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Experimental study of the optimal acceleration mode of the tower crane slewing mechanism

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Abstract. Tower cranes play a crucial role in construction. They are designed for material handling, and to ensure maximum efficiency, it is essential to minimize load oscillations during transitional movement phases (acceleration or braking). The purpose of this study is to verify theoretical calculations by analyzing experimental results regarding the optimal acceleration control of the slewing mechanism of a laboratory tower crane setup. The study involved calculating the duration of individual acceleration stages of the boom system under varying parameters—load mass, boom outreach, and flexible suspension length, which were the independent research factors. A total of 12 experiments were conducted. The experiments were performed using a laboratory tower crane setup equipped with instruments to measure changes in load pendulum oscillations and boom slewing. The dataset obtained from the experiments was analyzed based on numerical deviations between theoretical and experimental data (quantitative analysis) and graphical dependencies (qualitative analysis). The results confirm that the experimental studies validate the hypothesis regarding the practical feasibility of implementing optimal acceleration control of the crane boom slewing mechanism.

Keywords: tower crane, optimal acceleration, load oscillations, analysis, estimation index.

INTRODUCTION

Tower cranes are widely used for material handling on construction sites. To enhance their efficiency, tower cranes must be capable of rapidly moving loads while eliminating load oscillations on a flexible suspension at the end of the transitional movement phase (acceleration/braking).

Many researchers have worked on developing optimal motion modes for this mechanism. In [1], an innovative methodology was presented for predicting and controlling the slewing angle in overhead crane systems using a long short-term memory (LSTM)-based recurrent neural network. In [2], a study was conducted on the dynamic model of the trolley movement mechanism during the steady slewing of a tower crane. Using differential equations, the minimum values of the criterion were determined, based on which an optimal law for load motion was obtained. In [3], a two-mass dynamic model of the "trolley-load" system with a variable suspension length was examined. The problem of determining time-optimal control for a crane transporting loads from an initial to a final position was considered. In [4], a structural-functional scheme for the optimal control system of the trolley movement and slewing mechanisms was developed, enabling the implementation of optimal motion laws that eliminate pendulum oscillations of the load on a flexible suspension. The study's novelty lies in determining the initial and final load positions, executing control actions, and correcting the load's position. In [5], the objective was to identify the most promising directions for further research on crane mechanism control methods based on an analysis of approaches to mitigating load oscillations on a flexible suspension. The study indicated that future research should focus on abandoning oscillation elimination during acceleration, increasing trolley speed, and implementing modern drive and control systems.

In [6], a method for generating input data for effective crane slewing control was described. A neural network was used to suppress load oscillations, with the ability to adjust its response based on cable length. In [7], a method for controlling crane mechanisms using two regulators was developed—one for damping system oscillations and another for controlling the motion of crane mechanisms. In [8], research findings on the oscillation and vibration characteristics of tower cranes were presented. It was demonstrated that the load mass has minimal influence on the spatial slewing angle during motion, while the angle change rate increases with the crane's height.

PURPOSE OF THE PAPER

The purpose of this study is to obtain and verify experimental data that ensure the elimination of load oscillations at the end of the boom system's motion when implementing optimal acceleration control.

RESEARCH RESULTS

For the research, an experimental laboratory setup of a tower crane was used (Fig. 1) with a boom length of 3.57 m, located in the Machine Dynamics Laboratory of the National University of Life and Environmental Sciences of Ukraine. The setup replaced the slewing mechanism with a worm gearbox with a slewing mechanism utilizing propeller thrust. The slewing mechanism with propeller thrust (Fig. 2) is installed at the end of the boom, allowing the experimental setup to apply less driving force to reach the nominal slewing speed of the boom.

The study proposes investigating the influence of load outreach r, flexible suspension length *l*, and load mass m on the dynamics of the setup's slewing motion under optimal control of the crane's slewing mechanism. The detailed plan of full-factor experiments is presented in Table 1.

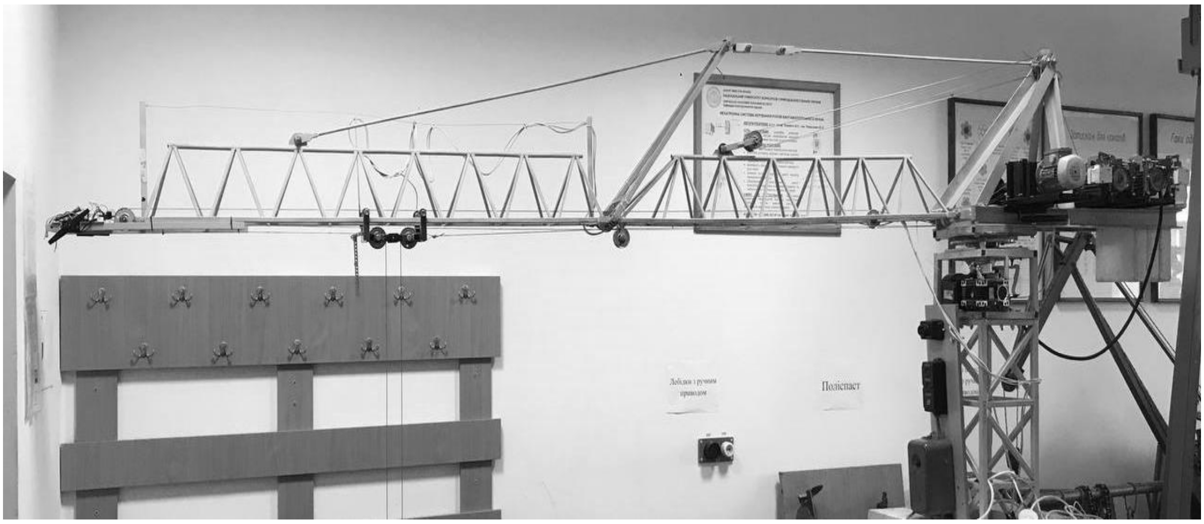

Fig. 1. Experimental laboratory setup of the tower crane

Table 1. Full-factor experimental plan for studying the slewing dynamics of a tower crane with propeller thrust

Factor	Factor Values											
Boom outreach, m	1.95						2.95					
Flexible suspension length, m	1			14			1			1.4		
Load mass, kg	6	13	16	6	13	16	6	13	16	6	13	16
Experiment number	1	2	3	4	5	6	7	8	9	10	11	12

These factors were selected as they have the most significant impact on the dynamics of the tower crane setup.

For all experiments, the duration of each movement stage was calculated. Table 2 presents numerical values of the durations of individual acceleration stages of the setup. To process the experimental data on changes in the boom slewing angle φ, slewing speed $\dot{\varphi}$, deviation angle of the cable from the vertical α, and angular speed of cable deviation $\dot{\alpha}$, absolute evaluation indices were used to show the numerical discrepancy between theoretical and experimental data.

The absolute evaluation index of the maximum discrepancy between experimental and theoretical data was determined using the formula:

$$x_{abs.\max} = \frac{\max(|\Delta|)}{\max(x_e)}, \qquad (3)$$

where x_e is the characteristic measured experimentally (e.g., crane boom angular position, crane boom slewing angular speed, cable deviation angle from the vertical, angular speed of cable deviation from the vertical); Δ – is the array representing the difference between experimental and theoretical data:

$$\Delta = x_e - x_m, \qquad (4)$$

where x_m is the characteristic determined by theoretical calculations.

The absolute evaluation index for the root mean square (RMS) discrepancy between theoretical and experimental data was determined using the formula:

$$x_{abs.RMS} = I^{-1}\sqrt{\sum_{i=1}^{I}\Delta_i^2}; \qquad (5)$$

where I is the length of the experimental data set.

Table 3 presents the calculated numerical values of evaluation indices when comparing theoretical and experimental data.

Table 3 shows the magnitude of the difference between data obtained through theoretical calculations and data obtained experimentally. Analyzing Table 3 reveals that the largest er-

Table 2. Duration values of stages for the optimal acceleration mode of the slewing mechanism of the laboratory tower crane setup

Stage duration	**Experiment number**											
	1	2	3	4	5	6	7	8	9	10	11	12
First stage, s	2,27	2,31	2,33	2,39	2,52	2,55	2,31	2,39	2,43	2,53	2,62	2,65
Second stage, s	2,24	2,11	2,05	2,49	2,53	2,49	2,09	1,76	1.63	2,52	2,21	2,07
Third stage, s	2,27	2,31	2,33	2,39	2,52	2,55	2,31	2,39	2,43	2,53	2,62	2,65

Table 3. Numerical indices of the difference between theoretical and experimental data

Index	**Range of Values**
Minimum load position error	-0.220 … -0.150
Maximum load position error	0.150 … 0.203
RMS load position error	0.050 … 0.053
Minimum load angular velocity error	-0.230 … -0.150
Maximum load angular velocity error	0.155 … 0.210
RMS load angular velocity error	0.050 … 0.053
Minimum boom position error	-0.096 … -0.065
Maximum boom position error	0.067 … 0.095
RMS boom position error	0.022 … 0.023
Minimum boom angular velocity error	-0.024 … -0.019
Maximum boom angular velocity error	0.018 … 0.024
RMS boom angular velocity error	0.006

rors are the minimum load position error ranging from -0.22 to -0.15 and the maximum load angular velocity error ranging from – 0.155 to 0.210. However, compared to the useful signals of physical quantities, these errors are relatively small.

After processing the theoretical and experimental data for the first experiment variant, system motion graphs were obtained (Fig. 3). From the graph in Fig. 3, significant load deviations are evident during the acceleration and braking stages of the system. However, during steady motion, the deviations remain within 0.1 degrees, which is a very small value, confirming the adequacy of theoretical calculations.

Figure 3 presents the graph of the angular speed of load deviation. As seen in Fig. 3, during the acceleration and braking phases, the pendulum oscillations of the load increase and then decay by the end of the transition phase. In the system's steady-state motion, the load oscillations remain within 0.1 rad/s, confirming that the experiment met the established requirements and fulfilled the conditions for eliminating oscillations at the end of the braking phase and during steady motion. The boom position graph is shown in Fig. 4.

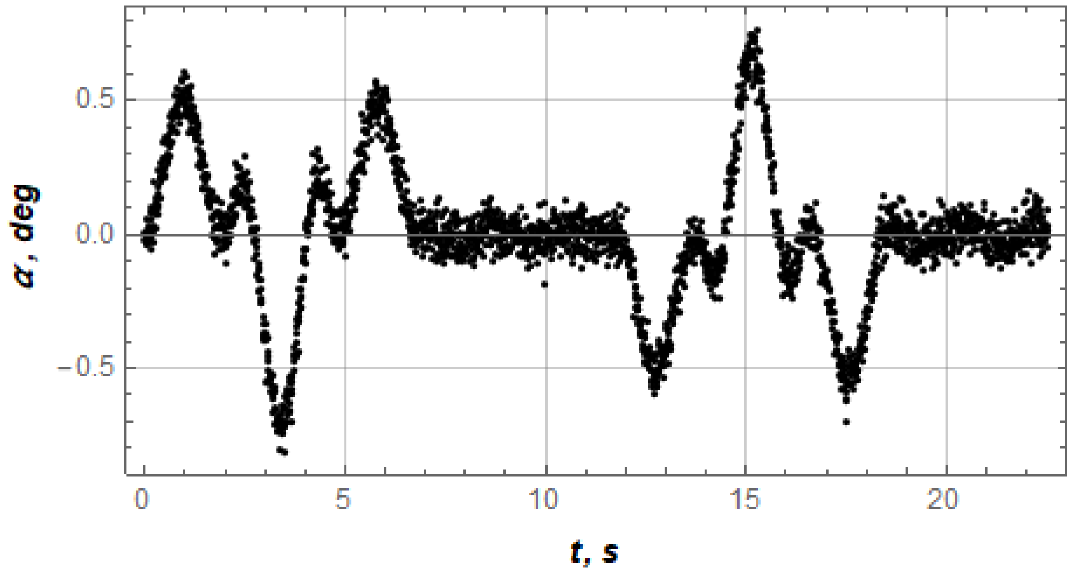

Fig. 2. Graphical representation of the load deviation angle relative to the boom over the entire motion range of the boom system (for the first experiment variant)

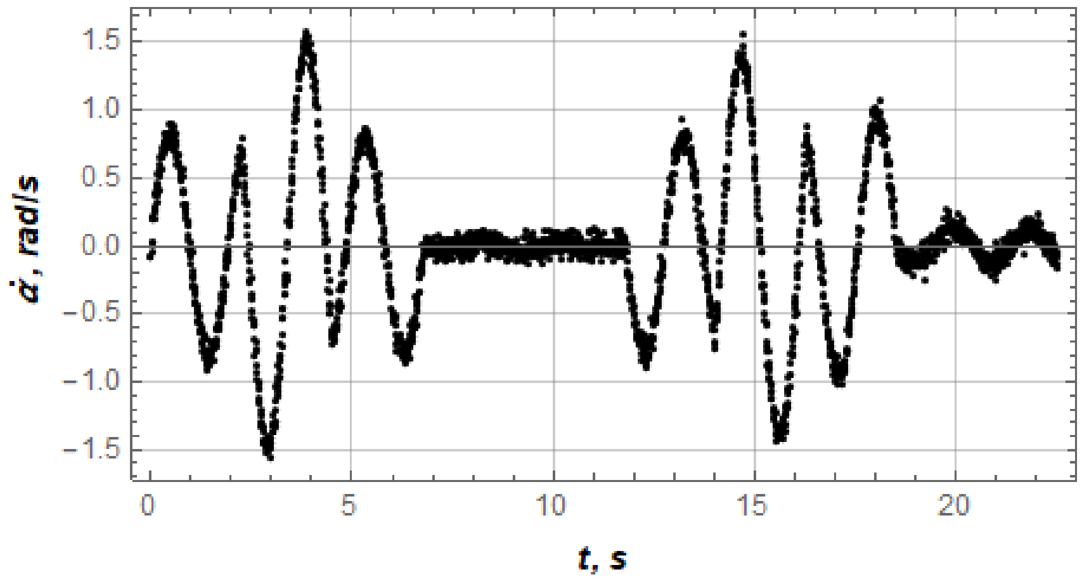

Fig. 3. Graphical representation of the angular speed of load deviation from the vertical over the entire motion range of the boom system (for the first experiment variant)

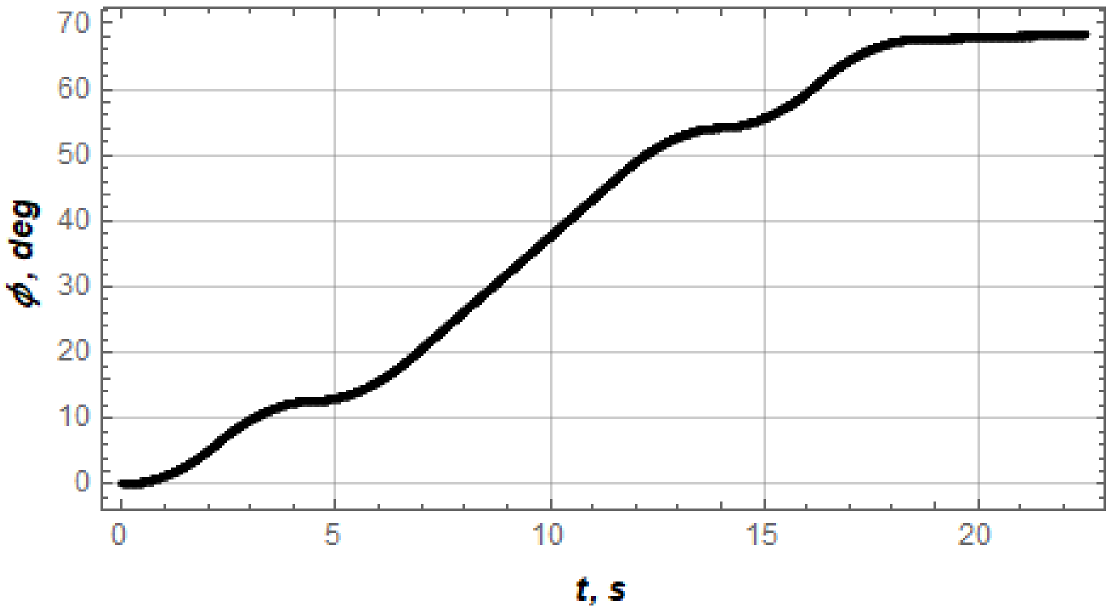

Fig. 4. Graphical representation of the boom position throughout the motion of the boom system (for the first experimental scenario)

From the boom angular position graph (Fig. 4), it is evident that the boom rotated 70 degrees over the entire experiment. Additionally, the noise in the received signals regarding the boom position was insignificant. The boom angular velocity graph is presented in Fig. 5.

As seen in Fig. 6, throughout the experiment, the boom's angular velocity varied from 0 to its nominal value of 0.10 rad/s. Notably, the angular velocity never dropped below zero, indicating that no reversal of the boom's motion occurred.

Thus, it can be concluded that the conducted experiments fully satisfy the conditions for eliminating pendulum oscillations of the load under optimal acceleration control of the tower crane slewing mechanism.

CONCLUSIONS

Experimental studies were conducted on the optimal acceleration control of the tower crane slewing mechanism with a propeller drive. To implement the research program, twelve experiments were conducted, each repeated three times.

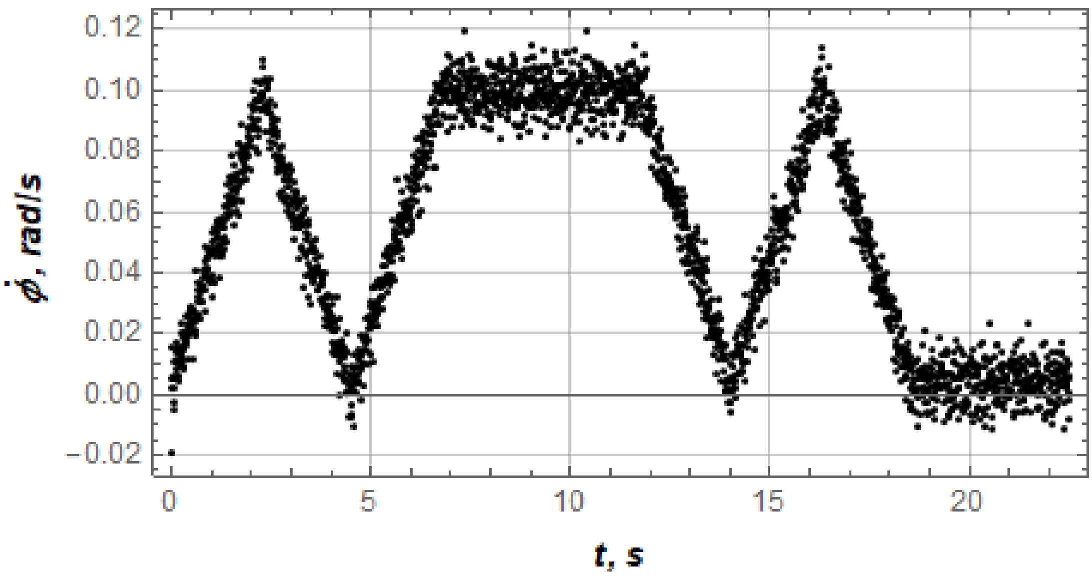

Fig. 5. Graphical representation of the boom angular velocity throughout the motion of the boom system (for the first experimental scenario)

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The methodology for processing experimental data was described using absolute evaluation indices that quantify the discrepancies between theoretical and experimental data. The numerical values of these indices made it possible to determine the extent of the discrepancy between theoretical and experimental data, which, in turn, allowed for a qualitative assessment of the implementation of optimal control for the tower crane slewing mechanism. The control implementation was found to be adequate for practical application. It is important to note the presence of minor residual oscillations of the load on the flexible suspension. Their amplitude does not exceed 0.1 degrees, which ensures safe execution of subsequent load-handling operations (lowering onto a surface, removal from the hook, etc.

For several experimental scenarios, graphs of the load deviation angular velocity relative to the crane boom and the boom's angular velocity throughout the motion of the boom system were presented and analyzed.

The conducted analysis of experimental data confirmed that the study was performed following the stated objective and met the key requirement: eliminating load oscillations during steady motion and at the moment of stopping the boom system.

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Експериментальне дослідження оптимального режиму розгону поворотно-поворотного механізму баштового крана

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Анотація. Під час будівництва баштові крани відіграють важливе значення. Вони призначені для переміщення вантажу і щоб таке переміщення виконувалось із максимальною продуктивністю важливо мінімізувати коливання вантажу на перехідних режимах руху (при гальмуванні або розгоні) за найкоротший час. Метою статті є перевірка розрахованих теоретичних даних шляхом стосовно оптимального за швидкодією керування механізмом повороту лабораторної установки баштового крана. Проведено розрахунок тривалостей окремих етапів розгону стрілової системи із змінними параметрами – масою вантажу, вильотом стріли, довжини гнучкого підвісу вантажу, які були незалежними факторами дослідження. Загалом було проведено 12 експериментів. Для проведення експериментів використано лабораторну установку баштового крана, на яку встановлено обладнання по визначенню характеру змін маятникових коливань вантажу та повороту стріли. Масив даних, який отримано під час виконання експериментальних досліджень, було проаналізовано виходячи із чисельних значень відхилення теоретичних даних від експериментальних

них (кількісний аналіз) та за графічними залежностями (якісний аналіз). У результаті отримано, що експериментальні дослідження підтверджують тезу стосовно достатньо якісного (з точки зору практичної реалізації результатів) реалізації оптимальної за швидкодією керування механізмом повороту стріли крана.

Ключові слова: баштовий кран, оптимальна швидкодія, коливання вантажу, аналіз, оціночний показник.