UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

ANTI-SWAY CONTROL OF AN OVERHEAD CRANE WITH THE USE OF A MACHINE VISION SYSTEM

Booklet of PhD Theses

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1. INTRODUCTION

In every level of economic activities, each industrial and commercial, we reach the handling equipment present in the transitional phase of the development cycles of materials and products. Also, they are significantly crucial in transportation [1]. Cranes structure is one of the most broadly utilized solutions in the field of dealing with and transshipment. They take numerous forms and are truly versatile to multiple conditions [2]. The substantial development of the transporting tool market increases load volume to be dealt with, forcing progressively strict necessities regarding overhead cranes performance. These performances are expressed in the form of a compromise between the criteria of speed, execution, precision, and operator safety. Therefore, handling gantry crane or overhead cranes requires a lot of involvement from an experienced operator. In general, the computerization of production systems has been one reaction to this trade-off. This automation had a double target: to increase the system efficiency (cost reduction, reliability, accessibility, quality) and improved direct administrator security [3, 4, 5].

Generally, a crane consists of a hoisting mechanism (hoisting line and a hook) and a support mechanism (trolley). The payload hook cable gathering is attached from a point on the support mechanism. The support moves the payload around the crane workspace. At the same time, the raising system lifts and brings the load down to maintain a strategic distance from impediments in the way and store the payload at the objective point without causing an enormous swing [6].

Many researchers have suggested solutions by designing multiple controls scheme for a crane system to solve the control problems discussed. However, the majority of the current methods are not appropriate for realistic implementation. For that reason, most commercial cranes are not automatic and nevertheless rely on operators, who fail to atone for the swing. This failure can also additionally put the load and the surroundings in danger. Another crane automation problem is the crane surroundings character, which is frequently unstructured in shipyards and manufacturing facility floors. In the following, we focus on reviewing the overall techniques used in the controlling topic. The crane operation steps automation is feasible, and some research studies have been pointed at this mission [7]. The most consuming task is to move the payload from the initial position to the target position and needs a skillful operator to perform it. Suitable techniques to facilitate moving the payload fast without inducing large swings are focal of several researchers [8]. An overhead crane basic motion can be described as object hoisting or lowering, trolley travel, and lifting. To increase the production, the crane movements must take place at high speeds without generating undesirable sway of the payload and being safe to the surrounding. There are two main approaches for crane automation: the first is that the operator is retained in the loop, and the payload dynamics are adjusted to make his job more manageable by feeding back the payload sway angle and its ratio [9, 10]. This response provides a different trajectory to that generated by the operator. Another way is to not excite the payload close to its natural frequency by adding a filter to eliminate the undesirable input frequency [11]. This causes a delay between the crane input and the operator action, which may affect the system negatively. Another method is installing a mechanical absorber to the crane structure, which requires a large amount of energy, making it impractical. The second approach is to take away the operator from the cycle, making the operation fully computerized. Different control methods can be used to achieve the above goal. Numerous researchers have commonly used open-loop control schemes, in particular for manipulating the payload swinging. There are different open-loop techniques: The input-shaping crane control method is one of the widely used open-loop methods in the literature [12, 13, 14]. It consists of a sequence of acceleration and deceleration pulses. These sequences are generated such that there is no residual swing at the end of the transfer operation. Cutforth et al. [15] designed an adaptive input shaping based upon flexible mode frequency variations to handle the uncertainties of the parameters. Also, an adaptive discrete-time control was proposed in [16], where the timing of impulses and amplitude are adapted to cater for the system uncertainties. In order to acquire the most realistic model of the crane system, several researchers have included other parameters in their models like damping and elasticity of the structure [17], air resistance, and variable length of cable that hold the payload [18]. It has been known that time delay may produce significant damping of the oscillations [19, 20]. A control technique was founded on time-delayed position feedback of the payload cable angles where the vibration of the payload is reduced by obliging the trolley to follow inertial reference coordinates. The objective of this control technique is to add damping to the system. The majority of research works are based on the contact detection of the payload sway displacement [21, 22]. The sway angle or the pendulum displacement is measured with different sensors like Hall-effect switches [23], inductive sensors, etc. Machine vision systems are being developed very fast in the last two decades [24]. Researchers start working on the contactless detection of the payload sway performed using machine vision applications [25-28]. In our system, the vision system is based on a web-camera and a personal laptop as hardware, and for software, a Visual Studio C++ with OpenCV library as a programming tool for image processing. A delayed reference non-collocated control approach for container cranes was developed by Sano et al. By taking into consideration the delay due to the vision sensor, which usually has a negative impact on the controlling, two novel swing angle observer-based control methods is developed in [29]. The investigated model in this mentioned research is only two degrees of freedom, and the suspending element is a rigid bar. Also, the parameters P and I of these controllers were not given. While in our system, the model has a multi-degree of freedom due to the suspending element, which is a chain.

1.1 THE PURPOSE OF DISSERTATION

The main aim of this research work is to design and implement a robust, fast, and practical controller for overhead cranes. The crane controllers are made to transfer the load from the starting position to the target position without consuming too much time, without overshooting, and to make the swinging of the payload as small as possible during the transfer and to make them completely disappears when the payload reaches its target position.

To formulate a linear model that behave similar to nonlinear model so it can be used as an observer in order to provide the non-measurable state-variables for the feedback.

To develop a new two-level hierarchical approach. At the first level, a simple mathematical pendulum model will be analyzed considering the time delay due to the use of a vision system. In the second level, a chain model is developed, extending the previous pendulum model considering the vibration of the suspending chain. The gain parameters associated with the payload are used from the first level model, and the rest of the parameters related to the state variables of the chain are determined by the pole placement method. The unmeasured state-variables will be determined by a collocated observer.

Another aim is to validate the successful use of the web-camera as capturing sensor, Visual Studio C++ with OpenCV library as a programming tool for image processing, and industrial Programmable Logic Controller as a programming tool for crane control on a laboratory overhead crane.

2. LINEAR AND NONLINEAR DYNAMICAL ANALYSIS OF A CRANE MODEL

This chapter shows the results of a dynamical analysis of a crane model. A nonlinear and linear dynamical model of an overhead crane with chain is formulated, analyzed, and compared. In addition to the payload, the inertia of the independent DoF of the suspending chain is considered. The finite element method is applied for the formulation of the nonlinear and linear models. The flexible suspending chain has no bending stiffness. The nonlinear model can be derived with the help of truss elements, which can transfer only axial force [30] and perform 2D motions. The linear model practically is a taut string [31], which is also discretized with linear two node elements approximating only lateral motions. The solutions of the linear models are compared to the nonlinear counterpart.

The picture of a crane model is shown in Figure 1. It is assumed that the displacements of the two parallel chains are the same; therefore, a single chain with double mass is a good substitution in a dynamical analysis. The chain is regarded as an elastic, one-dimensional structure and can transmit only axial force along its x1 coordinate. The motion of the structure in a plane (x, y) is investigated with nonlinear and linear approaches.

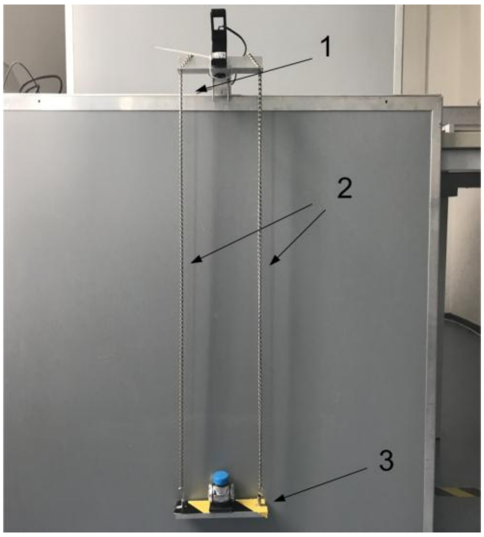
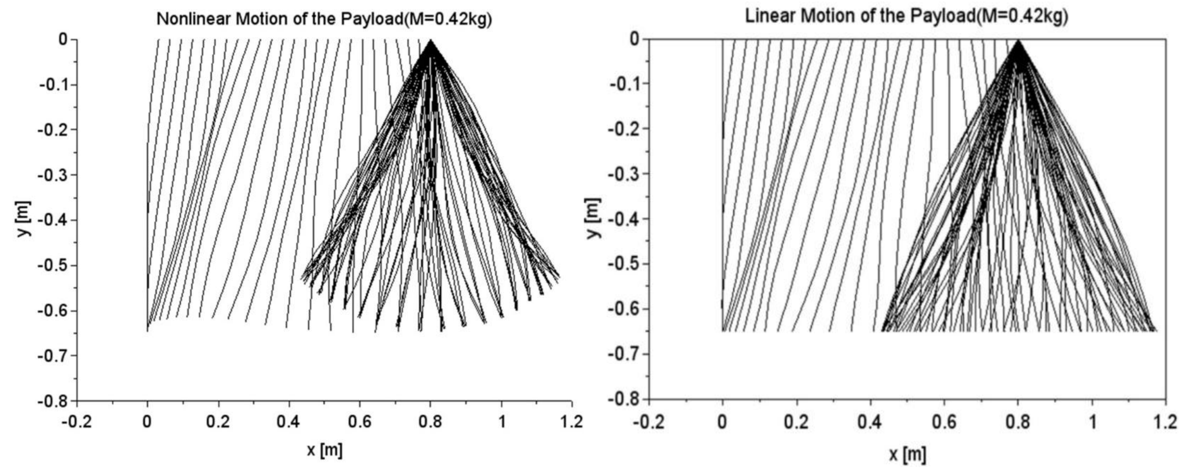


Figure 2.1. Part of overhead lab crane model: 1. Trolley; 2. Chains; 3. Payload.

Nonlinear and linear FEM programs have been developed. The length of the chains is 0.8 m, and it is subdivided into ten uniform finite elements. The linear version will also be analyzed with an FE mesh of two elements chain models. The mass of the chain is 0.22 kg, and two different payloads are exerted on the crane. The heavy one is 0.42 kg, the light one is 0.07 kg. In order to compare their performances, a simple crane motion will be simulated. In the beginning, the trolley is moving with constant velocity v1=0.8 m/s along the length x1=0.8 m, and then it stops suddenly. After that, the payload and the suspending chain will swing freely.

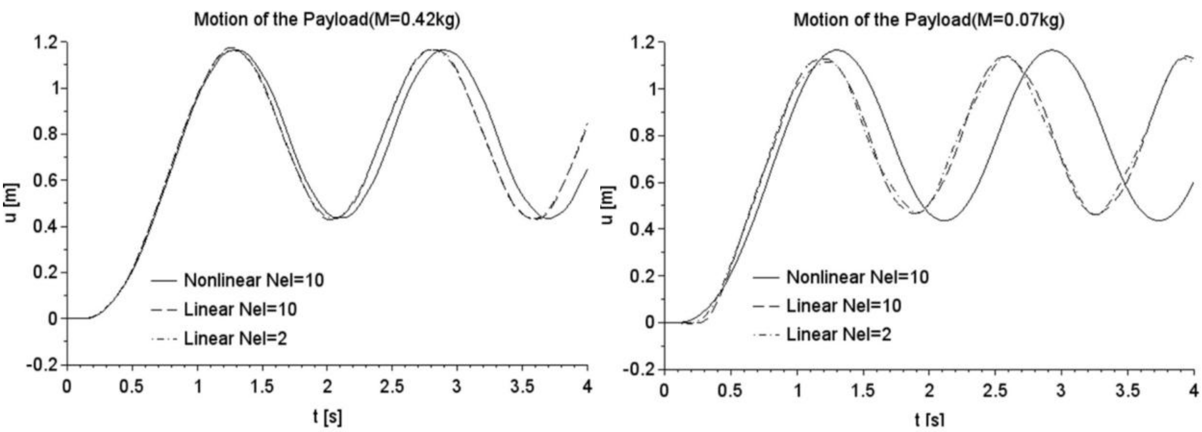
Motions of the cranes obtained for heavy payload using linear and nonlinear models are displayed in Figure 2.2. It is clearly seen that the payload performs only horizontal motions in Figure 2.2/b. However, the deformed shapes of the chains for both models are comparable in both Figures.



a/ b/

Figure 2.2. a/ Nonlinear motion of the crane. b/ Linear motion of the crane.

The computations have been performed for heavy and light payloads. Absolute and relative motions of the payloads, and the relative motions of the middle of the chain are shown in Figure 2.3 – Figure 2.5.



a/ b/

Figure 2.3. a/ Absolute motion of heavy payload. b/ Absolute motion of light payload

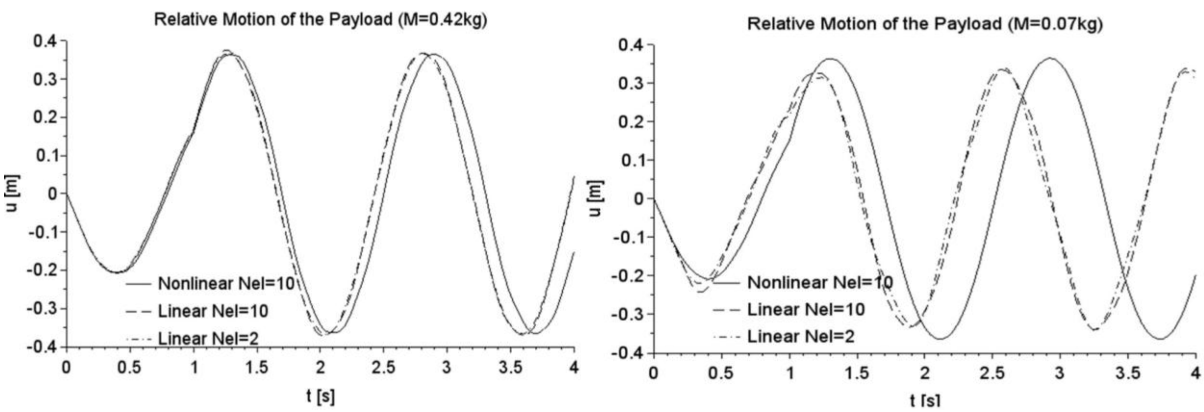


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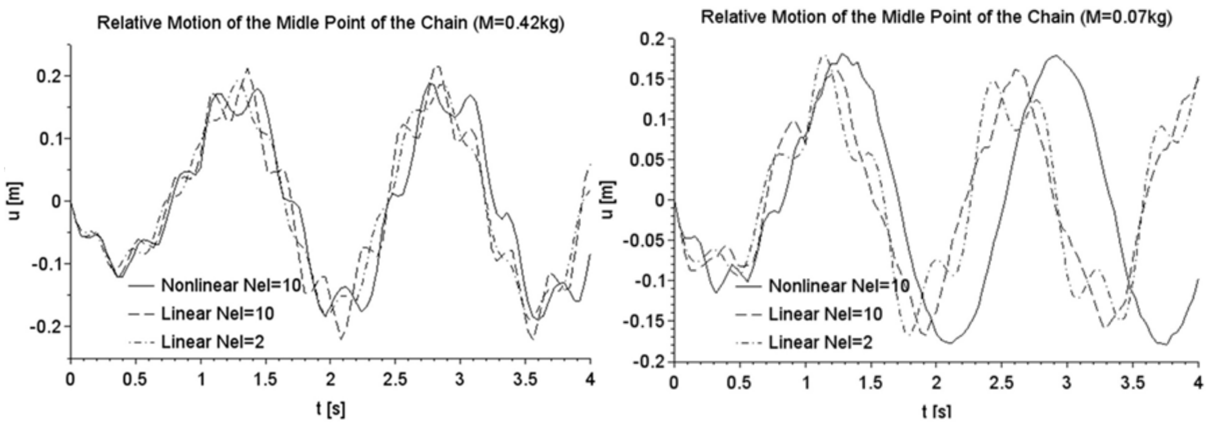
Figure. 2.4. a/ Relative motion of heavy payload. b/ Relative motion of the light payload



a/ b/

Figure 2.5. Relative motions of the middle point of the chain for a/ Heavy payload model. b/ Light payload model.

The displacements of nonlinear and linear models for heavy payload show good agreement in Figure 2.3a and 2.4a, while the discrepancies are bigger for the light one in Figure 2.3b and 2.4b.

Also it is clear from Figure 2.5a and 2.5b that the chain vibration is significant. The discrepancies between the nonlinear and linear models are negligible for the heavy payload in the beginning, then only relatively small shift can be detected later on. Except in the beginning the results of chain vibrations are less similar for light payload. However during the controlling of the crane, the displacement of the payload is enforced to be close to the real motion of the crane. Therefore, a small shift in the solution is not a major problem.

3. CONTROLLING OF TROLLEY POSITION AND PAYLOAD SWINGING OF AN OVERHEAD CRANE

A new two-level hierarchical approach to control the trolley position and payload swinging of an overhead crane is proposed. At the first level, a simple mathematical pendulum model is investigated considering the time delay due to the use of a vision system. Two gain parameters associated with the state-space variables of the payload are selected within a stability region. In the second level, a chain model is developed, extending the previous pendulum model considering the vibration of the suspending chain. The relative displacement of the payload is measured with a vision sensor, and the rest of the state-space variables are determined by a collocated observer. The gain parameters related to the state variables of the chain vibration are determined by the use of a pole placement method. The efficiency of the proposed controller is verified by numerical simulation and experimentally on a laboratory test bench.

After the use of D-subdivision method, we determined the gain parameters of the sample mathematical model of the system for different time delays τ (0.1 s; 0.15 s; 0.2 s) due to the use of the vision system. As shown in Figure 3.1. The higher the time delay, the smaller the stability region.

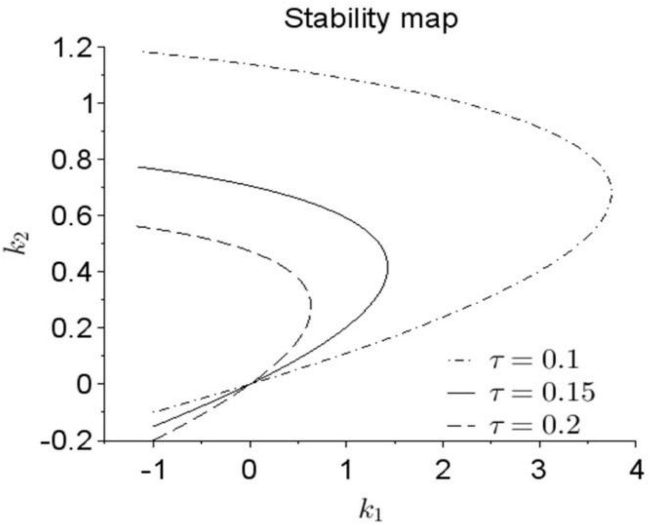


Figure 3.1. Stability regions for different delays.

It can be seen from Figure 3.1 that the curves of the stability regions are intersecting each other at points k1=0, k2=0. The size of the stability region is shrinking as the time delay is increasing. Therefore, choosing the parameters approximately at the vicinity -2<k1<0 and k2=0 will make the system stable and robust since it remains in a stable state with a high range of time delay.

The anti-swing control scheme of the crane model is illustrated in Figure 3.2. The measured position of the trolley is slightly different from the desired one. This difference is gradually decreased in the controlling process.

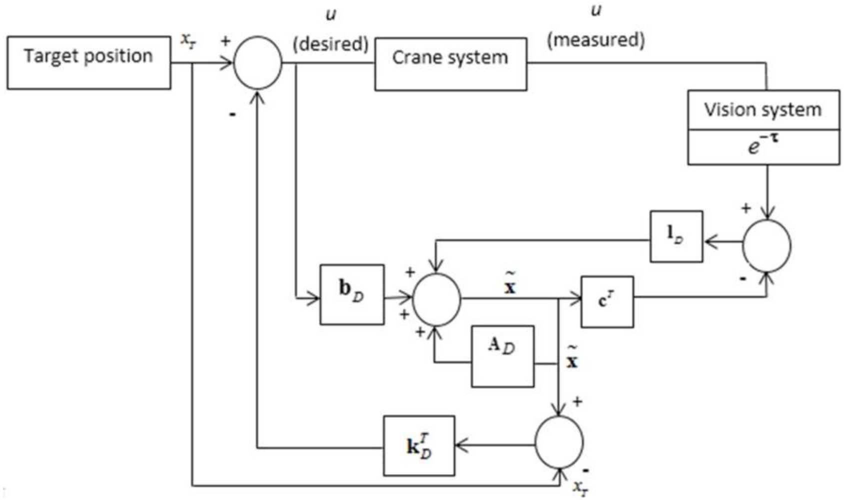


Figure 3.2. Control scheme of the overhead crane model

The parameters explanation of the figure 3.2 can be found in the thesis. The experiment of the developed controller were made in a laboratory overhead crane, figure 3.3.

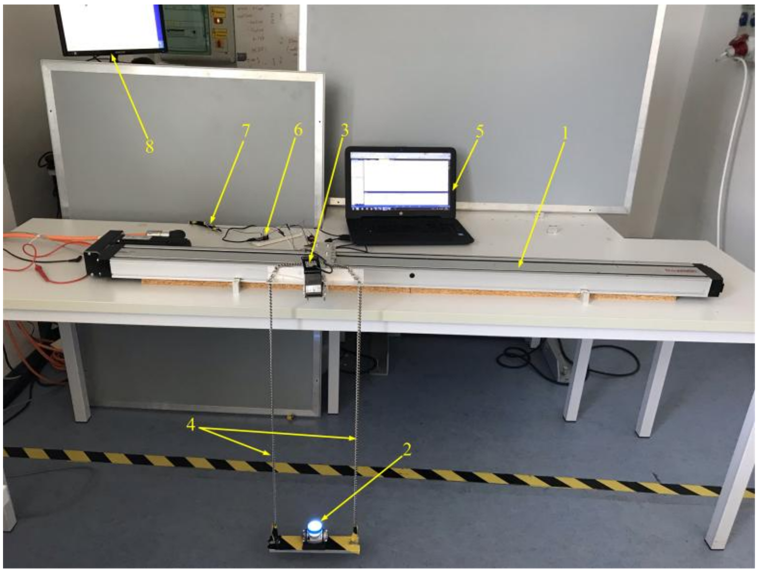


Figure 3.3. Configuration of the crane model: 1. Linear, compact module, 2. Payload with lamp, 3. Camera mounted on the trolley, 4. Chains, 5. PC, 6. Arduino Nano, 7. D/A converter, 8. PLC

The parameters of the experimental crane model shown in Figure 3.3 are given: mass of the chains is 0.22 kg, the payload is 0.419 kg, and the target distance of the trolley is x_1=800 mm. The time increment *dt* of the first experiment equal to 0.15 s, the gain parameters and the matrixes of the observer are as follows:

$$\mathbf{A}_D(\Delta t = 0.15s) = \begin{bmatrix} -0.7371381 & 0.7629382 & 0.036768 & 0.0506495 \\ 0.1479837 & 0.7887384 & 0.0098243 & 0.1380671 \\ -8.9574487 & 3.4067666 & -0.7460993 & 0.7663399 \\ 0.6607952 & -2.1439156 & 0.1486435 & 0.7865806 \end{bmatrix}$$

$$\mathbf{b}_D(\Delta t = 0.15s) = \begin{bmatrix} 0.9741999 \\ 0.0632779 \\ 5.5506821 \\ 1.4831203 \end{bmatrix}; \quad \mathbf{l}_D(\Delta t = 0.15s) = \begin{bmatrix} -0.4415241 \\ -0.010011 \\ 25.405014 \\ -3.4306935 \end{bmatrix}$$

A simulation program has been developed under Scilab 6.0.2 software. The results of the simulation and the experiment in Figure 3.4 show a good agreement of the trolley motions. The simulation model correlates with the experimental results closely. However, results obtained for the relative motion of the payload display higher discrepancies in the beginning, but after four seconds, the results are converging. A minimal fluctuation is seen after four seconds can be explained by the digital circuit employed in the experimental setup. The overshooting for the experiment and the model for trolley motion is 87 mm and 98 mm, respectively. The relative motions of the payload converge to 0 between 5-6 seconds.

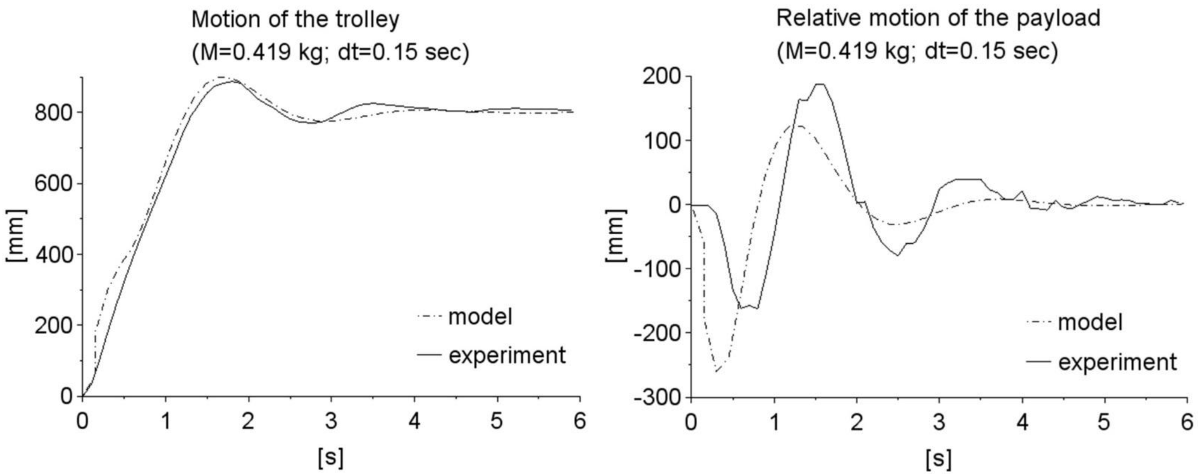


Figure. 3.4 Comparison of the results of the simulation model and the experiment

The responses of the proposed controller have been tested for different gain parameters of the payload $\hat{k}_2, \hat{k}_4$, with time step dt=0.15 s. The previous gain parameters $\hat{k}_1, \hat{k}_3$ will be maintained. The parameter $\hat{k}_4 = 0.02$ is constant while different values of $\hat{k}_2$ were tested, as shown in Figure 3.5. The experimental results show that the trolley movement is not sensitive to the parameter change while the payload is a little bit more.

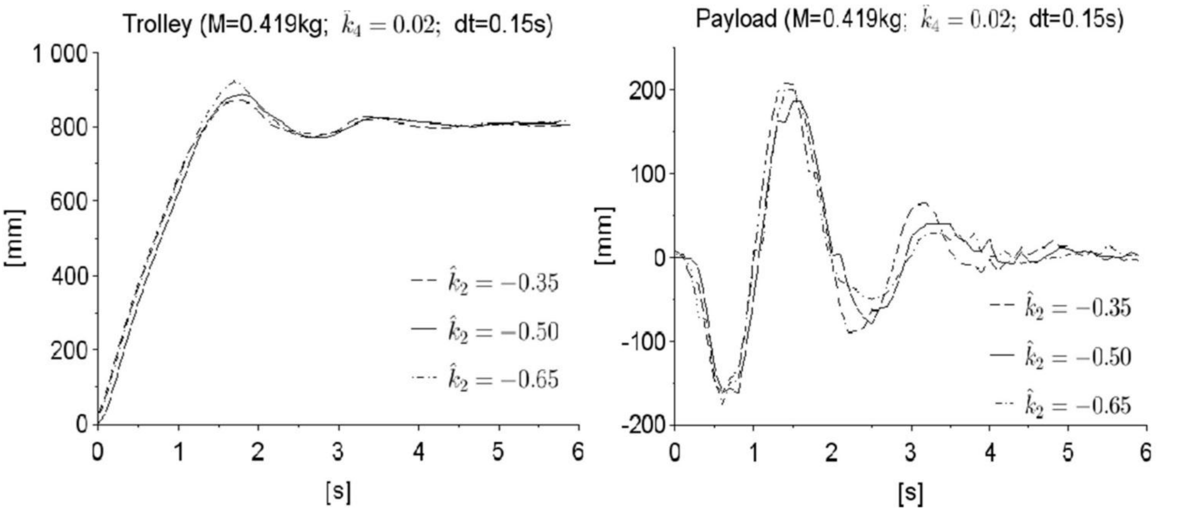


Figure 3.5. Comparison the results of anti-swing control for different $\hat{k}_2$ parameters

The In the following experiment, the parameter $\hat{k}_2 = -0.5$ is constant while different values of $\hat{k}_4$ were tested, as shown in Figure 3.6. The experimental results show that the motion of the system is more sensitive to the changes of this gain parameter compared to $\hat{k}_2$.

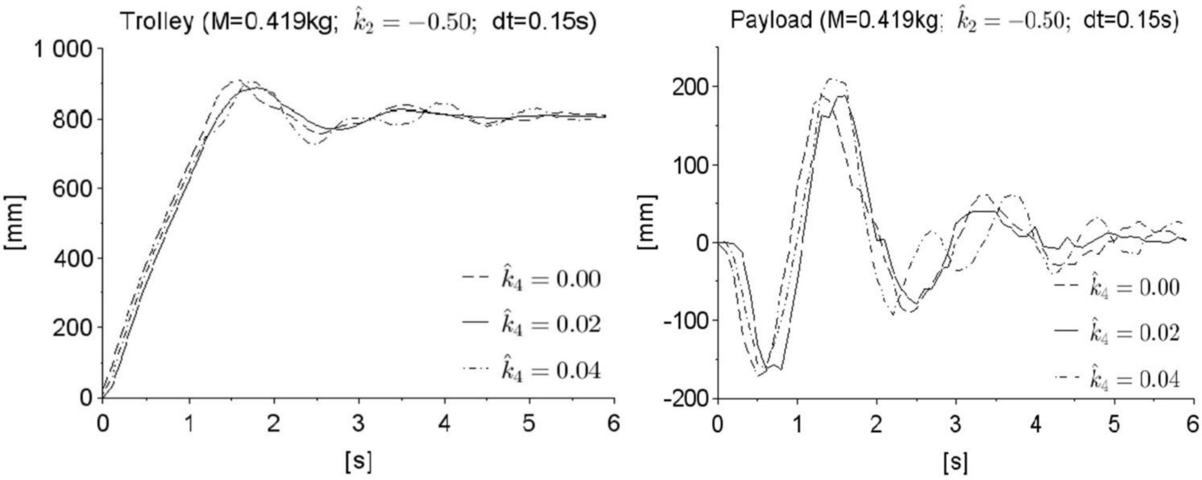


Figure 3.6. Comparison the results of anti-swing control for different $\hat{k}_4$ parameters

Finally different time increments *Δt*[0.10 s; 0.15 s; 0.20 s] have been tested. The matrix of the observers are given as follows:

$$\mathbf{A}_D(\Delta t = 0.10s) = \begin{bmatrix} -0.0742061 & 0.4830562 & 0.0591938 & 0.0184559 \\ 0.0936962 & 0.8919063 & 0.0035798 & 0.0961056 \\ -15.968022 & 7.0318315 & -0.0901801 & 0.4900862 \\ 1.3639328 & -1.9043587 & 0.0950598 & 0.8899923 \end{bmatrix}$$

$$\mathbf{b}_D(\Delta t = 0.10s) = \begin{bmatrix} 0.5911499 \\ 0.0143975 \\ 8.9361901 \\ 0.5404258 \end{bmatrix}; \quad \mathbf{l}_D(\Delta t = 0.10s) = \begin{bmatrix} -0.7987121 \\ 0.0580099 \\ 16.063697 \\ -2.2193061 \end{bmatrix}$$

$$\mathbf{A}_D(\Delta t = 0.20s) = \begin{bmatrix} -0.869268 & 0.7760892 & -0.006247 & 0.0904905 \\ 0.1505345 & 0.6829104 & 0.017552 & 0.1747341 \\ 3.9522234 & -3.0091483 & -0.8653151 & 0.773071 \\ -0.583671 & -2.0660731 & 0.1499491 & 0.6808269 \end{bmatrix}$$

$$\mathbf{b}_D(\Delta t = 0.20s) = \begin{bmatrix} 1.0931789 \\ 0.166555 \\ -0.9430665 \\ 2.6497433 \end{bmatrix}; \quad \mathbf{l}_D(\Delta t = 0.20s) = \begin{bmatrix} 0.1984911 \\ -0.1208698 \\ 26.689188 \\ -3.8673205 \end{bmatrix}$$

The experimental results are displayed in Figure 3.7. For the time increments *Δt* equal to 0.15 s and 0.20 s the solutions convergent. However, for *Δt*=0.10 s it gives undesirable oscillations at the vicinity of the target position.

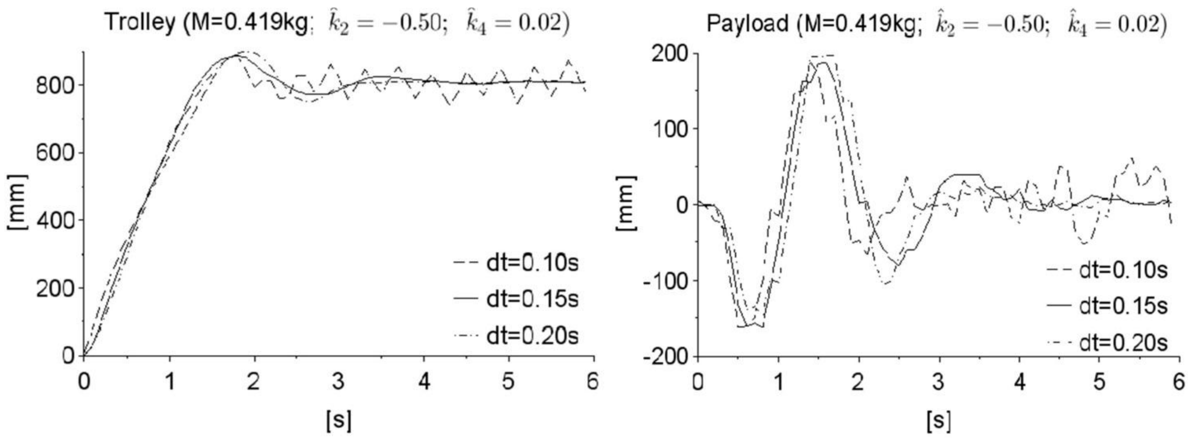


Figure 3.7. Comparison the results of anti-swing control for different time steps

The simulation results show that the displacement of the trolley and the swinging of the payload can be damped in approximately 4 to 6 seconds. The trolley quickly arrives at its target position within 2 seconds with no excessive overshooting. Then an additional 2 to 3 seconds are needed to fully damp the vibration of the payload. The results of the newly proposed method could be compared with the paper [29]. However, the presented experimental setup is slightly bigger in sizes and weights, and the suspending element of the payload is a chain instead of a straight rigid bar in this paper. Also the investigated model in this paper has multi-degrees freedoms, while in [29], the model has only two degrees. The trolley in [29] reaches the target position much slower than in the presented one. Though this fact, the swinging of the payload was damped around at the same time.

4. NEW SCIENTIFIC RESULTS – THESES

T1. A linear and nonlinear model of the overhead crane has been developed considering the vibration of the payload and also the suspending chain. The simulation results of both models, linear and nonlinear, show a good agreement, making the linear model a good candidate to be used as an observer in order to provide the non-measurable state-variables for the feedback.

T2. Assuming that the mass of the payload is significantly higher than the suspending chain of the crane system the stability region of the dynamic system can be expressed by two gain parameters using a D-subdivision method of the simple pendulum model. The determined curves of the stability regions are shrinking as the time delay is increasing (see Fig. 3.2). The boundary curves are intersecting each other at point k_1=0, k_2=0. Therefore, choosing the parameters within the interval of ($-2<k_1<0$) at the vicinity of k_2=0, will make the system stable and robust, since it remains in always in stable state with a high range of time delay.

T3. The newly designed controller is based on a two-level hierarchical approach. At the first level, the time delay due to the vision system is considered by the use of the D-subdivision method of T2, which provides the gain parameters assosiated with the state-variables of the payload. In the second level, the extended model is also considering the vibration of the suspending chain, and its gain parameters are determined with the use of pole placement method. The anti-swing control of the overhead crane system is performed by a PLC program, which contains the collocated observer of T1. The robustness of the proposed controller has been validated by experimental measurements and it proved to be competitive with other methods published in literature.

5. LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

(1) M. Hmoumen: *A Review of Optical Character Recognition System*, Design of Machines and Structures, Vol. 7, pp. 5–12., 2017

(2) M. Hmoumen, T. Szabó: *Linear and Nonlinear Dynamical Analysis of a Crane Model*, Pollack Periodica, Vol. 7, pp.1–12, 2020

(3) M. Hmoumen, T. Szabó: *Crane Payload Position Measurement Vision-based System*, Doctoral Students' Forum, pp.1-7., 2020

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