Whitepaper
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Sway Control Technology and Its Application for Overhead Traveling Cranes

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Material Handling

Overhead cranes and gantry cranes occupy a crucial role within industry. They are used throughout the world in thousands of factories, steel mills, foundries, ship yards, warehouses, nuclear power plants, waste recycling facilities and other industrial complexes.

In many manufacturing operations, operator controlled cranes account for as much as 20% of the production cycle. Material handling engineers have long sought systems to dampen loads and improve load spotting as a way to improve production throughput and operational safety.

Even experienced crane operators have difficulty controlling load sway. Furthermore, the trend in industry is to remove the operator from the crane cab in order to free him up to perform other functions, to have less experienced workers at each work station hitch and independently move their loads, or to automate the handling system and eliminate manual operation entirely.

In this paper, we will examine the problems of controlling load sway as well as the various methods that can be employed to control sway.

Dynamics of Load Sway

A typical overhead crane is a 3-axis machine having a bridge (X-axis), trolley (Y-axis) and hoist (Z-axis) as shown in Figure 1. The load is suspended from a moveable trolley by means of cables, and behaves much like a pure pendulum.

Figure 1 illustrates bi-axial swing of the load caused by simultaneous motion of both trolley and bridge. When displaced to an initial angle and released, the pendulum will swing back and forth with periodic motion until dampened by gravity or other external forces.

The time it takes for a pendulum to make one complete swing is called the period of the pendulum.

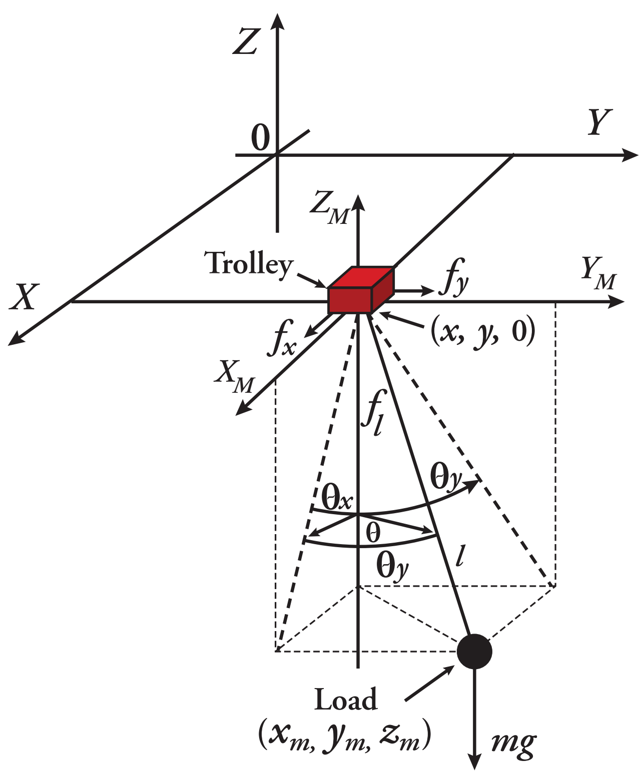

Figure 1[i]

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The period of a pendulum is independent of its mass and angle of displacement. It is dependent on its length and can be represented by this simplified expression:

$$T = 2\pi\sqrt{\frac{\ell}{g}}$$

Where:
T = period of pendulum
l = distance from holding drum to center of gravity of load
g = force of gravity

Under certain conditions, such as when long slings or a lifting attachment are used, the pendulum dynamics become complicated by the creation of a double pendulum effect.

A sway control system can be developed if the following variables are known:

- Acceleration rate of the trolley or angular displacement of the load caused by the trolley motion
- Acceleration rate of the bridge or angular displacement of the load caused by the bridge motion
- Distance to the center of gravity of the load (L1) plus the C.G. Offset (L2) to compensate for slings, attachments or large loads.

Passive Methods of Sway Control

Crane Operator

The typical crane operator has several ways to control a swinging load. One is to position the load exactly over the target position, then wait until the sway dampens to an acceptable level. Another option is to pick up the load and move at a rate at which sway never occurs. Both methods are feasible but are inefficient and slow down production.

Some experienced crane operators are known for their ability to manually place delicate loads on a dime and control load sway using only standard operator control switches and certain techniques. They frequently "plug", i.e. rapidly reverse bridge and trolley motors to develop a counter-torque that slows or even stops a crane. In addition, a drift point is often used on the motion master to release the electric brake, thus permitting the bridge or trolley to 'coast' until retarded by friction or the foot brake.

Highly skilled, experienced crane operators counter sway by driving into the swing to dampen it. After picking up the load, the operator starts the crane, slowly at first, to judge how the load sways. If the crane operator momentarily stops or slows the crane and waits for the load to swing forward, he can again start the crane moving at the same speed as the load at the moment that the load is directly under the trolley. The operator repeats this maneuver as needed until achieving the maximum desired speed.

Getting closer to the target position, the operator reduces speed, drifts, or even applies negative power to brake (Reverse-Plug) and, as such, induces a forward sway. As the load nears the target position, the operator increases speed slightly so as to position the load point on the trolley over the target position with little sway. These complicated load control maneuvers, often referred to as "catching the load," depend on both the skill of the operator and on the speed and acceleration of the crane.

The performance of individual crane operators varies and success in controlling sway not only depends upon individual skill but the responsiveness of the crane's control system. Controlling sway manually always adds to the theoretical cycle time, slowing down production.

Mechanical Guides

A structural frame, mounted on the underside of the crane, is typically used in conjunction with some type of guided load bar or lifting device to limit sway and assist in positioning. This type of mechanism is typically used in dipping operations. However, the guides and guiding mechanisms are expensive, add weight to the crane, and impose a bending moment on the crane structure.

Anti-Sway Reeving

Various anti-sway reeving systems have been developed to stabilize loads. They are commonly used on container handling cranes. Most involve diagonal reeving and some type of spreader bar. These systems tend to be complex, require additional headroom, as well as more maintenance. They also tend to be more expensive than most electronic means of sway control.

Electronic Methods of Sway Control

Closed Loop with Optical or Inertial Feedback

Optical anti-sway systems are closed loop and typically include feedback from a high resolution "Load Position Sensor" consisting of a camera mounted on the trolley and a reflector target mounted on the load block or spreader. The camera records images directly beneath the camera including the position of the target. From these images, the relative position of the load to the trolley can be determined by an image processor and then fed back to the sway controller.

These systems correct for actual sway in real time and, unlike open loop systems, can correct for existing initial sway and sway induced by external forces such as wind or picking an off-center load. However, feedback systems like this tend to be somewhat slow since they are reactive rather than anticipatory. They are also more costly, due to the expensive cameras, defoggers, complicated reflector mechanisms, high-intensity lights and image processors needed to determine sway.

Other closed loop electronic systems may use inertial feedback from accelerometers and/or gyroscopes to measure sway.

Open Loop

In open loop systems, the anti-sway control uses an algorithm that dampens load sway by controlling the acceleration and deceleration of the bridge and/or trolley motions through the crane's adjustable frequency drive (AFD) motion controllers.

Most sway control systems use technology patented by Massachusetts Institute of Technology (MIT) and marketed by Convolve, Inc. called Input Shaping™ (a.k.a. Command Shaping). Further study and testing of this concept has been conducted at the Manufacturing Research Center of Georgia Technical Institute.

Input Shaping™ alters the output frequency of the adjustable frequency drive to dampen out the harmonics of the system. It simply modifies the command signal to the system so that all moves, regardless of length, are sway free. Input shaping does not require the feedback mechanisms of closed loop controllers. Instead, the control reduces oscillations in an *anticipatory* manner, as opposed to the *reactive* closed loop manner. Oscillation suppression is accomplished with a reference signal that anticipates the error before it occurs, rather than with a correcting signal that attempts to restore deviations back to a reference signal. In the context of crane control, this means that sensing the actual sway angle is not necessary.

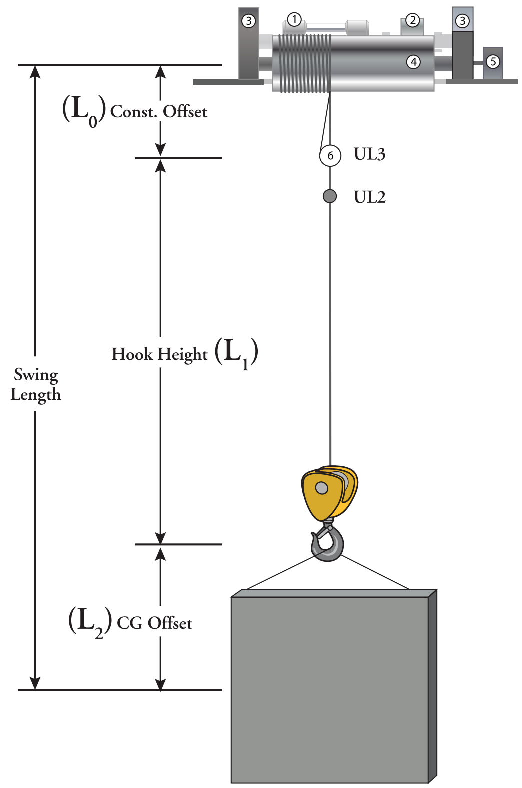


Figure 2

The software model of the sway controller samples data many times per second to ensure smooth continuous control. The scheme is similar to that used by an experienced crane operator, i.e. the crane is accelerated to bring the load into motion, an almost constant speed is maintained for a short interval to allow the load to catch up, and the process repeats several times until the commanded speed is achieved without sway. The crane is decelerated and stopped in a similar fashion. (See Performance Curves)

As noted in the Dynamics of Load Sway section, sway can be controlled if the acceleration/deceleration forces plus the swing length of the pendulum arm (distance to the center of gravity of load) are known.

The acceleration/deceleration rates and velocities can be obtained from the respective motion AFD.

The ***Hook Height (L_1)*** can be obtained by various means:

- Preprogrammed, which requires raising the load to a predetermined height before moving (commonly used in so called "sensor-less" systems)
- Manual input from a selector switch providing two or three height settings
- Automatic input from a hoist geared limit switch providing two or three height settings
- Automatic input from an absolute encoder utilizing a spring-loaded spool and flexible cable attached to the load block to precisely measure vertical position. ("Monkey-On-A-String")
- Automatic input from an incremental encoder on the hoist motor.

The ***optional CG Offset (L_2)*** is a variable that depends on the geometry of the load and attachments. It allows for operator input from separate toggle or selector switches, each having preprogrammed values. An analog signal may also be used for variable sling length adjustment.

The ***total calculated swing length*** is the sum of a preprogrammed Constant Offset (L_0) (distance from center of drum to upper limit switch) plus the Hook Height (L_1) plus the CG Offset (L_2). This value should be within 10% of the actual height for optimal performance.

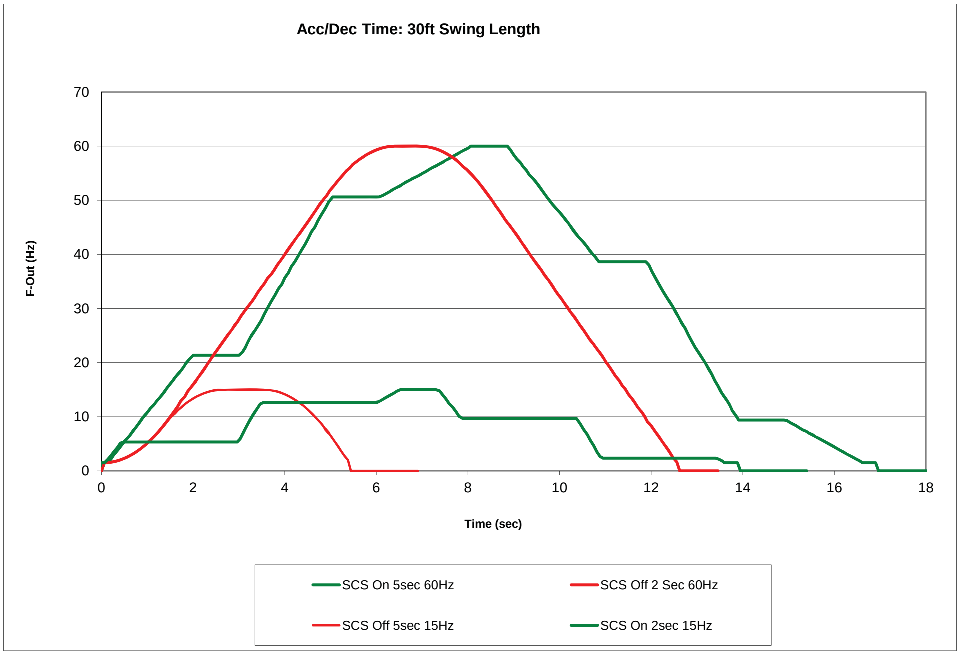
The anti-sway software can reside on either a separate computer, programmable logic controller (PLC), or special control module, or preferably be embedded into the software of an adjustable frequency drive. It shares and exchanges data with the AFD many times per second, and responds to operator commands in real time by instantly translating these commands into carefully timed acceleration/deceleration patterns.

Two profiles are shown in the graph below, one for high speed operation, the other for slow speed. The red lines represent the variable speed drive ramps without anti-sway. The green lines represent the anti-sway function and illustrate how the acceleration or deceleration profile is automatically adjusted in real time. Although only two changes in speed/time profiles are shown, an infinite number are possible.

Limitations

Both open loop and closed loop anti-sway systems insert one or more hesitations in the slowing process as shown in the preceeding graph. Given this it will take slightly longer to come to a stop and the crane and trolley will travel a bit longer before stopping. This means that the operator will need to begin slowing or release the control master a little earlier than usual. Some crane operators may find this disconcerting and

Performance Curves



may require additional practice and training.

The motion illustrated by the stair-step speed/time profile shown on the graph may induce a motion sickness affect on some operators of cab controlled cranes. This can normally be mitigated by fine tuning the aggressiveness of the sway control acceleration/deceleration settings.

Open loop systems have some limitations. They do not compensate for an already swinging load or swing induced by wind or picking an unbalanced or eccentric load and can only be enabled when the motor is not spinning.

Selecting an Open Loop Sway Control System (SCS)

Most open loop sway control systems on the market today are based on the dynamics of a simple pendulum and dampen load sway using algorithms that continually adjust the acceleration/deceleration profiles of bridge and trolley adjustable frequency drives.

When selecting a sway control system (SCS), consideration should be given to those systems that provide the crane user with the ultimate in safety, functionality, simplicity, flexibility and efficiency.

Optimal sway control can be achieved through a SCS that operates without the need for an external programmable logic controller (PLC), control module, or supplemental option card which can potentially reduce reliability and add cost. High maintenance feedback devices such as an absolute encoder should not be required. Ideally the system is able to work with multiple hoists on the same bridge. For new applications, it is desirable to embed the sway control system in the motion's adjustable frequency drive, such as Magnetek's IMPULSE®•G+ Series 4. Easy adaptation into existing drives for retrofit applications or automation using optional firmware is also optimal. The SCS should be equally effective in controlling sway in Voltz/Hertz, Open Loop Vector and Closed Loop control methods.

Another desirable feature in an SCS is the ability to define operating hook height "zones" by accepting hook height inputs from operator controlled toggle/selector switches or limit switches – or permit automatic height input from an incremental encoder on the hoist motor which allows an operator to move the crane with the load at any height, even while raising or lowering. Optional inputs for fine tuning the pendulum length when using multiple below the hook attachments or to compensate for varying load sizes also increases efficiency.

Also important is seamless integration with special functions within AFDs such as fine speed control, end of travel slow down and stop limits, and functions that allow for smooth stopping and direction changes without setting the parking brake. The control should be compatible with existing master switch and radio control configurations such as Multi-step and Stepless Uni-Polar/Bi-Polar analog.

Finally, a sway control system should be easy to install and configure without the need to have an engineer on-site to tune the system.

Conclusion

A sway control system (SCS) can improve productivity by allowing the crane operator to concentrate on load engagement/disengagement rather than focusing on minimizing load swing. An SCS can also improve the accuracy of load placement and reduce material damage caused by incidental contact of swinging loads.

A properly designed and adjusted sway control system can reduce load sway by 85 to 95% thus reducing the risk of damage and personal injury. A crane with sway control allows an operator to use full speed commands for all movements, resulting in shorter cycle times. Field tests have demonstrated that sway control improves productivity by 25 to 50%, plus reduces operator fatigue and the need for extensive operator training.

Sway control improves throughput in automated handling systems by allowing higher operating speeds and faster acceleration and deceleration rates than would be possible with a manually controlled system. A fully automated system controls the load, prevents dangerous sway at every phase, and stops the load precisely at the target, every time.

Closed loop systems are best utilized on high cycle outdoor systems such as container cranes that are subject to external influences such as wind, thereby justifying the higher initial cost and maintenance expense.

Open loop systems have a decided economic advantage over mechanical means, and closed loop systems with feedback and are best applied in industrial applications where wind and external influences may be of less significance.

[i] Cho, Sung-Kun, and Ho-Hoon Lee. "An Anti-Swing Control of a 3-Dimensional Overhead Crane." *Proceedings of the American Control Conference, Chicago, IL June 2000.* Print.