AKADÉMIAI KIADÓ

Controlling of payload swinging of an overhead crane

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Pollack Periodica • An International Journal for Engineering and Information Sciences

17 (2022) 2, 54–59

DOI: 10.1556/606.2021.00474

Received: July 19, 2021 • Revised manuscript received: September 22, 2021 • Accepted: September 23, 2021
Published online: December 13, 2021

ORIGINAL RESEARCH PAPER

ABSTRACT

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. 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 proposed controller is verified by numerical simulation and experimentally on a laboratory test bench.

KEYWORDS

overhead crane, delay, stability, observer, payload

1. INTRODUCTION

The control of a crane can be applied to adopt an optimal theory of open-loop control [1] to minimize the swing of the payload. A modified input shaping control design method is presented in [2] to reduce residual vibration at the end-point and to limit the sway angle of the payload during traveling in crane systems. Furthermore, Cutforth et al. [3] designed an adaptive input shaping based upon flexible mode frequency variations to handle the uncertainties of the parameters. The open-loop technics, besides being easy to implement, there is no obligation for extra sensors in order to get the payload displacement, which saves costs [4]. However, there is a significant drawback of this approach that it is very responsive towards external disturbances.

In engineering practice the Proportional-Integral-Derivative (PID) controller is widely applicable method in controlling tasks [5]. Feedback control is known to be less affected by parameter variations and disturbances. In [6], the Generalized Predictive Control (GPC) and Linear Quadratic Gaussian (LQG) were well applied and compared for controlling the pendulation of the payload for an offshore crane. An anti-swing crane control method is developed in [7]. The authors built a novel manifold and the corresponding analysis, ensuring that the system state variables would converge to the equilibrium point.

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 [8]. It has been known that time delay may produce significant damping of the oscillations [9].

A delayed reference non-collocated control approach for container cranes was developed by Sano et al. In [10] a delay due to the vision sensor was considered but parameters P and I of these controllers were not given. The authors of this paper analysed nonlinear and linear models of an overhead crane [11]. The results of the simulations showed that the vibration of the suspending chain is significant, and it should be considered.

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In this work a new two-level hierarchical approach 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. D-subdivision method [12] is applied to determine the stability regions expressed by gain parameters for different time delays. In the second level, a chain model is developed, extending the previous pendulum model considering the vibration of the suspending chain. However, only the relative displacement of the payload is measured with a vision sensor, and the rest of the variables of the state-space are determined by a collocated observer. 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 a pole placement method. The effectiveness of the proposed controller is verified by a numerical simulation and experimentally on a laboratory test bench. In the proposed method, the vibration of the chain suspending payload is considered by an observer. The motion of the payload is measured by a vision system and its delay is taken into consideration by the observer. The main novelty of this paper is the implementation of a new two-level hierarchical controlling approach, which considers vibration of the suspending chain and delay due to a vision system. The non-measured state variables are determined by a collocated observer.

2. MATHEMATICAL PENDULUM MODEL OF THE OVERHEAD CRANE

In this Section, the model of the first level of the proposed hierarchical controller is described using a simple mathematical pendulum.

The motion of the crane payload in Fig. 1 can be written as:

$$x_M = u + x_r, \tag{1}$$

$$y_M = -L\cos\theta, \tag{2}$$

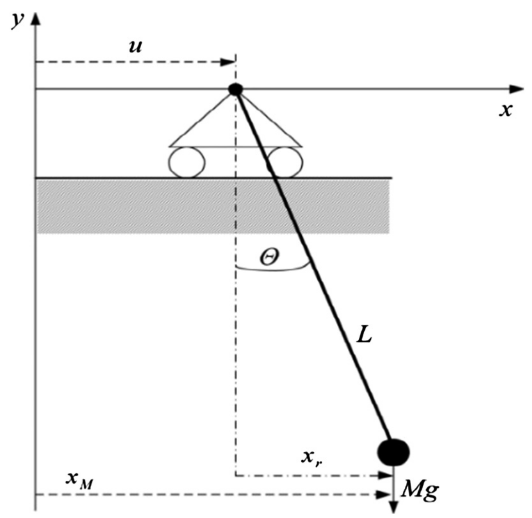

Fig. 1. Overhead-crane model ($L = 0.8$ m, $M = 0.419$ kg)

where u is the prescribed position of the trolley L, θ are the length and the angle of the pendulum, respectively, $x_{M,}$ x_r is the horizontal absolute position, and $x_r = L\sin\theta$ is the relative position of the payload M.

The Lagrangian approach is used to derive the mathematical model, which resulted a nonlinear differential equation, then it is linearized by assumption of small angles, i.e., $\sin\theta \approx \theta$; $\cos\theta \approx 1$:

$$\ddot{\theta} + \frac{g}{L}\theta = -\frac{\ddot{u}}{L}. \tag{3}$$

Since the position of the payload is controlled by the motion u of trolley, the following approximation is substituted in Eq. (3):

$$\theta = \sin\theta = \frac{x_r}{L} = \frac{x_M - u}{L}. \tag{4}$$

The resulting equation of motion is expressed by the position x of the payload

$$\ddot{x}_M + \frac{g}{L}x_M = \frac{g}{L}u. \tag{5}$$

The main objective is to determine the position u of the trolley in Eq. (5) as a function of time to decrease the oscillation of the pendulum considering the delay of the system.

In order to design anti-swing control of the payload, the state variables must be measured. The experimental setup contains a machine vision system that is mounted on the trolley, and it determines the relative displacement of the payload. The measured data is sent to a PLC via Arduino Nano and D/A converter with a sample rate. The position of the trolley is updated in each time step Δt from the initial to a target position x_T. It means that the state feedback has got a delay τ, which must be considered.

The control signal u is defined by the state feedback:

$$u(t) = -k_1(x_M(t-\tau) - x_T) - k_2\dot{x}_r(t-\tau) + x_T. \tag{6}$$

Substituting Eq. (6) into Eq. (5) and taking into consideration Eq. (1), the equation of motion with delay is obtained:

$$\ddot{x}_M(t) + \frac{g}{L}x_M(t) + \frac{g}{L}k_1x_M(t-\tau) + \frac{g}{L}k_2\dot{x}_M(t-\tau) = \frac{g}{L}[k_2\dot{u}(t) + (k_1+1)x_T]. \tag{7}$$

Characteristic of Eq. (7) is written in Laplacian domain:

$$s^2 + \frac{g}{L} + \frac{g}{L}k_1e^{-s\tau} + \frac{g}{L}k_2se^{-s\tau} = 0. \tag{8}$$

In order to use D-subdivision method, substitution of $s = (i\omega)$ into Eq. (8) is required. After straightforward manipulations, the gain parameters can be separated and expressed as functions of ω:

$$k_1 = \left(\frac{L}{g}\omega^2 - 1\right)\cos(\omega\tau),\ k_2 = \left(\frac{L}{g}\omega^2 - 1\right)\sin(\omega\tau). \tag{9}$$

The gain parameters in Eq. (9) determine stability regions of the system for different time delays τ (0.1 s, 0.15 s, 0.2 s), as it is shown in Fig. 2. The higher the time delay, the smaller the stability region.

Eq. (5) can also be written in state-space form with state variables $x_1 = x$ and $x_2 = \dot{x}$.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\dfrac{g}{L} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\dfrac{g}{L} \end{bmatrix}, \tag{10}$$

where the gravity acceleration $g = 9.81\,\mathrm{m/s^2}$.

The gains of a non-delayed linear system can be determined, e.g., using the pole placement method with MATLAB or Scilab software. According to the control theory, if the poles of the transfer function are located on the left half-space of the complex domain the linear system is stable. Prescribing the poles as $p_{1,2} = -0.12 \pm i2.5$, it provides gain parameters $k_1 = -0.5$, $k_2 = 0.02$, which are within the stable region of Fig. 2 for different time delays. This way, the stability of the system is granted. Equation (10) can be solved with its discrete-time state-space equation with time step Δt, which is proportional with the delay of feedback:

$$\mathbf{x}[n+1] = \mathbf{A}_D \mathbf{x}[n] + \mathbf{b}_D u[n],\ y[n] = \mathbf{c}^{\mathrm{T}} \mathbf{x}[n]. \tag{11}$$

$$u[n] = -[k_1(x_M[n-1] - x_T) + k_2 \dot{x}_r[n-1]] + x_T, \tag{12}$$

where $\mathbf{x}[k] = \begin{bmatrix} x_1[n] \\ x_2[n] \end{bmatrix}$, $\mathbf{A}_D = \begin{bmatrix} 0.8651897 & 0.1431969 \\ -1.7559517 & 0.8651897 \end{bmatrix}$, $\mathbf{b}_D = \begin{bmatrix} 0.1348103 \\ 1.7559517 \end{bmatrix}$ are determined using Scilab software with $\Delta t = 0.15$ s and y[n] is the output of the system, ie., the displacement of the payload, matrix $\mathbf{c}^{\mathrm{T}}$ =[0 1 0 0] is the output matrix. It is noted that in Eq. (12), the state variables of the feedback are given in time step n-1 in order to consider the delay $\tau = \Delta t$.

In the right-hand side of Eq. (12) the variables are taken in time step n-1 instead of n due to time delay τ=0.15 s. The results obtained for the control $u[n]$ and $x_r[n]$ are shown in Figs 3 and 4. The displacement of the trolley is shown in Fig. 3. Figure 4 displays the displacement of the payload relative to the trolley. The simulation shows that the proposed controller provides good active damping; the

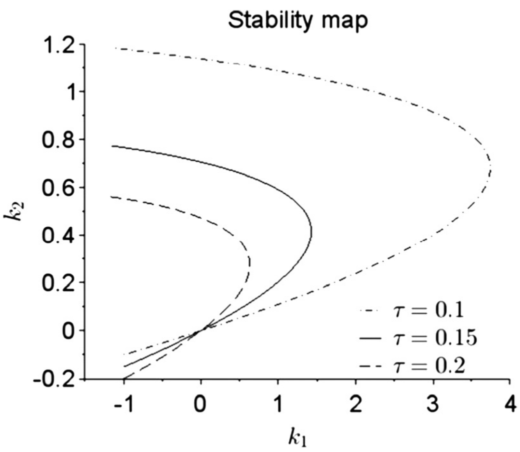

Fig. 2. Stability regions for different delays

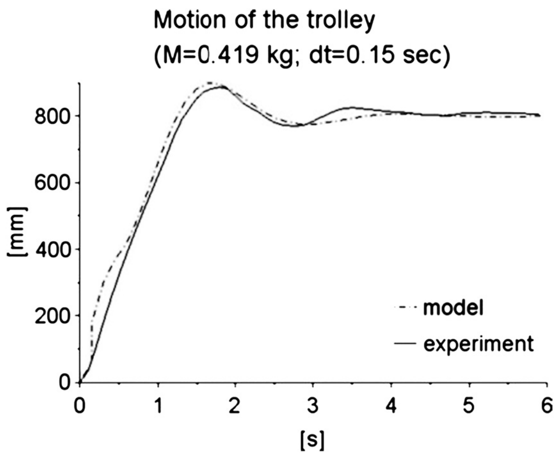

Fig. 3. Position of the trolley

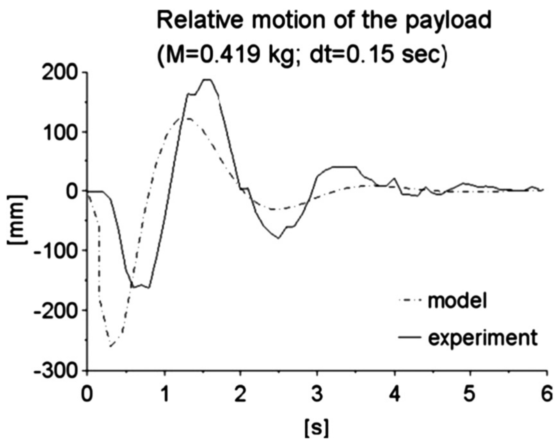

Fig. 4. Relative motion of the payload

vibration of the payload is suppressed effectively within 5 seconds.

The payload will inevitably be dominant in an extended model, where the suspending chain will be considered in the next Section. Therefore, the gain parameters $k_1 = -0.5$, $k_2 = 0.02$ related to the state variables payload will be used in the extended model.

3. FORMULATION OF CHAIN MODEL

In the extended model, the vibration of the payload and the suspending chain is considered with a linear model of a taut string. The mass of the chain is $m_L = 0.22$ kg. It is assumed that the displacement of the payload is negligible in the vertical direction compared to the horizontal one. The chain in Fig. 5 can be discretized with two-node linear line elements.

The present model containing two two-node elements considering the kinematical boundary condition, which provides a 2 degree of freedom (DoF) equation of motion. The use of lumped matrix instead of the consistent one, the motion of the equation in a simpler form can be given as

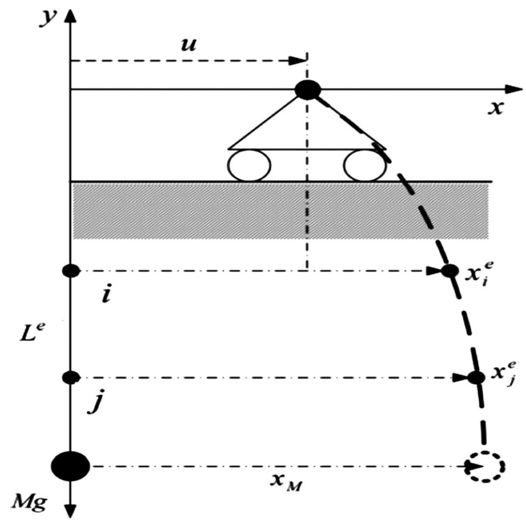

Fig. 5. Overhead-crane model ($L = 0.8$ m, $M = 0.419$ kg, $m_2 = 0.22$ kg)

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{b}_1 u, \tag{13}$$

where $\mathbf{M} = \begin{bmatrix} \mu L^e & 0 \\ 0 & \frac{\mu L^e}{2} + M \end{bmatrix}$, $\mathbf{K} = \begin{bmatrix} \frac{F^1 + F^2}{L^e} & -\frac{F^1}{L^e} \\ -\frac{F^2}{L^e} & \frac{F^2}{L^e} \end{bmatrix}$,

$\mathbf{b}_1 = \begin{bmatrix} -\frac{F^1}{L^e} \\ 0 \end{bmatrix}$, $\mathbf{q} = \begin{bmatrix} x_2 \\ x_M \end{bmatrix}$.

In control theory, the state space form of the differential Eq. (13) is preferred, which is shown as:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{b}u, \tag{14}$$

where $\mathbf{A} = \begin{bmatrix} 0 & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & 0 \end{bmatrix}$, $\mathbf{b} = \begin{bmatrix} 0 \\ \mathbf{M}^{-1}\mathbf{b}_1 \end{bmatrix}$ and $\mathbf{x} = \begin{bmatrix} \mathbf{q} \\ \dot{\mathbf{q}} \end{bmatrix}$.

In this model the state vector contains four state variables. The objective of controlling the motion of the trolley is to damp the excessive swing of the payload within a short time. To achieve this, the following state feedback is used: $d\xi = dy$.

$$u = -[\widehat{k}_1(x_2 - x_T) + \widehat{k}_2(x_M - x_T) + \widehat{k}_3\dot{x}_2 + \widehat{k}_4\dot{x}_M] + x_T, \tag{15}$$

where $\widehat{k}_1$ $\widehat{k}_2$ $\widehat{k}_3$ $\widehat{k}_4$ are gain parameters, which can be represented in a row vector $\mathbf{k}_D^T = [\widehat{k}_1 \quad \widehat{k}_2 \quad \widehat{k}_3 \quad \widehat{k}_4]$.

The payload parameters $\widehat{k}_2$ and $\widehat{k}_4$ in (15) have the same role as k_1 and k_2 in Eq. (9) of the first level the hierarchical approach. Therefore, the values $\widehat{k}_2 = -0.5$, $\widehat{k}_4 = 0.02$ are also used in this level. Using pole placement function of Scilab 6.0.2 software and prescribing different stable poles and gain parameters, with the condition of keeping the previous values of $\widehat{k}_2$ and $\widehat{k}_4$, the rest of the parameters $\widehat{k}_1$ and $\widehat{k}_3$ are associated to the chain vibration and they could be determined: $\widehat{k}_1 = -0.07$, $\widehat{k}_2 = -0.5$, $\widehat{k}_3 = 0.003$, $\widehat{k}_4 = 0.02$ by these poles $p_1 = -0.0878902+2.3587906i$, $p_2 = -0.0878902–2.3587906i$, $p_3 = 0.2896223+16.901392i$, $p_4 = -0.2896223–16.901392i$.

4. RESULTS OF SIMULATIONS AND EXPERIMENTS

The parameters of the experimental crane model shown in Fig. 4 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.

A simulation program has been developed under Scilab 6.0.2 software. The results of the simulation and the experiment in Figs 6 and 7 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

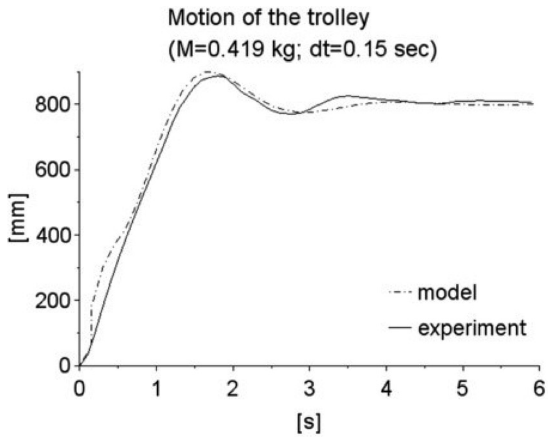

Fig. 6. Comparing positions of the trolley

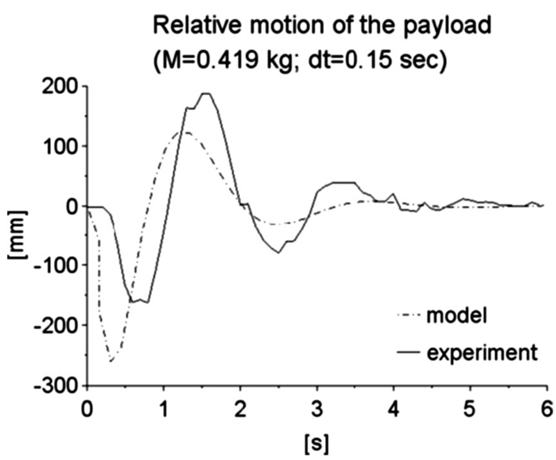

Fig. 7. Comparing positions of the payload

experimental setup. The overshooting for the experiment and the model for trolley motion is 87 and 98 mm, respectively. The relative motions of the payload converge to 0 between 5 and 6 seconds.

The responses of the proposed controller have been tested for different gain parameters of the payload $\widehat{k}_2$, $\widehat{k}_4$, with time step $dt = 0.15$ s. The previous gain parameters $\widehat{k}_1$, $\widehat{k}_3$ will be maintained.

The parameter $\widehat{k}_4 = 0.02$ is constant while different values of $\widehat{k}_2$ were tested, as it is shown in Figs 8 and 9. The experimental results show that the trolley movement is not sensitive to the parameter change while the payload is a little bit more.

In the following experiment, the parameter $\widehat{k}_2 = -0.5$ is constant while different values of $\widehat{k}_4$ were tested, as shown in Figs 10 and 11. The experimental results show that the motion of the system is more sensitive to the changes of this gain parameter compared to $\widehat{k}_2$.

Finally different time increments Δt [0.10 s, 0.15 s, 0.20 s] have been tested. For the time increments Δt equal to 0.15 and 0.20 s the solutions convergent. However, for $\Delta t = 0.10$ s it gives undesirable oscillations at the vicinity of the target position.

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.

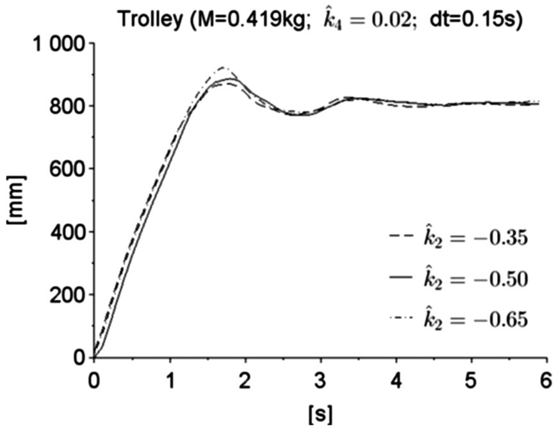

Fig. 8. Positions of the trolley for different $\widehat{k}_2$

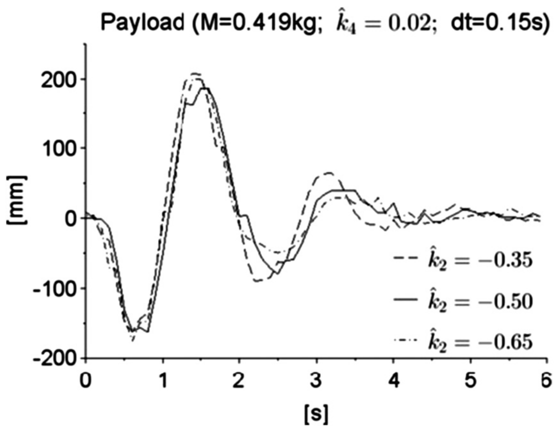

Fig. 9. Positions of the payload for different $\widehat{k}_2$

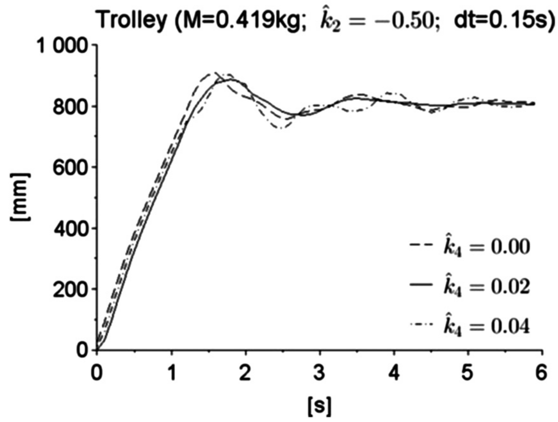

Fig. 10. Positions of the trolley for different $\widehat{k}_4$

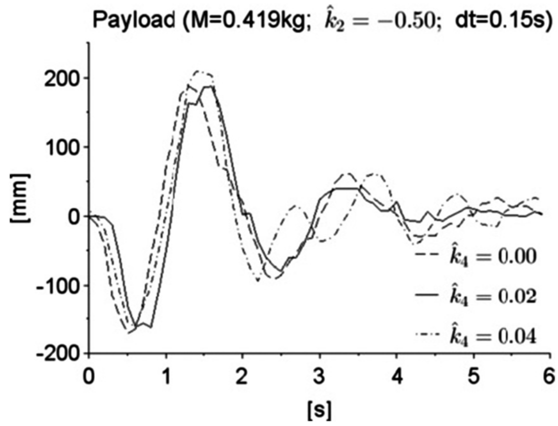

Fig. 11. Positions of the payload for different $\widehat{k}_4$

5. CONCLUSION

This paper proposed a new control of trolley positioning and payload swinging of an overhead crane. A novel hierarchical approach is introduced, which has two levels. At the first level, the delay caused by the vision sensor is considered in a simple mathematical pendulum model by the use of the D-subdivision method, and the gain parameters of the feedback are determined.

At the second level, the vibration of the suspending chain is also considered in addition to the payload. Since the payload motion is dominant in the dynamics of the crane system; therefore, the gain parameters of the first level related to the payload's state variables are used in the extended model. The rest of the gain parameters related to the chain vibration are determined by a pole placement method. The displacement and velocity of the chain, i.e., the unmeasured state-variables, are determined by a collocated observer.

The effectiveness of the novel controller is verified by a test bench, which consists of a PLC controlled positioner of the trolley and a vision system providing the position feedback of the payload. The robustness of the designed controller was tested for different gain parameters and sampling times. The designed anti-swing controller with the tracking controller effectively reduces payload oscillations in a reasonable time, and its performance is comparable to the results of a theoretical model. The presented method is competitive with the existing methods.

ACKNOWLEDGEMENTS

The described article was carried out as part of the EFOP-3.6.1-16-2016-00011 "Younger and Renewing University - Innovative Knowledge City - institutional development of the University of Miskolc aiming at intelligent specialization" project implemented in the framework of the Szechenyi 2020 program. The realization of this project is supported by the European Union, co-financed by the European Social Fund.

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