DYNAMIC DAMPING OF PAYLOAD MOTION FOR CRANES

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ABSTRACT: The paper describes a novel strategy for damping of payload motion for various kinds of cranes used in construction, i.e., mobile cranes, boom or tower cranes and so forth, which can be implemented on existing equipment. Most research in this area concentrates on controlling the velocity and accelerations to eliminate inertial forces. However, it is almost impossible to realistically model the effects of wind, slippage of tires, or settlement of supports, etc. The research proposes an approach to control the swaying of the payload, regardless of the cause. The control strategy is based on applying periodic balancing forces and moments to the cable to damp out oscillations as and when detected. A feedback control system applied to the cable has the potential of providing an inexpensive and easily implemented solution. This is achieved by decoupling the payload and cable system from the structural members of the crane during the development of the control strategy. Effective control of the payload will improve safety, productivity and timeliness for a number of material handling operations.

INTRODUCTION

Cranes constitute a significant class of material handling equipment used for construction projects. Crane safety is a major issue in construction, and improved safety can improve the performance and increase the overall efficiency of the construction process.

Among the various types of cranes found in construction, mobile cranes are more prone to severe effects of dynamic loading (Patten 1980; Finn 1982). A major cause of crane related accidents is overturning, caused by an unbalanced dynamic condition resulting in a tipping moment. Accidents are also caused by uncontrolled swaying of the payload resulting in damaging impacts with other objects in a cluttered environment. There are several dynamic effects that acting singly or in combination can contribute to this condition.

The construction industry has been slow in implementing advanced technology to improve safety. Current practice requires that control of the crane's dynamic behavior is the responsibility of a skilled operator ("Trust" 1990). The operator applies corrective measures based on experience when any undesirable swaying is detected. The absence of automated sensing and control not only leave room for accidents arising because of human error and/or a delayed response from the operator, but also can greatly reduce the productivity of the operation. There is also a potential danger of an exaggerated response, which will lead to an uncontrollable load swing.

The biggest source of dynamic forces is the pendulum motion of the payload suspended by a cable. When the direction of motion is altered,

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residual vibration from earlier motion compounds the problem. Control of the sway of the payload can result in greatly improved safety.

The deflection and velocity of the hoist cable from vertical is a measure of the dynamic forces acting on the crane, which may result in the overturning moment being increased, either momentarily or for considerable periods. Dynamic forces arise due to the swinging of the load, an outward radial displacement of the load, centrifugal forces, the crane being out of level, and other miscellaneous factors. Typical factors that cause these behaviors are movement (accelerations) of the crane, slipping or settlement of the anchored base or tires due to loose soil conditions, vibrations along the crane boom, short duration wind gusts, and so forth.

PRIOR WORK

Several researchers have studied forces and dynamic responses of cranes and have developed control strategies to damp the load swing. Eden et al. (1985) analyzed the static and dynamic factors that contribute to a reduction in mobile crane stability. Ito et al. examined the dynamic behavior of a load lifted by a mobile crane during boom hoisting as well as during boom hoisting and lowering performed at the same time (Ito et al. 1978) and also studied dynamic stability of a truck crane carrier (Ito et al. 1985).

Information received from Epoch Engineering Incorporated ("Antipendulation" 1992) reveals that initial attempts to develop swing-free control strategies started in the late 1970s. Robert F. Cecce first designed an antipendulation crane. Although satisfactory results can be obtained through his approach, the implementation does not appear to be practical and will require major rework for existing cranes.

Patton (1980) developed an analytical model for a crawler crane. The model allows for translation and rotation of the crane base, pendulation of the load, rotation of the boom, and nonlinear elastic backstays. Finn (1982) developed a simplified model. Because of its simplicity, Finn's model provides an opportunity to add auxiliary devices to the crane with comparative ease.

Moustafa and Ebeid (1988) developed a nonlinear dynamic model for an overhead crane. An anti-swing control system that uses feedback control to specify the crane speed at every moment was also developed. Sakawa and Sato (1989) derived a dynamic model for the control of a flexible rotary crane. Hara et al. (1989) researched the simulation of a jib crane control strategy that transfers a load under the condition of suppressing the load swing both in the transfer process and at the objective position, making the transfer time as short as possible. This work was restricted to the extending or shrinking motion of the boom, which causes the load to swing.

Starr (1985) presented a method for transporting suspended objects with a path-controlled robotic manipulator such that the objects are stationary at the end of the motion. Jones and Patterson (Jones and Patterson 1988) presented the mathematics describing oscillation damped trajectories for simply suspended payloads using controlled acceleration. However, their control strategy is intended for robot manipulators, and application is limited to overhead cranes.

Ridout (1989) discussed several commercially available and alternative closed loop overhead crane control systems. Caron et al. (1990) presented a control methodology for overhead cranes, taking into account the length variations of the load suspension cable. The work done by Shimoyama and

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Oppenheim (1990), and Petrosky and Oppenheim (1988), focused on control of manipulators, and the counteracting of a specific path or motion.

The Robot Systems Division of the National Institute of Standards and Technology (NIST) utilized the basic concept of the Stewart platform parallel link manipulator for robot cranes (Albus and Goodwin 1992). The unique feature of the NIST approach is to use cables as parallel links and winches as the actuators. The implementation is limited to designing custom built cranes. Implementations for existing cranes used for typical construction operations does not appear to be a practical option.

The review of existing literature discussed reveals that several control systems to damp the swing of the load have been successfully applied to overhead cranes. These control strategies are based on control over accelerations of the crane members and adjustment of the length of the load hoist cable.

For mobile cranes, the swaying of the load is caused by a variety of factors, both predictable and unpredictable. The existence of unpredictable variables in the dynamic response of the load complicates the problem. Control based on manipulating accelerations is difficult to implement. Hence, control strategies applied to overhead cranes are inadequate for mobile cranes.

Currently, little quantitative information is available to accurately predict the effects caused by slipping of the wheels, action of wind and structural vibrations of the crane itself. Hence, an attempt to control the payload swing at the cable, independent of the cause of excitation would result in better control.

This paper describes a continuous real-time control strategy to respond to adverse effects of predictable and unpredictable forces. The control strategy is based on sensing the dynamic response at the load hoist cable, and applying periodic balancing forces and moments to the cable to damp the oscillation of the load, as and when detected, regardless of the cause of excitation.

MOTIVATION

The construction industry has been slow in implementing automation, compared to the manufacturing industry. A major reason for this is that technologies typically used for manufacturing and robotics are often unsuitable for the construction process, either because of difficulties in implementation or cost considerations. The construction site is an ill-structured environment and it is often impossible to accurately predict all factors that would affect a designed sequence of operations. Other significant factors are large payloads, which cause significant structural deformations of material handling equipment parts and environmental factors such as dust and rain.

Hence, to successfully implement any automated system in the construction industry, it is of vital importance that the system should be capable of handling unforeseen circumstances. Ease of implementation is also a major issue.

At present, most construction processes rely heavily on human expertise and experience to successfully and efficiently perform a specified task. This is a potential hazard in heavy construction where human error or a delay in operator response to any undesirable occurrence may result in a serious accident. Also, nonavailability of skilled staff for a particular operation can cause delays. Increased automation would improve the performance of construction projects in terms of safety, productivity, and timeliness.

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The use of cranes for material handling is a typical operation that is affected by the factors just described. Undesirable sway of the payload can result in serious accidents during crane operations. However, currently, the industry relies mainly on operator expertise to control the crane's dynamic behavior. The operator, based on past expertise, tries to take the necessary actions that keep the sway of the payload to a minimum.

It is because crane safety and stability are such important issues confronting the construction industry that there is a need to introduce a control strategy to control the dynamic effects on the crane due to swinging suspended loads.

Control of payload oscillation for mobile cranes is a complex problem. It is difficult to control accelerations of crane members to damp the swaying of load. Also, it is not possible to control the dynamic behavior caused by wind forces, slipping of tires, and so forth, by controlling accelerations. Hence, strategies used for damping oscillations for overhead cranes are not adequate for mobile cranes.

The dynamic behavior of the payload is a complex nonlinear dynamical problem, especially for mobile cranes. The dynamic response to the slipping of tires, bumps in the road, and so forth cannot be accurately predicted. Hence, a control strategy based on controlling accelerations of crane members to eliminate payload oscillations does not always provide an effective solution. Also, such strategies are difficult to implement on existing equipment.

There is a need for a control strategy that aims at controlling payload oscillations, regardless of the cause of excitation. This can be done in a simple, straightforward manner if the oscillations of the payload can be detected and controlled at the hoist cable.

The aforementioned problem can be better solved if the payload and cable are considered as a decoupled system during the development of a control strategy. An automatic feedback control system that monitors payload excitation and exerts the necessary controlling forces to damp the oscillation has the potential for providing a solution.

By applying balancing forces and moments to the hoist cable, it is possible to control more easily and effectively the swaying of load. This paper presents a strategy to control payload oscillations of mobile cranes.

DESCRIPTION

Overturning is the single major cause for mobile crane related accidents (Eden et al. 1985). A crane overturn condition occurs when a tipping moment greater than the restoring moment is applied for an adequate duration of time. There are, however, a number of dynamic responses that acting singly or more often in combination, can contribute to this condition.

The deflection of the hoist cable from the vertical is a measure of the dynamic forces acting on the crane, which may result in the overturning moment being increased either momentarily or for considerable periods. Factors that may be responsible for dynamic behavior of the payload are swinging of the load (caused by a variety of factors, predictable and unpredictable), outward radial displacements of the load, centrifugal force, crane out of level, and action of wind.

The effects of the contributing factors often cause crane related accidents. Some of these factors can be predicted, but others are unknown variables that cannot be measured or predicted. Hence a control strategy is required that utilizes a feedback control system and actuators to minimize the dynamic response of the crane to the aforementioned forces. Such a continuous, real-time controller will respond to the dynamic effects, which might otherwise cause the crane to overturn, or induce large stresses in the crane components.

The control strategy proposed is to apply balancing forces to the hoist cable whenever any oscillations are detected. The actuator must be capable of applying variable forces in the plane perpendicular to the cable. Real-time information of cable length, cable strain, and accelerations at the tip of the boom need to be known to achieve proper control.

The proposed control system would consist of a yoke around the load hoist cable, suspended from the boom. The yoke will be free to sway along with the cable. Pistons controlled by actuators will apply the controlling force on the periphery of the yoke, in the horizontal plane. Fig. 1 illustrates the conceptual design of the system.

As shown in Fig. 1, the yoke will encompass the load hoist cable and move with it. The cable is, however, free to move up and down through the yoke over pulleys. A flexible sleeve will cover the cable at the point of contact, which will avoid potential damage to the cable because of shear forces and stress concentration whenever a controlling force is applied.

A sensor placed at the yoke will receive the feedback data about the strain, cable length, and 3-D accelerations at the boom tip. Four pistons mounted around the yoke will exert the proper forces to the yoke, which will be transmitted to the load hoist cable to damp the swing. Fig. 2 illustrates the proposed arrangement of the system. Two hydraulic cylinders will anchor the piston assembly to the boom such that the pistons are always in the horizontal plane. These cylinders will adjust themselves based on information obtained through lean and tilt sensors, as the boom leans or tilts.

There are two different ways to measure the weight suspended by the crane cable. In the first method, an in-line load cell or a strain-gaged shackle is installed at the end of the cable. A battery powered A-D converter will be used to digitize the data, and the data will be sent through the cable as vibrations in a binary stream to the control device on the yoke. This method of data transmission has been successfully used in the drilling industry to

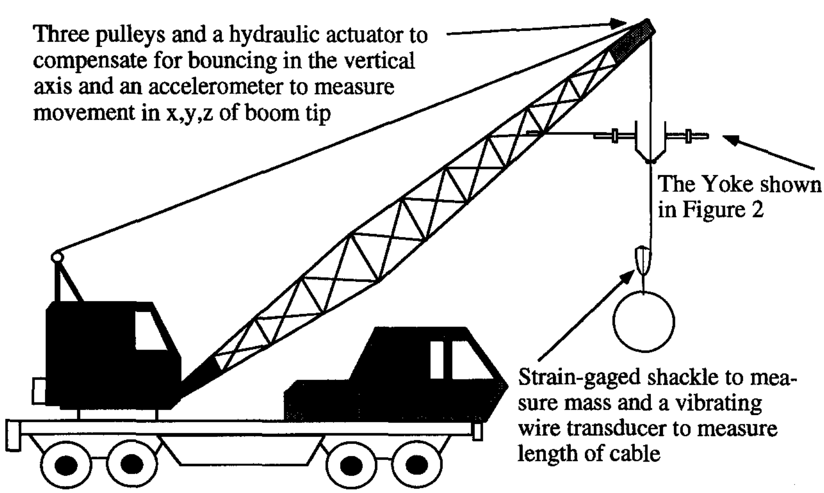

FIG. 1. Conceptual Design of System

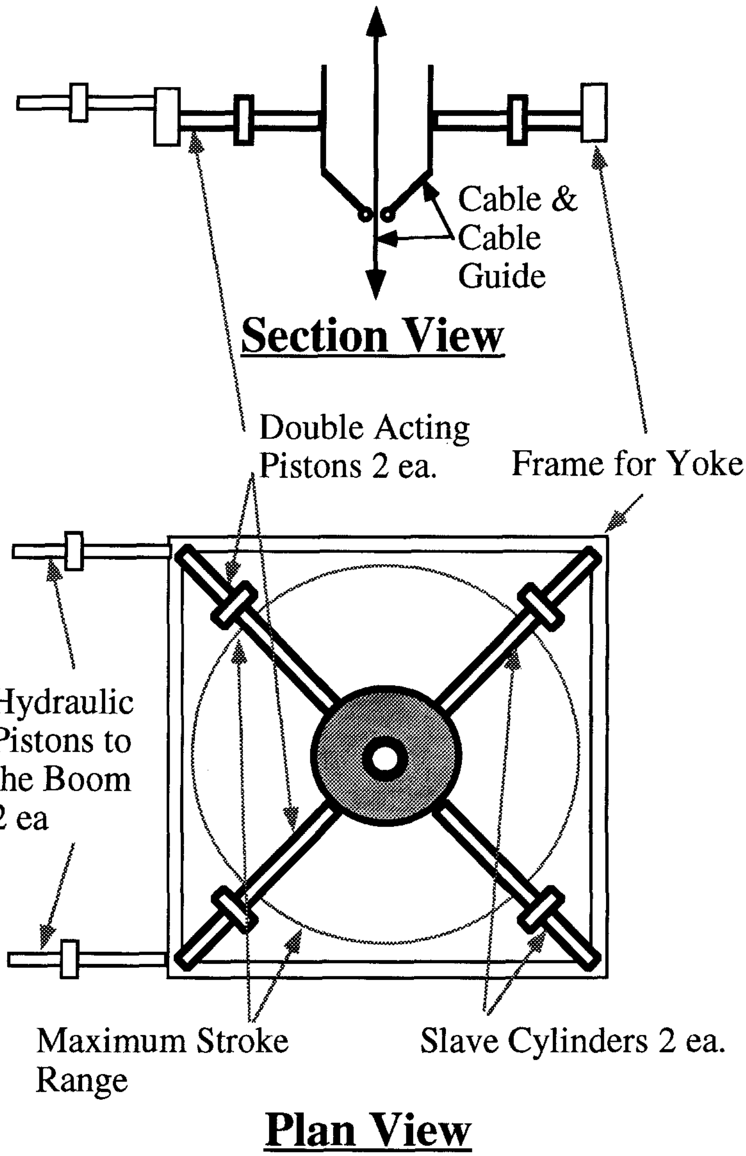

FIG. 2. Yoke Assembly

transmit data collected from test devices deep underground through the drill rods to the drill rig on the ground surface. The second method will rely on pressure measurement in the upper hydraulic cylinder. With knowledge of this pressure and the length of cable unreeled, the weight suspended by the cable can be determined either analytically or experimentally.

There are also two different methods that can be used to determine the length of the cable unreeled at any time. In the first method, the cable drum is encoded by magnets. A hall effect transducer would be installed at a fixed location adjacent to the drum to sense the passing magnets. This type of arrangement has been successfully used at Virginia Tech to measure line unreeling from drums (Martin 1989) and also to measure positions of flywheels in vibratory compactors (Filz 1992). The second method would use the same principle as the vibrating wire transducer. If the weight of the load suspended by the cable is known, measuring the frequency of the cable would allow its length to be calculated. It is anticipated that the cable will be "plucked" with an electromagnetic system, and the resulting frequency will be measured.

A 3-D accelerometer located at the tip of the boom will transmit information about the accelerations of the boom tip in the x-, y-, and z-directions. To eliminate the bouncing of the load in the z-direction, three pulleys and an actuator will be added to thread the load hoist cable. This will provide the necessary balance to negate the effects of the movement in the z-direction at the tip of the boom. The location of this three-pulley system or other length adjustment system can be determined experimentally, based on strength requirements and response considerations. The system design is simple and allows for implementation on existing cranes with minimal effort and cost.

DEVELOPMENT OF DYNAMIC MODEL

A mathematical model for the dynamic behavior will be the basis for the control strategy and the subsequent development of a suitable control model. The problem can be modeled in 3-D coordinates to analyze the effects of the force applied to the cable at the yoke by the hydraulic pistons. When such a force is applied, the cable and payload system essentially behaves as a simple pendulum with two pivots, a fixed pivot at the boom tip and a moving pivot at the yoke.

Knowing the load, the variables in the system are the accelerations at the boom tip, the length of the cable, the tension in the cable, and the external force applied at the piston. The differential equations of motion for this system can be established. These can then be solved for the external force that will damp the oscillations.

That part of the cable below the yoke and the load may be considered as a simple pendulum with a moving pivot. The acceleration of this pivot is controlled by the external force applied by the hydraulic pistons. A mathematical model that validates the proposed strategy is described next. For the derivation of this model, coupling forces between the hoist cable and the boom, the crane body and soil foundation are not considered. This assumption is consistent with the design intent. The following assumptions are made for the model:

- The load is regarded as a point mass.
- The dynamics of the boom, crane body and soil foundation are not considered.
- Load hoist cable is extensional, and dl/dt term is included in the equations.
- For small displacements, $\sin \theta \approx \theta$, and $\cos \theta \approx 1$.
- No damping is assumed for the current model. However, after evaluating the test results, an appropriate damping coefficient(s), ξ, will be determined. This coefficient will be multiplied with the velocity vectors for the derivation of equations of motion.

As depicted in Fig. 3 (x, y, and z) are the coordinates of the pivot. $\hat{\imath}$, $\hat{\jmath}$, $\hat{k}$ frame has the same orientation as $\hat{x}$, $\hat{y}$, $\hat{z}$ if the pivot does not rotate, as assumed here.

The position of the load in space can be expressed as:

$$\mathbf{r} = (x - 1 \sin \theta \sin \phi)\hat{\imath} + (y + 1 \sin \theta \cos \phi)\hat{\jmath} + (z + 1 \cos \theta)\hat{k} \quad \ldots (1)$$

The velocity and acceleration expressions can be derived from the position expression as follows:

$$\frac{d}{dt}(\mathbf{r}) = \mathbf{v} \text{ (velocity)}$$

$$= (\dot{x} - \dot{1} \sin \theta \sin \phi - 1 \cos \theta \sin \phi\dot{\theta} - 1 \sin \theta \cos \phi\dot{\phi})\hat{\imath}$$

$$+ (\dot{y} + \dot{1} \sin \theta \cos \phi + 1 \cos \theta \cos \phi\dot{\theta} - 1 \sin \theta \sin \phi\dot{\phi})\hat{\jmath}$$

$$+ (\dot{z} + \dot{1} \cos \theta - 1 \sin \dot{\theta})\hat{k} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2a)$$

$$\frac{d^2}{dt^2}(\mathbf{r}) = \mathbf{a} \text{ (acceleration)}$$

$$= (\ddot{x} - \ddot{1} \sin \theta \sin \phi + 1 \sin \theta \sin \phi\dot{\theta}^2 - 21 \cos \theta \cos \phi\dot{\theta}\dot{\phi}$$

$$+ 1 \sin \theta \sin \phi\dot{\phi}^2 - 1 \cos \theta \sin \phi\ddot{\theta} - 1 \sin \theta \cos \phi\ddot{\phi})\hat{\imath}$$

$$+ (\dot{x} - \dot{1} \sin \theta \sin \phi - 1 \cos \theta \sin \phi\dot{\theta} - 1 \sin \theta \cos \phi\dot{\phi}) \frac{d\mathbf{i}}{dt}$$

$$+ (\ddot{y} + \ddot{1} \sin \theta \cos \phi - 1 \sin \theta \cos \phi\dot{\theta}^2 - 21 \cos \theta \sin \phi\dot{\theta}\dot{\phi}$$

$$- 1 \sin \theta \cos \phi\dot{\phi}^2 + 1 \cos \theta \cos \phi\ddot{\theta} - 1 \sin \theta \cos \phi\ddot{\phi})\hat{\jmath}$$

$$+ (\dot{y} + \dot{1} \sin \theta \cos \phi + 1 \cos \theta \cos \phi\dot{\theta} - 1 \sin \theta \sin \phi\dot{\phi}) \frac{d\mathbf{j}}{dt}$$

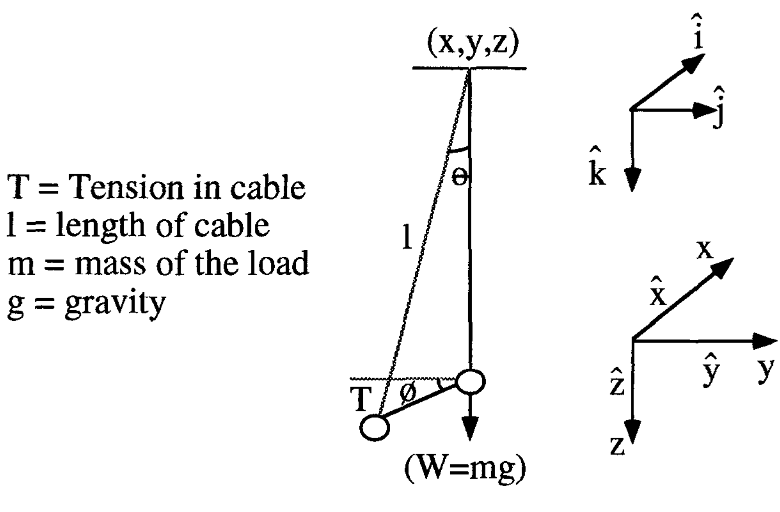

FIG. 3. **Diagrammatical Representation of Mathematical Model**

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$$+ (\ddot{z} + \ddot{l}\cos\theta - l\cos\theta\dot{\theta}^2 - l\sin\theta\ddot{\theta})\hat{k} + (\dot{z} + \dot{l}\cos\theta - l\sin\theta\dot{\theta})\frac{d\mathbf{k}}{dt} \quad (2b)$$

Terms with $d\mathbf{i}/dt$, $d\mathbf{j}/dt$, $d\mathbf{k}/dt$ are zero, because the pivot is assumed not to rotate. Therefore, if the pivot does not rotate:

$$\mathbf{a} = a_x\hat{\imath} + a_y\hat{\jmath} + a_z\hat{k} = a_x\hat{x} + a_y\hat{y} + a_z\hat{z} \quad (3)$$

$$a_x = \ddot{x} - \ddot{l}\sin\theta\sin\phi + l\sin\phi\dot{\theta}^2 - 2l\cos\theta\cos\phi\dot{\theta}\dot{\phi}$$
$$+ l\sin\theta\sin\phi\dot{\phi}^2 - l\cos\theta\sin\phi\ddot{\theta} - l\sin\theta\cos\phi\ddot{\phi} \quad (4a)$$

$$a_y = \ddot{y} + \ddot{l}\sin\theta\cos\phi - l\sin\theta\cos\phi\dot{\theta}^2 - 2l\cos\theta\sin\phi\dot{\theta}\dot{\phi}$$
$$- l\sin\theta\cos\phi\dot{\phi}^2 + l\cos\theta\cos\phi\ddot{\theta} - l\sin\theta\sin\phi\ddot{\phi} \quad (4b)$$

$$a_z = \ddot{z} + \ddot{l}\cos\theta - l\cos\theta\dot{\theta}^2 - l\sin\theta\ddot{\theta} \quad (4c)$$

Newton's law states that: $F_x = ma_x$; $F_y = ma_y$; $F_z = ma_z$ and here:

$$(F_x, F_y, F_z) = (T\sin\theta\sin\phi, -T\sin\theta\cos\phi, \text{mg} - T\cos\theta) \quad (5)$$

Hence the equations of motion can be expressed as:

$$m(\ddot{x} - \ddot{l}\sin\theta\sin\phi + l\sin\theta\sin\phi\dot{\theta}^2 - 2l\cos\theta\cos\phi\dot{\theta}\dot{\phi}$$
$$+ l\sin\theta\sin\phi\dot{\phi}^2 - l\cos\theta\sin\phi\ddot{\theta} - l\sin\theta\cos\phi\ddot{\phi})$$
$$- T\sin\theta\sin\phi = 0 \quad (6a)$$

$$m(\ddot{y} + \ddot{l}\sin\theta\cos\phi - l\sin\theta\cos\phi\dot{\theta}^2 - 2l\cos\theta\sin\phi\dot{\theta}\dot{\phi}$$
$$- l\sin\theta\cos\phi\dot{\phi}^2 + l\cos\theta\cos\phi\ddot{\theta} - l\sin\theta\sin\phi\ddot{\phi})$$
$$+ T\sin\theta\cos\phi = 0 \quad (6b)$$

$$m(\ddot{z} - l\cos\theta\dot{\theta}^2 - l\sin\theta\ddot{\theta}) - \text{mg} + T\cos\theta = 0 \quad (6c)$$

There is no closed form solution for this mathematical model. However, a Runge-Kutta scheme will be used to obtain a numerical solution.

A similar detailed and comprehensive mathematical model will be developed. This model will be used to generate the equations of motion. Knowing the load, the instantaneous acceleration, and length of the cable, and so forth, the instantaneous force that will damp the oscillations at the yoke are computed. This is the control force that needs to be applied at the yoke. At the final stage, control based on the distance through which the yoke needs to be moved will be easier to implement.

It is important to note that the coupling forces between the hoist cable and the boom, the crane body, and soil foundation are not considered for the current analysis. The model will be developed as a decoupled system, which would rely on sensors to detect excitation, and actuators to apply balancing forces, regardless of the cause of excitation. The decoupled system has the potential to yield satisfactory results. The model can be validated through subsequent experimental tests.

CONTROL ANALYSIS AND DESIGN

There are at least two stages in the analysis and design of controllers to improve crane performance. In the first stage, the control yoke will be used

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to stabilize the pendulation of the cable and load system, treating all disturbances, whether they come from flexure of the boom or from exogenous sources such as wind gusts, as equivalent. In this case, from the physical viewpoint, we will seek to control a pendulum by inducing a controlling motion at its point of support.

A careful distinction needs to be made between control of the linearized pendulum equations and control of the full nonlinear pendulum. It is well known (Struble 1962) that the latter may have multiple stable oscillations of differing amplitudes for a given oscillatory input. The design of control systems based on linearization about the nominal equilibrium point is predicated on the assumption that a good control will keep the system close to equilibrium and thereby make a nonlinear analysis unnecessary.

The proposed design is based on such a linearization. Two approaches can be used:

1. Controller design based on the linear quadratic optimal control approach (Russell 1979). This work will primarily consist of selecting appropriate weights to be applied to the state and control variables and use of standard packages, such as MATLAB, to compute the control feedback parameters and evaluate control performance as indicated by the mathematical model.
2. Controller design based on the H robust control design paradigm (Doyle et al. 1989). Here, this work will start with the control identified earlier and modify the controller design to achieve robustness with respect to parameters known to vary substantially in the context of industrial use, such as cable length, load mass, etc.

Testing of the preliminary linear design in a laboratory setting will determine any inadequacies vis a vis the actual nonlinear character of the control plant. If such inadequacies are noted, suitable nonlinear control procedures (Russell 1979; Lukes 1969) may be introduced in order to determine nonlinear feedback modifications to correct the controller design.

In the second stage design, a more comprehensive model involving both cable-load and boom dynamics, and their coupling to each other, can be used as a basis for the controller design. Decoupling procedures (Wonham 1974; Anderson et al. 1971), with a view to decouple the cable-load system from the boom to avoid unmanageable interactions between the two, may be of particular interest. An important part of subsequent research will be the development of an adequate model for lateral and torsional motions of the boom structure. The control design itself will combine the studies on decoupling with extension of the procedures described in connection with the first stage controller to this more comprehensive setting.

DEVELOPMENT OF CONTROL MODEL

The control strategy is simple, robust and effective, in keeping with the goal of having a readily implementable system that can be retrofitted to existing cranes. Once the dynamic model of the crane and load dynamics have been derived, a straightforward, yet flexible, controller will be implemented using off-the-shelf proportional-integral-derivative (PID) controllers that are the main stay of heavy-duty industrial control. Initial calculations indicate that all critical variables will be directly or indirectly measured.

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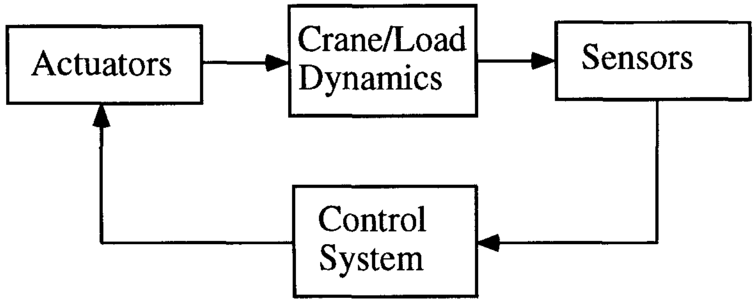

FIG. 4. General Feedback Configuration for Oscillation Damping

As a consequence, no elaborate signal conditioning appears to be necessary. Fig. 4 illustrates the generic feedback structure for controlling the system.

The signal path indicated as a single line between the various subblocks represents multiple parallel connections. For example, the signals sent from the *Sensors* block to the *Control System* block would effectively comprise eight signals:

- A "lean and tilt" sensor.
- A three-axis boom tip accelerometer (three signals).
- A shackle strain gage.
- A sensor to measure cable length.
- An accelerometer to measure both *x*- and *y*-axis accelerations of the yoke.

Similarly, the *Actuators* block of Fig. 4 involves four actuators:

- The hydraulic piston to control the cable tension.
- The lean and tilt actuator.
- The on- and off-axis yoke actuators.

After an initial design is made using standard control techniques, other design methods may be considered and compared to see if more sophisticated control is worthwhile. One such approach would be to use neural networks to identify the nonlinear dynamics of the plant (crane and load) as well as to construct an adaptive controller. The purpose of having an adaptive controller would be to ensure a certain degree of robustness to the system (i.e., insensitivity to inaccurate measurements, variation of crane and actuator parameters due to wear and weather effects).

SUMMARY

Crane safety is an extremely important issue in construction. Crane accidents due to overturning result in severe damage to the crane and other equipment and can endanger human lives. Crane operators are required to be highly skilled to reduce oscillations. A significant loss in productivity is also attributed to the inability to maintain a stable payload. Payload oscillations caused by dynamic forces during crane operation increase the overall tipping moment, and can be the root cause of crane failure. These oscillations may also result in the payload striking other objects in the environ-

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ment. The proposed control over payload oscillations will significantly improve the safety for crane operations.

The paper describes a conceptual design for controlling the oscillations of the payload for cranes. The research involves a novel concept of controlling oscillations at the cable from which the payload is suspended. The strategy proposed is simple and can be easily implemented on existing cranes.

The dynamic model described is a simple example to justify the proposed strategy. However, a much more complex model needs to be developed for actual implementation. This model will have to be experimentally validated. The control strategy evolved can be fine-tuned through experiments.

In real-life situations, the pendulation of the load is often accompanied by a rotational motion. It is believed that a similar strategy can be used to control the torsional effects. This can be achieved by a two-cable system. Forces can be applied to these cables to balance the torsional effects of payload rotation.

The work to date has yielded a dynamic behavior model that will be used to verify theoretically various control strategies. It is expected that the theoretical work will be done by December 1992. The experimental work awaits further funding.

CONCLUSION

The control strategy described can be implemented for most cranes used in the construction industry. The system design is based on responding to an excitation of the payload automatically, regardless of the cause of excitation. Traditional approaches to control by manipulating actuators and controlling accelerations of crane members requires that a dynamic model and control strategy be developed for each different type of crane. In contrast, the proposed system can be applied universally for all types of cranes, with minimum modification. This is because the control is provided at the cable, and is not significantly dependant on the construction of the crane.

The z-axis control, i.e., the control over the length of the cable, will have other advantages. This control will enable an improvement in crane operation for cargo handling on ships or floating docks. In these situations, the bobbing caused by the water (tides) is at issue. Distance between the hook and the floor can be monitored with sensors. The cable length can then be adjusted automatically to compensate for the effects of the bobbing. This will significantly improve the efficiency and safety of cargo handling operations.

A simple control strategy for damping payload swing during crane operation is proposed. The strategy is based on a feedback control system that will detect payload excitation and apply forces to the hoist cable to damp the oscillations. The control will be provided at the cable and will damp the payload oscillation, regardless of the cause of excitation.

Ongoing research will study the dynamic behavior of the crane payload and develop a detailed control model. A theoretical model will be built for testing the accuracy of the design. Test results will be evaluated and the necessary corrections will be applied.

The research will also address the issue of the long range required for the yoke to boom piston. This has several potential solution. However, until the distance down the length of cable for effective control is studied, the most appropriate approach cannot be determined.

Another study area will be the man/machine interface for areas of dynamic response outside the range of the damping system. It is hoped that with the

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dynamic damping system that response outside the range is not possible. Significant jarring or settlement has the potential to place the dynamic behavior outside the limits of the damping system. However, these types of behavior are expected to be infrequent or under proper operation limits and control should be near impossible.

The dynamics of the crane's boom and the payload will be modeled analytically. The level of detail in the analytical model may vary according to the accuracy of the results obtained from preliminary experiments. The dynamic behavior of the suspended load and the response of the crane to this dynamic loading will be simulated visually on a graphics workstation. Such a visualization will ensure reliable modeling, prediction, and control of dynamic behavior of the payload and response of the crane.

The proposed system, because of the simplicity of design, can be easily implemented on existing cranes. The proposed strategy will provide an inexpensive yet effective solution to the problem of undesirable motion of the payload during crane operation. This will result in not only improved safety, but increased efficiency during crane operation. The research will also provide insight into additional strategies that can be implemented at a later stage to control rotation of the payload.

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