is as follows:

$$\begin{cases} \dot{F} = \Phi; \\ m_1\ddot{x}_1 + m_2\ddot{x}_2 = F; \\ x_1 = x_2 + \dfrac{l}{g}\ddot{x}_2, \end{cases} \quad (1)$$

where m_1 and m_2 – the reduced masses of the crane and load, respectively; x_1 and x_2 – positions of masses m_1 and m_2, respectively; l – the length of the flexible suspension; g – acceleration of free fall; F – the dynamic component of the reduced driving force; Φ – rate of the drive force.

The system (1) was presented in a matrix form:

$$\begin{aligned} &\dot{\mathrm{x}}(t) = A\mathrm{x}(t) + B\mathrm{u}(t); \\ &\mathrm{y}(t) = C\mathrm{x}(t) + D\mathrm{u}(t); \\ &\mathrm{x} = \begin{pmatrix} x_1 & x_2 & \dot{x}_2 & \dot{x}_1 & \dot{F} \end{pmatrix}^T; \\ &\mathrm{u} = \Phi. \end{aligned} \quad (2)$$

where Ω – the frequency of the load's pendulum oscillations, under the condition of a stationary crane (mathematical pendulum), $\Omega = \sqrt{\dfrac{g}{l}}$.

The matrices A, B, C, and D are given below:

$$A = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \Omega^2 & -\Omega^2 & 0 & 0 & 0 \\ -\dfrac{\Omega^2 m_2}{m_1} & \dfrac{\Omega^2 m_2}{m_1} & 0 & 0 & \dfrac{1}{m_1} \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix};$$

$$B = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \end{pmatrix}^T;$$

$$C = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \end{pmatrix};$$

$$D = (0),$$

We set the following initial conditions:

$$\mathrm{x}(0) = \begin{pmatrix} x_1(0) & x_2(0) & \dot{x}_2(0) & \dot{x}_1(0) & F(0) \end{pmatrix}^T = \begin{pmatrix} -\dfrac{vt_1}{2} & -\dfrac{vt_1}{2} & -v & -v & F_0 \end{pmatrix}^T, \quad (3)$$

where v – the specified steady velocity of the crane; t_1 – the duration of the acceleration or of the dynamical system; F_0 – the value of the initial drive force, which may be set in an arbitrary way.

As we consider the dynamical system acceleration mode, we should set negative values of initial load and crane positions. At the end of the mode, the system must reach the origin (zero) point of the phase domain.

In a similar way, one may use initial conditions that are referred to the deceleration mode of the system movement, which are not considered in the frame of the current study.

The linear-quadratic regulator (LQR) criterion is as follows:

$$J = \int_0^\infty (\mathrm{x}^T Q\mathrm{x} + \mathrm{u}^T R\mathrm{u})dt, \quad (4)$$

where Q – the matrix of weight coefficients that show the importance of minimizing the norm of the state vector; R – the matrix of weight coefficients that show the importance of minimizing the norm of the control vector u.

We stress the importance of reaching the steady velocity v by setting the matrix Q as follows:

$$Q = diag\left(10^{-5} \quad 10^{-5} \quad 10^{5} \quad 10^{5} \quad 10^{\delta}\right);$$
$$R = \left(5 \cdot 10^{-7}\right).$$

where δ – the power of the weight coefficient in the integrand of criterion (4). Matrix R contains only one value, which in some sense reflects the constraint on the rate of F changing: the bigger its value the bigger cost of the Φ value. The solution of the LQR-control problem is well-known [12]:

$$\mathrm{u} = -R^{-1}B^{T}P\mathrm{x} = \mathrm{Gx}, \qquad (5)$$

where G – LQR-controller gains vector (G=(G_1, G_2, G_3, G_4, G_5)^T); P – solution of the Riccati equation:

$$A^{T}P + PA - PBR^{-1}B^{T}P + Q = 0. \qquad (6)$$

One may set all the system and movement mode parameters and obtain LQR-problem solution.

For example, for the values specified in Table I, the G-vector is G=(436887, -436881, -63982, 696443, 5.30153)^T.

Table I. Numerical values of system and movement mode parameters

Parameter	Unit	Value
m_1	kg	50000
m_2		16200
l	m	5.32
v	m/s	1
t_1	s	4
δ	-	-6.9

The plots, which correspond to the obtained solution are given in Fig. 3.

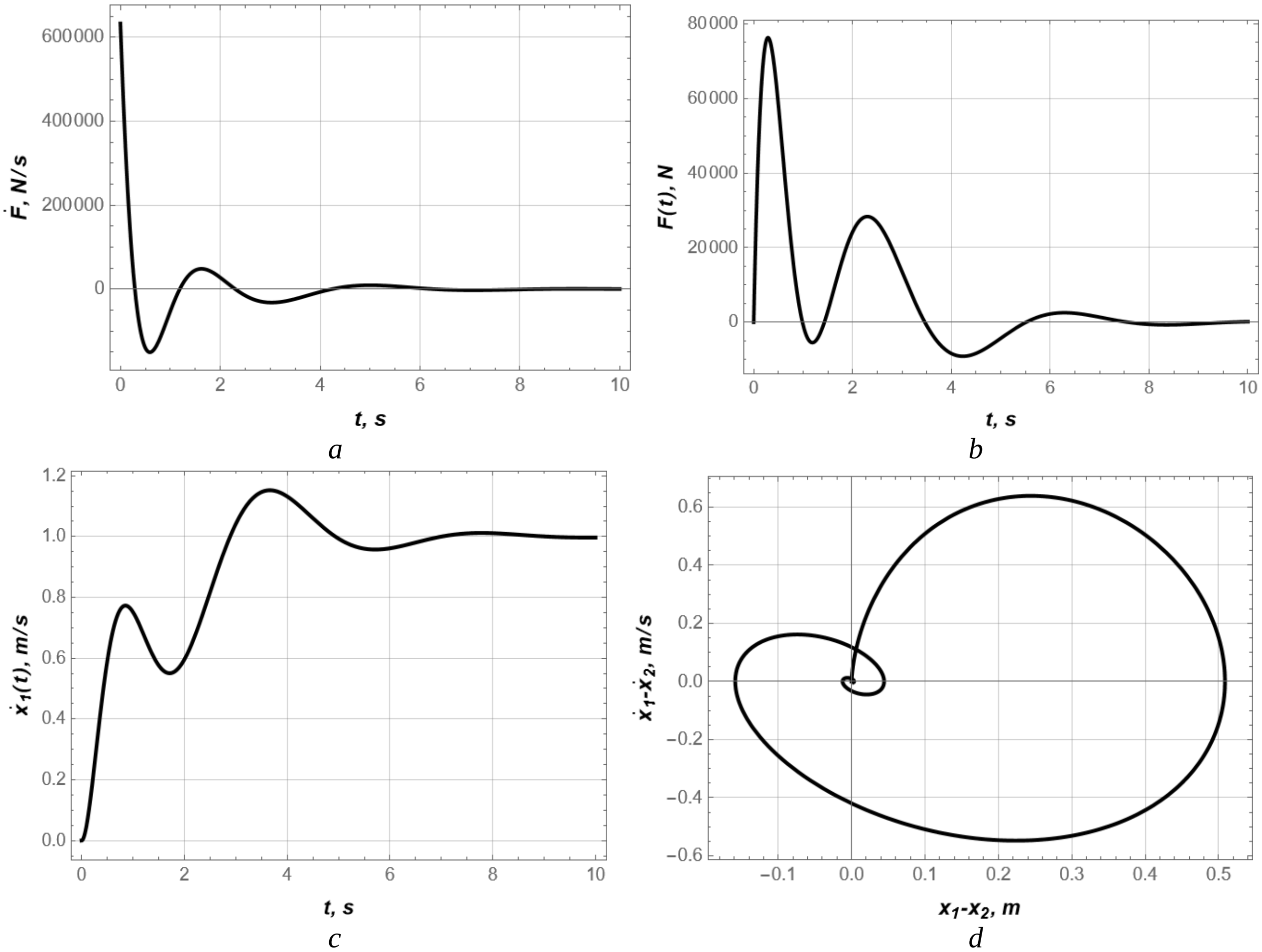

Fig. 3. Plots of control function (a), drive force (b), crane velocity (c), and phase trajectory of the load pendulum oscillations (d)

As one may observe from the Fig. 3,a the maximal rate of F changing is referred to the very first moment (t=0). Indeed, $\Phi(0)>600$ kN/s, which raises some difficulties in practical implementation of such control.

On the other hand, decreasing $\Phi(0)$ does not correspond to a fast transition process (desired feature). Anyway, to take into account value $\Phi(0)$ correctly, one needs to figure out the dynamical features of the cranes controlled drive (for instance, frequency inverter technical parameters).

It is clear, that one of the desirable features of the obtained control law is connected with opportunity of setting initial value of drive force $F(0)$. For the case of study we set $F(0)=0$ (Fig. 3,b). Such selection of $F(0)$ makes the controlled process „softer".

The dynamic impacts in the drive and in the crane metal structure are not as intensive, as they might be for the case $F(0)\neq0$.

Observing Fig. 3,c one may state the overshoot in crane velocity, which approximately equals 15%. For the frequency-controlled drive, it is not a significant problem.

However, this issue should be considered in further studies and an approach to its solution (reaching zero overshoot value) must be developed.

As for load pendulum oscillations (Fig. 3,d) its linear magnitude equals 0.5 m, which corresponds to 5.3^0. This value appears at the beginning of the movement when the control extensively changes (first three seconds of the system movement).

The found solution (G-vector) is optimal only for the set parameters (Table I). However, in practical cases of crane exploitation values of load mass m_2 and length l of load suspension (cable) are varied.

In addition, in order to meet variable requirements to movement mode, one may set different values of δ (the bigger δ the more smooth and slow motion mode is obtained, i.e. big drive force values are penalized by the value of criterion (4)). Thus, for specific crane with set parameters (m_1=50000 kg, v=1 m/s) multiple LQR-problem (1)-(4) solutions must be found.

Furthermore, they are considered as a data set for training, validation, and testing of ANN. The latter is considered as a general solver of LQR-problem. It covers all practical-based cases.

Thus, we must prepare the data set. In the frame of the current study LQR-problem (1)-(4) was solved 100000 times, each time with different values of m_2, l, and δ. The upper and lower limits of these are given in Table II.

Table II. Numerical values of upper and lower values of m_2, l, and δ

Parameter	Value	
	upper	lower
m_2	25000	60
l	12	1.2
δ	-5	-30

All the obtained data were arranged in the frames:

$$\{m_2, l, \delta, G_1, G_2, G_3, G_4, G_5\}. \quad (7)$$

For the sake of appropriate article volume, we have made a file „LQR-problem solutions.txt" and uploaded it to the shared Google-Drive folder. It may be downloaded by the link [13].

In order to train and test ANN in a proper manner, all the data must be normalized and arranged in training pairs:

$$(\tilde{m}_{2.i},\ \tilde{l}_i,\ \tilde{\delta}_i)^T \to \tilde{\mathrm{G}}_i \quad (8)$$

where $\tilde{m}_{2.i}$, $\tilde{l}_i$, and $\tilde{\delta}_i$ – the normalized values of load mass, rope length, and power of weight coefficient in the R matrix from i-th training pair. The counter i indicates the number of the pair ($i\in(\overline{1,100000})$). The tilde symbol shows a normalized value:

$$\begin{cases} \tilde{m}_{2.i} = 2\dfrac{m_{2.i}-m_{2.\min}}{m_{2.\max}-m_{2.\min}}-1; \\ \tilde{l}_i = 2\dfrac{l_i-l_{\min}}{l_{\max}-l_{\min}}-1; \\ \tilde{\delta}_i = 2\dfrac{\delta_i-\delta_{\min}}{\delta_{\max}-\delta_{\min}}-1, \end{cases} \quad (9)$$

where $m_{2.i}$ – the natural value of the load mass; $m_{2.\min}$ and $m_{2.\max}$ – lower and upper values of the load mass respectively; l_i – the natural value of the rope length; $l_{\min}$ and $l_{\max}$ – the lower and upper values of the rope length respectively; δ_i – the natural value of the power of control weight coefficient; $\delta_{\min}$ and $\delta_{\max}$ – the lower and upper values of the weight of control function power respectively (Table II).

Normalization (9) allows presentation of all the data on the scale from -1 to 1. Such values are appropriate for ANN feeding (they will not cause „saturation" effects in the artificial neurons of ANN).

In order to train and test ANN properly, all the data was split on three sets: for training purposes, validation, and test of ANN. The training set includes 85451 pairs, the validation set includes 4497 pairs, the test set – 10051 pairs. Each pair is arranged in the form (8).

Now the data is prepared for development of ANN. Description of this process and its application in the practical conditions of crane exploitation will be given in the second part of the study.

CONCLUSIONS

In the article, important scientific and practical issue is investigated. It is connected with the synthesis of optimal by LQR-criterion. The optimal control of the motion mode of the system „crane-load" is a linear combination of state variables and found coefficients. In order to make the control mode softer (i.e. decrease dynamical impacts in crane elements) the mathematical model of the system is used, which is completed with additional state coordinate – drive force. In this case, the control is the drive force rate.

The stated problem is solved 100000 times for the crane of 50000 kg reduced mass, and steady velocity of 1 m/s. Each solution is found for different values of m_2, l, and δ. This makes it possible to develop a data set for ANN training, validation, and testing. In the current study, ANN is considered as generalized approximator of LQR-problem solutions (or solver of the problem). Corresponding calculations will be described in the second part of the study.

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Розробка узагальненого лінійно-квадратичного нейрорегулятора системи „кран-вантаж”. Частина 1

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Анотація. У першій частині статті проведено опис концепції дослідження та представлено результати, які у подальшому дозволяють виконати розробку лінійно-квадратичного нейрорегулятора руху динамічної системи „кран-вантаж”. Для цього було виконано постановку задачі оптимального керування. У ній використано математичну модель в якій функція керування розглядається як швидкість зміни рушійного зусилля. Це збільшує порядок системи на одиницю. Для окремих компонентів інтегрального критерію обрано вагові коефіцієнти та обґрунтовано величини початкових умов. Вихідну задачу синтезу лінійно-квадратичного регулятора зведено до рівняння Ріккаті. Для одного випадку було отримано розв’язок рівняння Ріккаті і проведено побудову графічних залежностей, які відповідають отриманому оптимальному керуванню. Аналіз графічних залежностей дав змогу встановити недоліки і переваги отриманого оптимального керування. Серед переваг встановлено плавність руху системи та забезпечення нульового значення рушійного зусилля на початку руху. Це дозволяє зменшити навантаженість динамічними зусиллями приводу механізму переміщення крана та його металоконструкції. Серед недоліків оптимального керування – значна швидкість наростання рушійного зусилля на початку руху, що може викликати складнощі при реалізації оптимального керування на практиці, а також перерегулювання швидкості руху крана.

Багатократне розв’язування рівняння Ріккаті дало змогу отримати масиви даних для тренування, валідації та тестування штучної нейронної мережі, яка розглядається як універсальний апроксиматор розв’язків рівняння Ріккаті. Описано процес нормалізації даних та формування навчальних пар.

Всі дані стосовно оптимальних значень коефіцієнтів регулятора отримані для мас вантажу, які змінювались у межах 60…25000 кг і довжин гнучкого підвісу, які змінювались у межах 1.2…12 м. Крім того, у межах -5…-30 змінювався показник степеня вагового коефіцієнта, який відповідає за важливість мінімізації швидкості зміни рушійного зусилля.

Ключові слова: вантажопідйомний кран, лінійно-квадратичний критерій, регулятор, штучна нейронна мережа.