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TIME-OPTIMAL CONTROL OF CONSTRUCTION TRANSPORT SYSTEMS WITH SUSPENDED LOADS

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ABSTRACT

The paper describes time-optimal control of construction transport systems with suspended loads, for example gantry type robots. Permissible oscillations of the loads are restricted because of safety requirements while transporting, especially at the end point. A mathematical model of such systems is presented as a pendulum attached by a suspension to a rigid robot body. The time-optimal control consists of transferring the system from an arbitrary initial state to a final state without oscillations of the loads. A control function is velocity of the body. This velocity is bounded. The length of the suspension can be changed while transporting of the load. The optimal motion modes are described. The theoretical switch lines and their approximations are obtained. An implementation of the control system for the start with stopping oscillations, motion without oscillations and the braking with stopping oscillation at the set end point is presented. Simulation results are discussed.

KEYWORDS

Time-optimal Control, Construction Transport System, Suspended Load

1. ANTI-SWAY CONTROL OF SUSPENDED LOADS

Control problems for construction robotic systems with oscillating elements arise in automation of transportation of different suspended construction loads.

Examples of such transportation systems are gantry type robots and robotic cranes. Permissible oscillations of the loads are restricted because of safety requirements while transporting, especially at the end point.

Anti-sway control of suspended loads on shipboard robotic cranes was explored in [1]. Inverse kinematics and sliding mode control approaches were applied in this task. Methods and apparatuses for reducing the oscillatory motion of rotary crane payloads during operator-commanded or computer-controlled maneuvers were investigated in [2]. An input-shaping filter receives input signals from multiple operator input devices and converts them into output signals readable by the crane controller for damping the payload tangential and radial sway associated with rotation of the jib.

In this paper, the time-optimal anti-sway control problem is considered. The developed control system can decrease time and increase effectiveness of transportation. The control takes into account changing of the suspension length during transportation. It implements a three step motion mode: start with stopping oscillations, motion without oscillation and braking with stopping oscillation.

The mathematical model of the considered transport system is shown in Figure 1.

It consists of a suspension with the construction load of mass m. The suspension by length L is attached to a rigid body of the transport system.

The body can move with velocity V along the horizontal axis X.

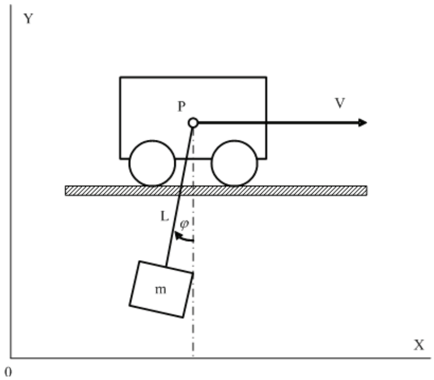

Figure 1 Model of the Transport System

The dynamic equations of the system motion for small oscillations in the vertical plane are given [3] by

$$\ddot{\varphi} + mgL\varphi = mL\omega$$
$$\dot{x} = V$$
$$\dot{V} = \omega \qquad , \qquad (1)$$

where x motion coordinate, φ angle of oscillations, g gravity acceleration, ω horizontal acceleration of the suspension point P. The velocity is bounded by the condition

$$-V_{\max} \le V \le V_{\max} \qquad , \qquad (2)$$

where Vmax is the maximal possible velocity of the transport system.

The feedback problem of the start with stopping load oscillations and motion without load oscillation is as follow: it is necessary to transfer the system (1), (2) from an arbitrary initial state φ *(0),* ω *(0)* to the final state without oscillations within minimum time *T*.

Introducing dimensionless variables [3] and variable

$$\psi = V - \dot{\varphi} \, ,$$

the motion equations (1) and the anti-sway condition are reduced to the following equations

$$\dot{\psi} = \varphi$$
$$\ddot{\psi} + \psi = V$$
$$\varphi(T) = 0 \qquad (3)$$

The velocity $V(t)$ is the control function which is assumed to be restricted between –1 and +1 that corresponds to the boundary conditions (2). The feedback control $V(\psi, \varphi)$ transferring the system (3) from the arbitrary initial state (ψ^0, φ^0) to the final state of the start mode with stopping oscillations $(V_{max},\ 0)$ is build similarly to the feedback control in [3]. The time-optimal control uses maximal value of the velocity forward and back in turn.

The theoretical switch lines and approximations of the implemented switch lines for the start with stopping oscillations, motion without oscillation and braking with stopping oscillation are shown in Figure 2.

The theoretical switch line 1 represents the start with stopping oscillations and motion without oscillation. The implementation of the switch line for the start with stopping oscillations and motion without oscillation is the line 2. The theoretical switch line 3 represents the braking mode with stopping oscillation. It has the final state (0, 0) on the phase plane.

The implementation of the switch line for the braking mode is the line 4.

A phase trajectory 5 of the braking mode for the theoretical system from an initial point (ψ^0, φ^0) is A-B-0. The proposed piece-wise-linear approximation of the switch lines is convenient for the implementation.

Simulation results show that transient time for the experimental switch lines exceeds the transient time for the theoretical switch line by less then 10% for the same initial deviation of the load.

This difference can be reduced if permissible accuracy at the end point of transportation is set by means of a dead zone for the drive system control. It accelerates the process of control also.

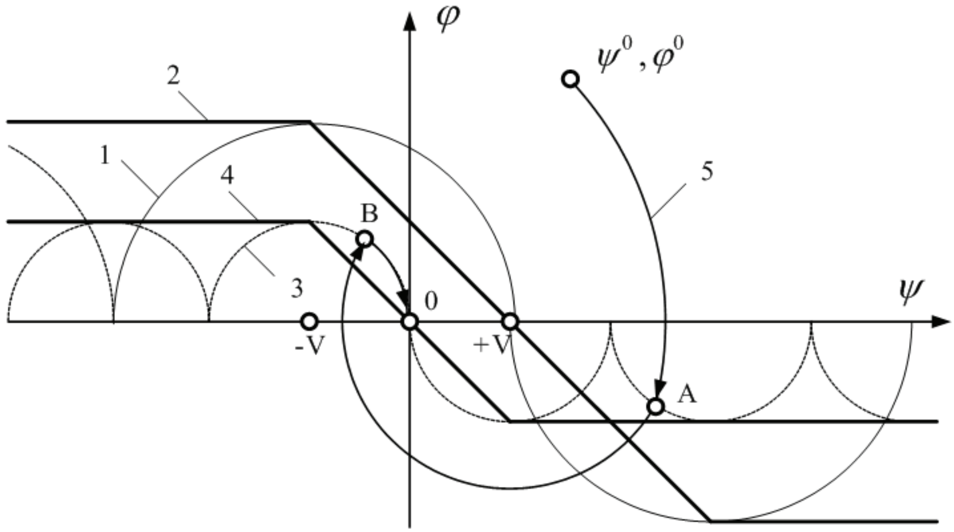

Figure 2 Theoretical Switch Lines and Implementation of the Switch Lines

A scale of the switch lines depends on the suspension length. The scale is corrected for different values of the suspension length. It implements using information from a suspension length sensor.

The correction is carried out by vertical changing of the switch line scale. Horizontal parts of the switch line for the start mode are changing according to the following equation

$$|\varphi| = 2VL^{-\frac{1}{2}}g^{-\frac{1}{2}}$$

Horizontal parts of the switch line for the braking mode are changing according to the following equation

$$|\varphi| = VL^{-\frac{1}{2}}g^{-\frac{1}{2}}.$$

The inclination of the switch lines in the central parts is proportional to the value V_{max}.

2. IMPLEMENTATION OF THE CONTROL SYSTEM

A block diagram of the control system is shown in Figure 3. The object to be controlled is a mobile transport system (TS) with the suspended load. The control parameter is the transport system velocity. It is necessary to control only the sign of the velocity, since its absolute value V_{max} is the same for the stationary regime in both directions for many types of such transport system with the suspended load [4].

The system operates as follows. An angle sensor (AS) generates the signal proportional to the angular velocity of the load oscillations by a differentiator (D). This signal is subtracted from the output signal of a transport system's linear velocity sensor (LVS).

As result, the signal corresponding to the velocity of the load is produced. The linear velocity V of the transport system is used for determination of the covered distance x. This value is formed by an integrator (I). The value x_f is an initial point of the braking mode. It is calculated in advance assuming that the suspension length is not changing while braking and there are no load oscillations at this point [5]. This situation is real because the distance of braking is relatively short and the mode with stopping oscillations is implemented before.

The values of the current coordinate x and the value x_f are compared. If the value

$x_f - x \geq 0$,

then the start with stopping oscillations and motion without oscillation have to be done. If the value

$x_f - x < 0$,

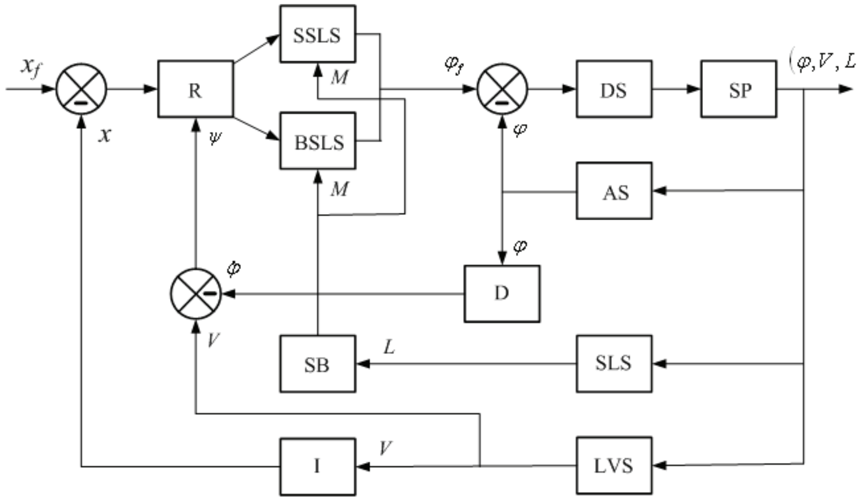

Figure 3 Block Diagram of the Control System

then transition to the braking mode should be produced.

A resulting signal of the comparison goes to a control input of a relay (R). A positive control signal connects an information input of the relay to a start switch line simulator (SSLS) that implements the switch line of the start mode as a function of the load velocity by means of a computational unit. A negative control signal connects an information input of the relay to a brake switch line simulator (BSLS) that implements the switch line of the braking mode.

The scale of the switch lines is corrected for different values of the suspension length by means of signals M from the suspension length sensor (SLS) using a scale block (SB).

A value of the corresponding ordinate φ_f of the switch line is generated on a simulator output. This output is compared with a current load angle φ by means of the comparator. If the difference

$$\varphi_f - \varphi \geq 0,$$

the phase point is under the corresponding switch line and control signal is + V_{max}.

If the difference

$$\varphi_f - \varphi < 0,$$

the phase point is over the corresponding switch line and control signal should be $-V_{max}$.

A drive system changes direction of its output velocity according to a sign of the described input control signal. As a result, the system implements anti-sway control for the suspended load transportation taking into account variable suspension length.

3. REFERENCES

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