Over-Head Crane Robust Control

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***Abstract*—This paper presents a robust controller designing procedure of an over-head crane using D-K iteration method. First, an $H\infty$ controller is employed to control the nominal performance. Robustness of the perturbed system is analyzed with a μ test. Finally, robust stability and performance is achieved using D-K iteration. The effectiveness of the designed robust controller is verified through simulations.**

***Index Terms*—robust control, D-K iteration, $H\infty$ control, μ-synthesis, over-head cranerobust control, D-K iteration, $H\infty$ control, μ-synthesis, over-head craner**

I. Introduction

Over-head cranes are widely used in factories and harbors for loading and unloading of all kinds of goods. It is desired for the crane to be able to move to the required position as fast and as accurately as possible while placing the load at the appropriate position. In addition to these two requirements, the load swing-angle should be kept as small as possible.

Several researchers have tackled the control problem of industrial cranes and provided some control methods such as state-feedback controller, fuzzy control, sliding-mode control and some other controllers to achieve the defined objectives. In this paper a robust controller is designed to reach the following objectives: 1) disturbance rejection 2) reference tracking 3) swing-angle minimization. Actually, we are trying to track an input reference under a noisy output measurement. In addition, the robust controller should be able to reject the disturbance that have been added to output measurements separately and of-course it should be able to minimize the load swing-angle caused by moving the crane position.

The paper is organized as follows. In Section 2, the model of a typical overhead crane is presented and the uncertainty structure is discussed. The design of an $H\infty$ controller is discussed in Section 3; its robust performance and stability are evaluated through simulations. In Section 4, the design of a robust controller is outlined using D-K iteration and closed-loop simulations in both frequency and time domains are presented. Finally, the conclusions are given in Section 5.

II. Dynamic Model of the Crane

Consider the crane truck shown in Fig. 1. The main system consists of two parts, horizontal and vertical positioning systems. Each part include a DC-Motor that can be controlled by an input voltage. There are two types of modeling procedure for crane, modeling the system in two separate part or modeling together. Here we used the combined model which include both two parts together in one state-space model.

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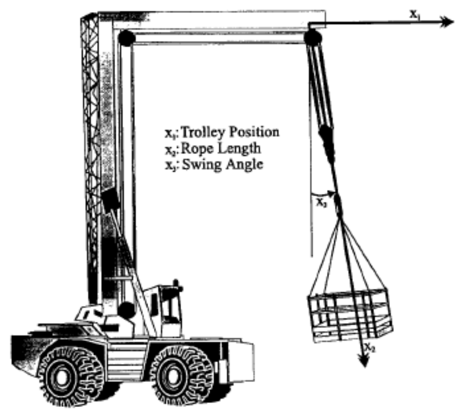

Fig. 1. Crane truck is a sample of using over-head crane type. As you can see in the figure, X_1 is the trolley position and X_2 is the vertical position of hoisting part. The swing-angle of load is also defined with X_3. power.

A. State-Space Representation

The linearized system around operating points is described as follow :

$$\begin{aligned}\dot{x} &= Ax + Bu\\ y &= Cx + Du\end{aligned} \tag{1}$$

where ,

$$A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 0 & 1\\ 0 & 0 & 1.4113 & -5.5556 & 0 & \\ 0 & 0 & 0 & 0 & -4.4444 & 0\\ 0 & 0 & -11.2213 & 5.5556 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0\\ 0 & 0\\ 0 & 0\\ 0.1852 & 0\\ 0 & 0.2222\\ -0.1852 & 0 \end{bmatrix} C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \tag{2}$$

Note that there is no direct path from input to output, therefore D matrix is zero. The model has a 3-by-2 MIMO structure in which the outputs are vertical and horizontal position and swing-angle of the load. The voltage of each motor is defined as it's input.

B. Uncertainty

As we discussed before, the dynamic of the system is fully decoupled for two positioning system, but the swing-angle is affected by two parts. therefore, the uncertainty of each motor can be modeled separately. There are two DC-Motors that we just have an ideal transfer function for each of them and absolutely some of the motor parameters are not considered here. In other side the friction between the cart and path is ignored in modelling. In addition the system can influence from external disturbances. The control problem consists of tracking (for positioning) and regulation(for disturbances and swing-angle of the load) under the complicating conditions described above. This set of requirements in the control problem, along with the plant characteristics makes the uncertain model a useful tool for robust control on an Over-Head Crane system.

III. $H\infty$ Controller

A. Weighting Functions

The uncertainties were all modeled as multiplicative SISO perturbations. In the case of the motors it meant that they could be modeled as P_i = (1 +Wh_i Δ)P_i, where $\|\Delta\| \leq 1$.

Weights were found using some initial value from the source article and adjusting through some simulation involving constraints. Since two DC-Motors are identical in parameters, identical uncertainty can be used to describe them both. All weighting functions for uncertainties, output performances, disturbances and noises are as follows :

$$W_{a1} = \frac{10s^2 + 5s + 1}{s^2 + 5s + 10}, W_{a2} = W_{a1} \tag{3}$$

$$W_{Pperf} = \frac{11}{100s + 1} \tag{4}$$

$$W_{Lperf} = \frac{11}{150s + 1} \tag{5}$$

$$W_{SAperf} = \frac{20}{0.1s + 1} \tag{6}$$

$$W_{d1} = \frac{2}{1000s + 1}, W_{d2} = \frac{4}{1000s + 1} \tag{7}$$

$$W_{noise1} = 0.01, W_{noise2} = 0.03 \tag{8}$$

The W_{a1} and W_{a2} blocks represent the actuation uncertainty weights used to compensate for actuator nonlinearities and input variations. The W_{noise1} and W_{noise2} blocks represent the noise weighting functions used to compensate for sensor noise. The W_{d1} and W_{d2} blocks represent the disturbance weighting functions used to define disturbance rejection importances. The W_{Pperf}, W_{Lperf}, $W_S A_{perf}$ blocks represent the performance weights for the trolley position, the cable length, and the load swing angle, respectively. Bode magnitudes of weighting functions are shown in Fig. 2.

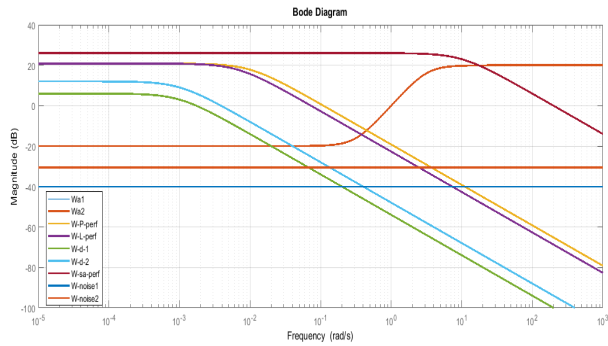

Fig. 2. Each transfer function is shown in a different color

B. $H\infty$ Controller Design

The objective is to have a non-sensitive controller to uncertainties and measurement noise, zero steady-state error at low frequencies and rejecting disturbance. Some mathematical manipulations are needed to design an $H\infty$ controller. The interconnection structure of the control design simulink model is shown in Fig. 3. All weighting functions are colored to green; orange block contains the 6 transfer functions from the trolley and cable inputs, ul and u2, to the outputs x1, x2 and x3.

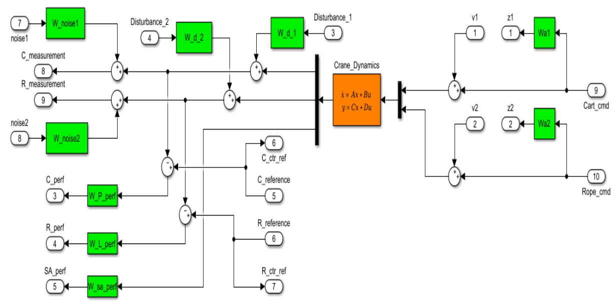

Fig. 3. Green blocks are weighting functions and the model is colored to orange.

An $H\infty$ controller that minimizes the upper bound to μ for closed loop nominal system was designed. Fig. 4 shows μ analysis to test the robustness of the designed controller. It is clear to see that $H\infty$ controller doesn't satisfy each robust stability and robust performance, which means there is a perturbed system not performing up to our standards.

IV. Robust Controller Using D-K Iteration

A. D-K Iteration Design

As it was seen, $H\infty$ controller didn't be able to satisfy the objectives and robust performances individually. In this section we tried to design a robust controller using D-K iteration method, after two iteration the designed controller satisfied both robust stability and robust performance well.μ synthesis is used to analyze the characteristics of designed controller. Fig. 5 shows μ test on closed-loop system including robust controller which was designed after two iteration.

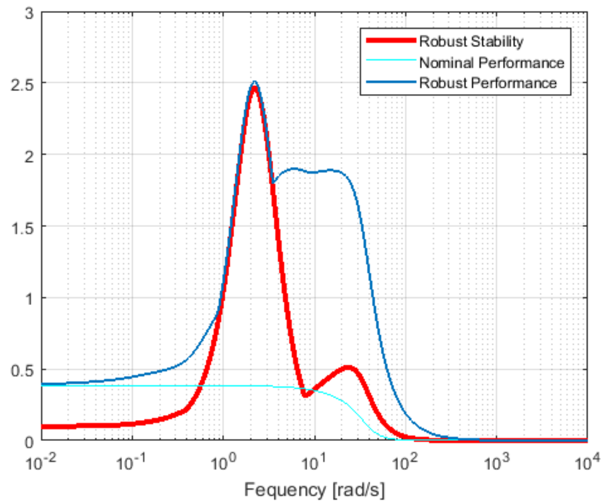

Fig. 4. As it's shown in the picture, robust stability(red) and robust performance(blue) are greater than unit.

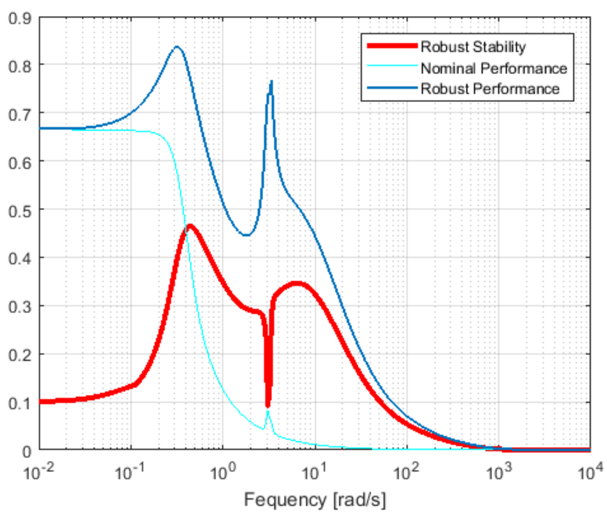

Fig. 5. μ analysis after 2-nd iteration

B. *Worst-Case*

Worst case Δ is calculated from the peak of the nominal $H\infty$ controller μ curve :

$$\Delta_{worst-case}(s) = \begin{bmatrix} \frac{-s+99.79}{s+99.79} & 0 \\ 0 & \frac{-s+10.86}{s+10.86} \end{bmatrix} \tag{9}$$

C. *μ synthesis*

In this section a μ analysis is used to compare the performance of nominal and robust controller under following circumstance :

1) Cart and rope position references were 5 and 2
2) minimizing swing-angle of hanging load
3) two disturbances of magnitude -8 and 5 were applied to system at t=10,20
4) two noises of magnitude 10 and 15 were applied to system at t=5,35

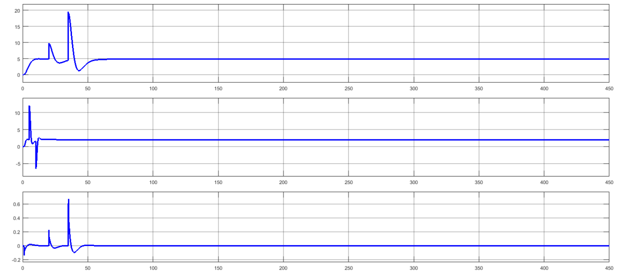

Fig. 6. Time domain response of nominal plant with nominal $H\infty$ controller. the outputs are as follow:1- cart position(horizontal position of load) 2- rope position(vertical position of load) 3- swing-angle of hanging load.

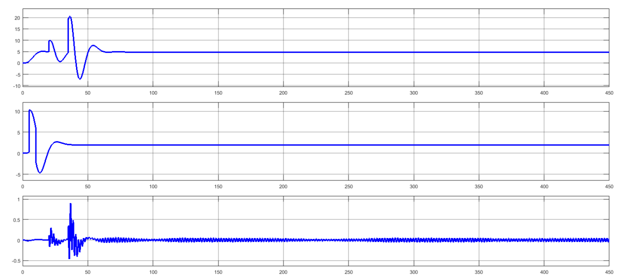

Fig. 7. Time domain response of nominal plant with robust controller. the outputs are as follow:1- cart position(horizontal position of load) 2- rope position(vertical position of load) 3- swing-angle of hanging load.

Fig. 6 and 7 show the time response of nominal plant with nominal and robust controller. As it can be seen from figures, the robust controller is more conservative and the effect of this situation is appeared in swing angle fluctuation and steady state error for rope and cart position.

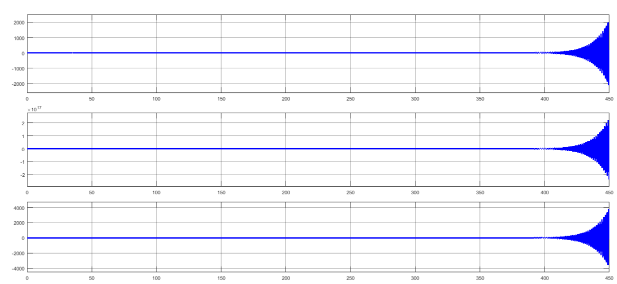

Fig. 8. Time domain response of perturbed plant with worst-case Δ included with nominal $H\infty$ controller.

Fig. 8 and 9 show the time responses of perturbed system under worst-case uncertainty. As it is shown in figures, the nominal controller couldn't control the system and it got unstable after a few minutes. the robust controller could handle all the objectives after a few second.

V. Conclusion

In this project a robust controller was implemented. The motivation to design a robust controller was the unstability of nominal controller. By using D-K iteration, the resulting controller can guarantee the robust stability of the system as

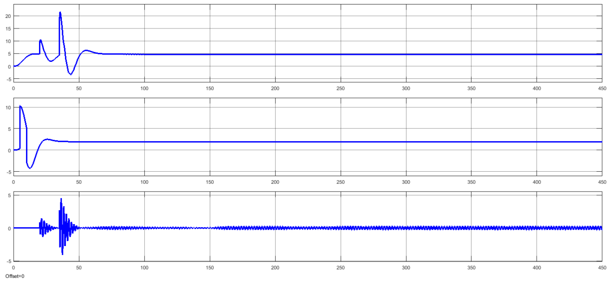

Fig. 9. Time domain response of perturbed plant with worst-case Δ included with robust controller.

well as the robust performance and of course satisfied our objectives. The simulation on worst case scenario of the uncertainties shows the effectiveness of the designed controller.

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