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Applications and Educational Uses of Crane Oscillation Control

This paper discusses the impact of moving load to dynamic behavior of flexible construction of mega quayside container cranes, and focuses on the dynamic interaction between trolley and supporting structure caused by the moving load. The scope of the presented research is to give tha basic principles of dynamics and mathematical modelling of mega quayside container cranes, as well as how to obtain dynamic response of the crane boom structure due to moving mass, as are deflections, bending moments, dynamic magnification factor and acceleration of moving mass in vertical direction.

Keywords: *Crane Control, Input Shaping, Control Education*

1. INTRODUCTION

Cranes are one of the most important elements of the global economy. They are used to perform important and challenging manipulation tasks such as construction of bridges, dams, buildings, and high-rise towers. Cranes are indispensable in commerce, as they load and unload ship cargo at every port. Energy exploration and production are also highly dependent on cranes; they are used on oil platforms, in refineries, and nuclear power plants. Tower cranes like the one shown in Figure 1 are commonly used in construction to provide a large workspace. Cranes used indoors often have the structure of the bridge crane shown in Figure 2.

While the physical structure of cranes varies widely, one essential element is constant - an overhead support cable is used to lift and transport the payload. This essential element provides the fundamental usefulness of cranes. However, it also creates one of the biggest problems: payload oscillation. This paper discusses new developments in oscillation reduction techniques and the integration of crane control into the engineering curriculum.

A real-time oscillation control method should filter out vibration-inducing components from the command signal. This modification can be accomplished by convolving the original command signal generated by the human operator with a sequence of impulses [1–3]. The result of the convolution is then used to drive the crane motors. This input-shaping process is demonstrated in Figure 3. Several variations of this idea have been developed for crane control [4-8].

Input shaping has been implemented on several large bridge cranes at nuclear facilities [6], the 10-ton crane at Georgia Tech shown in Figure 2, as well as portable cranes. The 10-ton crane at Georgia Tech has an overhead vision system that can track the motions of the payload. Figure 4 compares the responses of the crane payload for a typical maneuver under standard operation and when input shaping is enabled. The two responses are from the same human operator. The figure shows that under normal operation the payload has large oscillations. Input shaping virtually eliminates these dangerous swings.

Figure 1. Cranes at la Sagrada Familia in Barcelona

Cranes and crane oscillations are a familiar sight to most people, including engineering students. Furthermore, payload oscillation is a problem that all students can imme- diately see and understand. Because of this familiarity and the visual nature of the problem, cranes provide excellent examples for the system dynamics and controls curriculum. Students can immediately relate to cranes because they have been dealing with pendulum-like dynamics their entire lives. The pendulum oscillations that occur in everyday situations are ubiquitous: buckets carried by their

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handles, baseball bats, dangling iPod earphones, golf clubs, belts, and anything tied to the end of a string. Beyond the basic pendulum mode, cranes also have additional dynamic effects such as motor time constants, velocity limits, and nonlinear payload dynamics that make them well suited for both introductory and advanced study.

Figure 2. 10-Ton bridge crane at Georgia Tech.

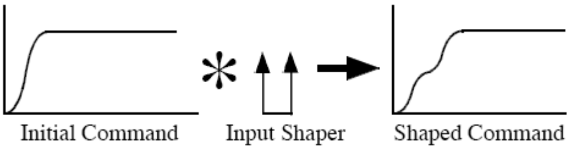


Figure 3. The input shaping process

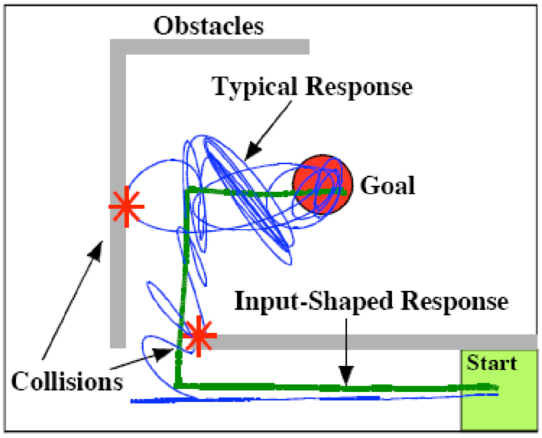


Figure 4. Thypical payload response

The next section describes three cranes that have been built at Georgia Tech for research and educational purposes. Section 3 reports on studies that demonstrate the usefulness and compatibility of input shaping with human operators. Input shaping can be extended to handle complex effects such as nonlinear actuator dynamics and multi-mode oscillations. To demonstrate such an extension, Section 4 develops an input-shaping controller for cranes exhibiting double-pendulum oscillations. Section 5 shows that combining input shaping with feedback control can enable the crane to reject disturbances both at rest and during motion. Finally, Section 6 describes how crane-based examples and laboratories have been integrated into the engineering curriculum.

2. CRANE FACILITIES

2.1 10-ton industrial crane

The crane shown in Figure 2 has been equipped with an advanced control system. Its workspace is approximately 20 ft. high, 30 ft. wide and 140 ft. long. The crane has been used in several mechanical and aerospace engineering courses to illustrate dynamics and controls problems. Additionally, students have implemented and evaluated control strategies on the crane.

Figure 5 shows a schematic diagram of the crane and how it generates the input-shaped control signal. Signals generated by the human operator travel from the control pendant to the hoist controls and to the bridge-and-trolley control box. A Siemens programmable logic controller

(PLC) performs the input-shaping algorithm. The resulting commands are then sent to the trolley and/or bridge motor drives. These drives use the incoming commands from the PLC as velocity set points for the motors. To ensure accurate execution of the commands, the drives are Siemens Masterdrives Series AC-AC inverters. This type of drive uses a pulse-width-modulated signal to accurately control the motors. Inverter duty capable motors were selected to ensure good compatibility with the drives.

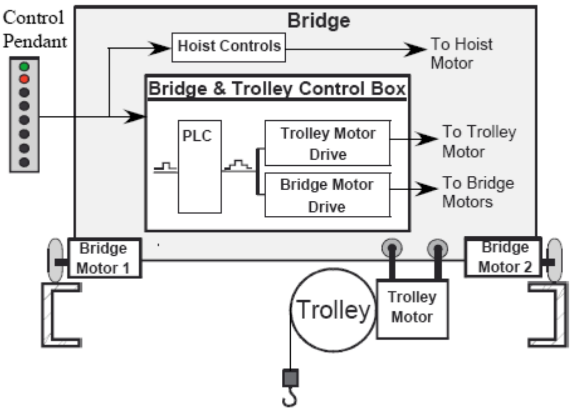


Figure 5. Hardware implementation

2.2 Portable bridge crane

A small, transportable bridge crane was built and is shown in Figure 6. One purpose of this crane is to provide a hands-on learning tool for students outside Georgia Tech that cannot use the 10-ton crane. The crane was transported to Georgia Tech Lorraine in France during the fall of 2004. In the spring of 2006 it was used in an Atlanta-area high school.

The portable bridge crane is approximately one cubic meter in volume. It is driven by Siemens AC synchronous servomotors. These move the trolley and bridge axes via two timing belts. A direct-drive DC motor is used for hoisting. A Siemens digital camera is attached to the trolley and points downward to measure the payload swing.

The portable crane was designed to be light, compact, and easily transportable. Almost all of the structural elements are lightweight aluminum and made as small as possible without degrading the structural integrity. In addition, the structure was designed to be easily disassembled and collapsed to fit into two traveling boxes.

The control pendant for the crane has directional buttons to drive the crane and two buttons to change the controller mode. The pendant signal is sent to a Siemens PLC that generates a series of velocity setpoints for the motors. The user also has the option to run a trajectory stored in a setpoint buffer.

Figure 6. Portable bridge crane

2.3 Portable tower crane

A small, transportable tower crane, shown in Figure 7, has also been constructed. Tower cranes present additional challenges because their cylindrical coordinate structure leads to nonlinear dynamics due to centripetal acceleration. The crane is approximately 2m tall with a 1m arm (jib). The crane has 3 degrees of freedom actuated by Siemens synchronous AC servomotors. The rotation axis is capable of 340° rotation. The trolley moves radially along the jib via a lead screw. The hoisting motor controls the suspension cable length. A Siemens digital camera is mounted to the trolley and records the swing deflection of the payload.

The portable tower crane has tele-operation capabilities that allow it to be operated in real-time from anywhere in the world via the internet. To achieve tele-operation, the controlling PC was equipped with UltraVNC. This program allows any user with internet access to remotely control a target PC. During the fall of 2005, this crane was simultaneously used in courses at Georgia Tech and the Tokyo Institute of Technology (Tokodai). The crane has been operated by researchers and students located throughout the United States, Japan, Korea, Switzerland, Spain, and Serbia.

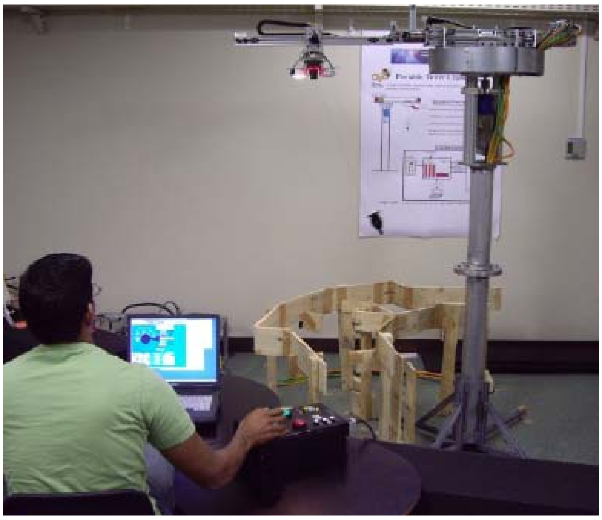


Figure 7. Portable tower crane

Figure 8 shows the layout of the tower crane system. A Siemens PLC sends velocity setpoints to the motor drives. The PLC receives the payload swing data from the camera and carries out the anti-swing control. The motors are powered with Siemens Sinamic drives, which use the motor encoder signals to provide Proportional-plus-Integral (PI) velocity control of the motors.

The PLC can receive velocity commands from either a control pendant or a PC. The PC controls the crane using the Graphical User Interface (GUI) shown in Figure 9. The upper left portion of the screen shows a real-time animation of the crane from an overhead view using the camera and encoder data. The square is the trolley position and the circle is the payload position. The current configuration is also numerically displayed in the bottom center of the display (slew angle, trolley pos, etc.). The crane can be manually driven using the directional arrows at the bottom left of the screen. In addition, velocity setpoints can be stored and then executed with the "Play" button. Other features include: input shaper selection, data recording, and a "Swing Reducer" that uses feedback from the camera to automatically damp out payload sway.

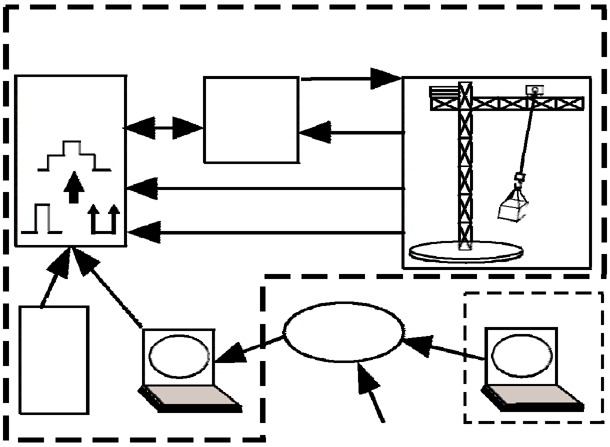
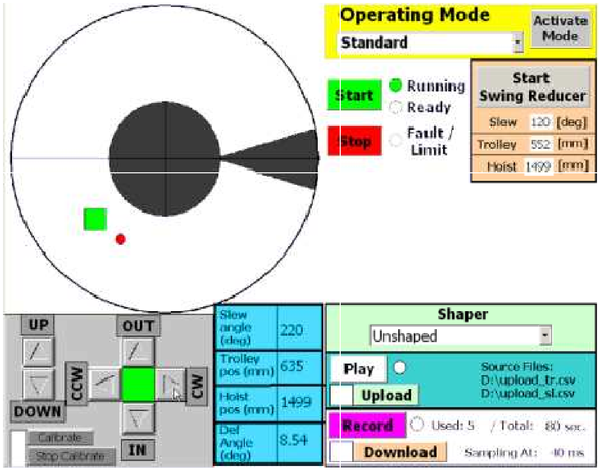


Figure 8. Tower crane system overview



Operating Mode: Standard

Slew 120 [deg]
Trolley 552 [mm]
Hoist 1499 [mm]

Slew angle (deg)	220
Trolley pos (mm)	635
Hoist pos (mm)	1499
Def Angle (deg)	8.54

Shaper: Unshaped

Source Files:
D:\upload_tr.csv
D:\upload_sl.csv

Used: 5 / Total: 80 sec.
Sampling At: 40 ms

Figure 9. Tower crane computer interface

3. EFFECTS OF INPUT-SHAPING CONTROL ON HUMAN OPERATOR PERFORMANCE

There is clearly a need to utilize human-in-the-loop control schemes with cranes. Human operators are well suited for real world complications, such as cluttered workspaces and time-varying manipulation goals. Human operators are also indispensable when safety issues at a disaster scene, in a warehouse environment, or on a ship deck are considered. Additional problems arise when crane is operated remotely via a video monitor. The human operator must deal with poor visibility and account for the tele-operation delays. Given that input shaping changes the dynamic nature of the crane, it is important to investigate how operator performance changes with the addition of input shaping.Volunteer operators drove the 10-ton bridge crane through two different obstacle courses. The courses differed in their difficulty; one required more turns than the other. Each operator ran the crane both with and without input shaping. The goal was to move the crane from a start region to an end region quickly, but without running into obstacles. The amount of time required to complete the manipulation task was recorded. Input shaping improved the completion time by 284% on Course 1 and 265% on Course 2. Although input shaping cancels out payload swing, skilled operators can also employ manual swing control techniques to reduce payload sway. On the other hand, most novice crane operators limit themselves to slow and simple movements in an attempt to avoid large oscillations. When large oscillations do arise, the operators usually have to take less challenging paths to the goal, or they make numerous small motions to proceed slowly through a dangerous region. This tactic works, but results in long task completion times.

In order to investigate the learning process of bridge crane operators, student volunteers were asked to drive the crane through an obstacle course multiple times over a period of several weeks. The average testing frequency was 2.2 trials/week. Some operators drove the crane only 3 times, whereas others drove the crane 9 different times. Figure 10 shows the progression of completion times without input shaping for all of the operators. There is a clear downward trend in completion time as the number of trials increases and the operators learn to complete the task faster. However, the completion times appear to level off after 4-5 trials.

Figure 11 shows the task completion times when input shaping was enabled. In these cases, operator learning does not have a significant effect on task completion time. However, the completion times with shaping are considerably faster, even after substantial operator learning on the unshaped crane. The results indicate that significant learning is not needed when input shaping is utilized. With input shaping, crane operation immediately became safer and more efficient.

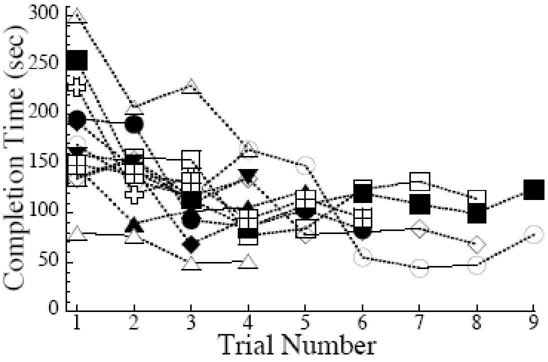


Figure 10. Task completition times without shaping

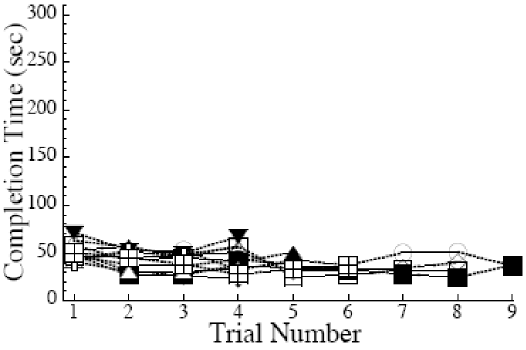


Figure 11. Task completition times with shaping

4. DOUBLE-PENDULUM DYNAMICS

Under certain conditions, crane dynamics are complicated when the payload creates a double-pendulum effect. Figure 12 shows a schematic representation of a double- pendulum crane. The crane is moved by applying a force, u(t), to the trolley. A cable of length L1 hangs below the trolley and supports a hook, of mass m_h . The rigging and payload are modeled as a second cable of length L2 , and point mass, m_p. Assuming that the cable and rigging lengths do not change during the motion, the linearized equations of motion for are:

$$\begin{aligned} \ddot{\theta}_1(t) &= -(\frac{g}{L_1})\theta_1 + (\frac{gR}{L_1})\theta_2 - \frac{u(t)}{L_1} , \\ \ddot{\theta}_2(t) &= -(\frac{g}{L_1})\theta_1 + (\frac{g}{L_2} + \frac{gR}{L_2} + \frac{gR}{L_1})\theta_2 - \frac{u(t)}{L_1} . \end{aligned} \tag{1}$$

where θ_1 and θ_2 describe the angles of the two pendulums, R is the ratio of the payload mass to the hook mass, and g is the acceleration due to gravity.

The linearized frequencies of the double-pendulum dynamics modeled in (1) are:

$$\omega_{1,2} = \sqrt{\frac{g}{2}}\sqrt{(1+R)(\frac{1}{L_1}+\frac{1}{L_2}) \mp \beta} \tag{2}$$

where,

$$\beta = \sqrt{(1+R)^2(\frac{1}{L_1}+\frac{1}{L_2})^2 - 4(\frac{1+R}{L_1 L_2})} . \tag{3}$$

The frequencies depend on the two cable lengths and the mass ratio. Knowing how the frequencies vary is useful for designing an effective input-shaping control scheme. If overall length is held constant, then the low frequency varies only slightly when mass ratio and length ratios change. On the other hand, the second mode can vary significantly [9]. This would seem to indicate that an oscillation control scheme would need more robustness to variations in the second mode than in the first mode. However, if the amplitude of the second mode is very small compared to the amplitude of the first mode, then the controller does not need to address the second mode.

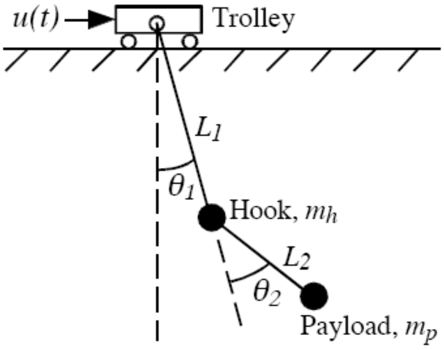


Figure 12. Double-pendulum crane

4.1 Input shaping for double pendulums

When the second mode causes the payload oscillation to exceed tolerable levels, it must be taken into account when designing an input shaper. There are a number of methods for designing multi-mode input shapers [10–13]. In this section, a technique is developed to suppress the two frequencies of a double-pendulum crane. Furthermore, the technique is made robust to any expected variation in the two modes. In order to determine the input shaper, a set of constraint equations ensuring vibration suppression and robustness is formulated and then satisfied.

Vibration can be limited by requiring the residual oscillation amplitude to be less than some tolerable threshold, Vtol. The percentage residual amplitude is formed by di- viding the vibration amplitude when shaping is used by the vibration amplitude without shaping [2]:

$$V(\omega_n,\varsigma) = e^{-\varsigma\omega_n t_n}\sqrt{[C(\omega_n,\varsigma)]^2 + [S(\omega_n,\varsigma)]^2} . \tag{4}$$

where,

$$C(\omega_n,\varsigma) = \sum_{j=1}^{n} A_j e^{-\varsigma\omega_n t_j}\cos(\omega_d t_j) , \tag{5}$$

$$S(\omega_n,\varsigma) = \sum_{j=1}^{n} A_j e^{-\varsigma\omega_n t_j}\cos(\omega_d t_j) . \tag{6}$$

A_i and t_i are the amplitudes and time locations of the impulses in the input shaper. A constraint on residual vibration can be expressed as:

$$V_{\mathrm{tol}} \geq V(\omega_n,\varsigma) . \tag{7}$$

If the input shaper impulse amplitudes are not constrained, then their values can approach positive or negative infinity. There are two possible solutions to this problem: limit the magnitude of the impulses to less than a specific value or require all the impulses to have positive values. To streamline the discussion, the shapers in this paper will contain only positive impulses:

$$A_i > 0, \quad i = 1, ..., n \tag{8}$$

where n is the number of impulses in the shaper.

If negative impulses are allowed, then the rise time will improve, but potential drawbacks such as excitation of unmodeled high modes and actuator saturation must be addressed. Techniques for managing the challenges of negative input shapers have been well documented [14–16]. The engineer desiring the highest level of performance should combine the methods presented in this paper with the techniques for using negative impulses previously presented.

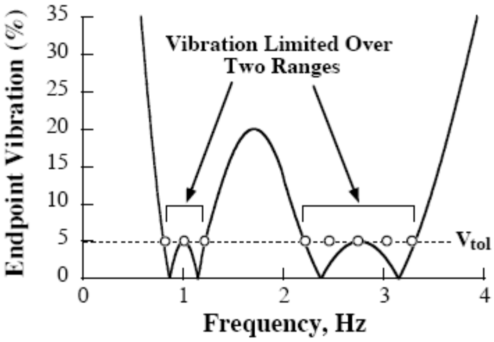


Figure 13. Frequency sampling over two ranges

A second amplitude constraint must be enforced so that the shaped command reaches the desired setpoint; the impulse amplitudes must sum to one:

$$\sum_{i=1}^{n} A_i = 1 . \tag{9}$$

The constraint in (7) can be used to limit the vibration at a single set of frequencies. If the actual crane frequencies coincide with those used to design the shaper, then the oscillation will be eliminated. However, to ensure robustness to modeling errors and parameter variations, the oscillation must remain small over a range of frequencies. Robustness can be ensured by suppressing vibration at several points near the modeling frequency. Because this approach allows the designer to specify the frequency range over which the vibration is suppressed, the resulting shapers are called Specified Insensitivity (SI) shapers [17]. Given a double-pendulum crane, we must extend the single-mode SI method by placing vibration constraints over frequency ranges near both of the expected frequencies. This approach is illustrated in Figure 13 for a case where modes near 1 Hz and 2.5 Hz are suppressed. Due to the transcendental nature of the residual oscillation equations, there are an infinite number of solutions. To select among these solutions and ensure that the system rise time is as fast as possible, the shaper duration must be made as short as possible. Therefore, the final necessary step is to minimize the time of the final input shaper impulse. To summarize, two-mode specified-insensitivity input shapers are designed by minimizing the shaper duration while satisfying (8) and (9) and using (7) to limit vibration over two frequency ranges that contain the expected frequencies. The input shapers designed for this paper were obtained using the MATLAB Optimization Toolbox.

4.2 Experiments on a double-pendulum bridge crane

The procedure described above was used to design an input shaper for the portable crane shown in Figure 6. The input shaper was designed for the crane with a payload- to-hook mass ratio of 2 and a suspension-to-rigging length ratio of 0.67. The shaper was designed to accommodate a ±5% variation in the expected frequencies (0.62 Hz and 1.9 Hz). The sensitivity curve for the resulting shaper is shown in Figure 14. Figure 15 compares the unshaped response to the response using the double-pendulum shaper. Both modes are effectively suppressed by input shaping.

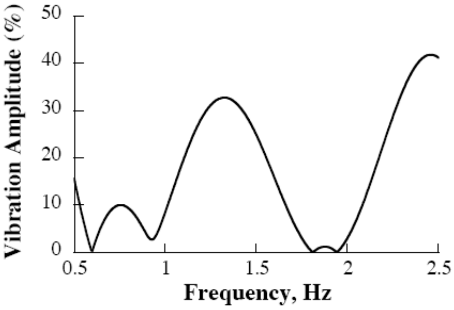


Figure 14. Sensitivity curve for a two-model SI shaper

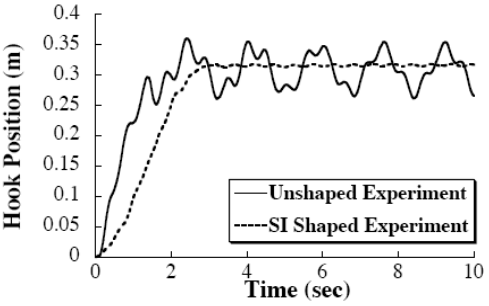


Figure 15. Experimental response of portable crane

To test controller robustness, the suspension and rigging cable lengths were varied and the tests were repeated to obtain the residual vibration in the presence of modeling errors. Figure 16 shows the unshaped and SI-shaped vi- bration amplitude over a large range of length ratios. The experimental results clearly demonstrate robustness.

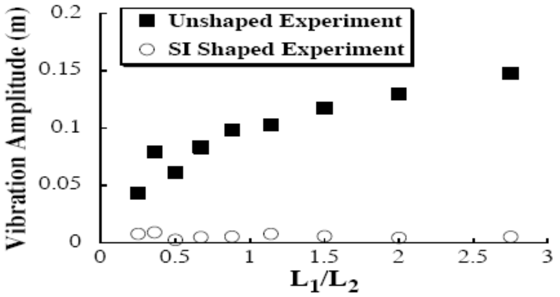


Figure 16. Oscillation amplitude vs. length ratio

5. COMBINED INPUT-SHAPING AND FEEDBACK CONTROL

This section presents an architecture in which input shaping is combined with feedback control. The block diagram of the controller in Figure 17 has an input shaper placed within a positioning feedback loop. An additional disturbance rejection loop interacts with the positioning loop. With this combined control architecture, precision positioning of the payload is accomplished while motion- induced oscillations and disturbance-induced oscillations are eliminated.

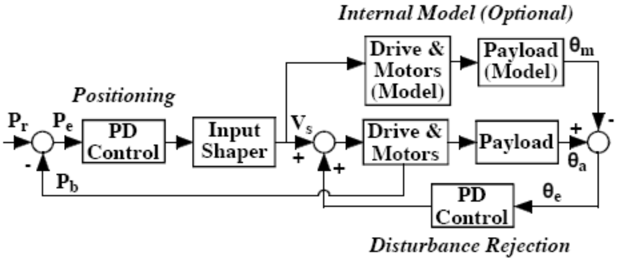


Figure 17. Combined input-shaping and feedback control system

The capability to precisely position the payload is achieved with the input shaping and positioning control loop. This part of the controller generates a shaped reference velocity that is used as the input to the disturbance rejection component. The module receives the shaped signal, Vs , and tracks it, while also rejecting disturbances. Because Vs continually drives the crane toward a desired position, the disturbance rejection module will achieve the dual objectives of positioning and disturbance rejection. Further- more, because Vs is an input-shaped command, motion-induced oscillations of the payload will be reduced. In this way, the controller eliminates motion-induced oscillations, rejects disturbances, and enables precise positioning.

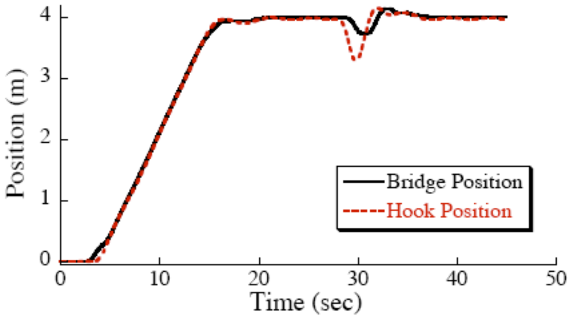


Figure 18. Bridge and payload response to a move followed by a disturbance

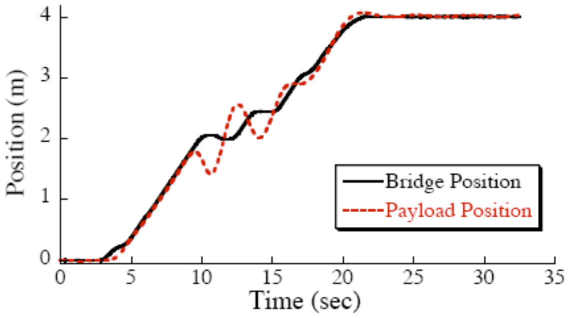


Figure 19. Response to a disturbance during motion

The control system was implemented and tested on the 10-ton bridge crane. Figure 18 shows the response when the crane was moved to a desired location. After coming to rest, an external disturbance was applied. The shaped velocity signals of the positioning controller prevented motion-induced oscillations of the payload, while also driving the crane precisely to the desired location. When the external disturbance was introduced at approxi- mately 30 sec, the control system eliminated the disruptive oscillations and returned the payload to the desired position. The control system can also suppress disturbances while the crane is in motion. Figure 19 shows a case when the crane again moved 4 m, but an external disturbance was applied half way through the intended move. Again, the control system prevented motion-induced oscillations, re- jected the disturbance, and precisely positioned the payload.

6. CRANE-BASED CURRICULUM

To integrate crane-based examples and problems into the curriculum in a constructive manner, one should consider how the educational paradigm moves students through the learning process. Interesting and illustrative demonstrations can push the students past Familiarity towards Understanding. However, requiring students to implement what they learn on realistic simulations, or better yet, on real physical hardware, will give them an Ability to Apply the technology. If the students apply the technology in several different situations and are required to make their own modifications and advancements to the technology, then they may even achieve an Ability to Innovate. Over the past 6 years, Georgia Tech has developed a crane-based curriculum to improve system dynamics and controls courses. Both the large and small-scale cranes have been equipped with advanced control algorithms and operator interfaces that allow students to easily conduct experiments. These learning tools supplement homework and lecture material with interactive and real-world examples of system dynamics, flexibility, and control techniques.

The cranes have been used in numerous courses. Many of the courses have term projects that require the students to conduct self-developed experiments on the cranes. During the fall of 2005, Georgia Tech and Tokyo Tech students worked together on their final projects. For example, a team of students in Tokyo collected dynamic responses of the portable tower crane under various operating conditions. Georgia Tech students collected similar data for the portable bridge crane. These two teams then compared and contrasted the dynamic properties of the two cranes. These projects were not only successful educational endeavors, they produced valuable research results; three of the projects were presented at international conferences.

6.1 Lab Descriptions

This section describes the laboratory exercises that were developed in conjunction with the portable tower crane. Two parallel courses at Georgia Tech and Tokyo Tech used the portable cranes during the fall of 2005. The Georgia Tech students primarily used the bridge crane in Atlanta with a lab sequence. The Tokyo Tech students primarily used the tower crane in Japan with a lab sequence described below. The students used the cranes in three ways: to perform labs, to conduct and participate in a remote manipulation study, and to collect data for their final projects. Because the two courses were taught in parallel, the U.S. and Japanese students had the opportunity to collaborate on the final projects.

Labs 1 and 2 Goals:

- Acquaint students with the equipment.
- Explore the oscillatory properties of the tower crane.

Tasks: A simple point-to-point move is programmed into the PLC. The students measure the motor response with encoders and with visual observation. The distance, velocity, acceleration, and suspension length are changed to show how these variables effect the dynamic response.

Results: Increasing the rise time causes a sluggish motor response. However, this makes the payload oscillate less. Distance, velocity, acceleration, and suspension length have a complex effect on the oscillation amplitude.

Labs 3 and 4 Goals:

- Students learn to design and implement input shapers.
- Students understand the strengths and weaknesses of input shaping and also understand the limitations of the underlying theory.

Tasks: Use input shaping to move the tower crane in point- to-point motion. Many of the trials from labs 1 and 2 are repeated, except with input shaping applied to the command.

Results: Students learn about the strengths and weaknesses of different kinds of input shapers.

Lab 5 Goals:

- Students learn about path planning and automation.

Tasks: Students automate the crane motion to move the payload through an obstacle course. Students compete to develop the best commands for moving in the shortest amount of time and with the fewest number of collisions. Figure 20 shows the obstacle course along with typical trolley and payload responses generated by the students. Results: Students learning about the complex interaction of path planning, command shaping, and feedback control.

Lab 6 Goals:

- U.S. and Japanese students work in teams to complete a final project.

Tasks: Students were given the option of choosing one of three projects:

1) Consider a crane where the trolley accelerates up to speed faster (or slower) than it can brake. Test a new input shaper developed for this system and develop an improved version of the shaper if possible.

2) Both tower and bridge cranes are governed by nonlin- ear dynamics. Given the equations of motion, verify these nonlinear dynamics and develop controllers that compensate for these nonlinearities.

3) Explore remote operation of tower and bridge cranes. Perform studies to test the effectiveness of input shaping when used to remotely control cranes.

Results: Students completed complex projects and pre sented their results at international conferences.

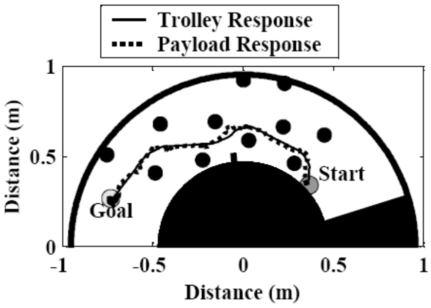


Figure 20. Student data from Lab 5

7. CONCLUSION

Crane oscillations can be greatly reduced by properly shaping the commands issued to the motors. Three cranes were constructed at G. Tech and equipped with input-shaping controllers, as well as feedback controllers that use vision systems to measure the payload motion. Studies demonstrated the compatibility of the control system with human operators. The three cranes have been integrated into the engineering curriculum at Georgia Tech and several other universities. This has allowed students to conduct experiments on oscillation control and tele-operation. The hands-on experiences gained by the students have allowed them to innovate in the area of oscillation control and produce useful research results.

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