別紙４－１（課程博士（英文））

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# Abstract (Doctor)

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| Title of Thesis | Load Swing and Skew Vibration Suppression and Excitation Controls of Crane Systems. |

Approx. 800 words


Transportation of heavy and hazardous payloads at various places such as harbors, factories, shipyards, etc. is mainly carried out by cranes. All types of cranes share a common structure, i.e., the payload is suspended under a trolley or a boom tip by flexible ropes. Therefore, pendulum-like motions of the payload called vibrations are induced when actuators start to exert accelerations on the payload through ropes. In fact, there are two types of vibrations present in crane systems. The first type is swing vibration, which occurs when changing the payload position. The second is skew vibration, which happens when adjusting the payload orientation. The swing vibration is spherical pendulum-like whereas the skew vibration is torsional pendulum-like. The central concept of crane control is to manipulate these vibrations as our wish to suit for different engineering purposes. As a result, a number of new control schemes and refined algorithms will be established in this dissertation to address both skew and swing vibration control problems of cranes. The current common school of thought views the vibration as a harmful phenomenon that needs to be eliminated, making the vibration suppression control widely studied in the literature. However, the vibration might be undesirable for some applications but favorable for others (e.g. bulk material transportation described in Chapter 6). Hence, crane control should be perceived in both vibration suppression and excitation control perspectives.

Part I of this dissertation focuses on the skew vibration control of crane systems. To solve the robust control problem of the skew transfer process in the presence of parametric uncertainties, two robust controllers are proposed. First, an integral sliding mode controller is established. A coupled integral siding function is introduced to inject the skew vibration information into the control law to drive the payload to a desired skew angle while effectively dampening out the vibration. The reaching phase as found with conventional sliding mode controllers is also canceled. Thus, the robustness can be achieved at the beginning of time. Second, a dynamic output feedback $H_\infty$ controller is also be applied on the system to compare with the integral sliding mode control. The robust stability condition of the $H_\infty$ controller is performed using the $\mu$-synthesis with a structure singular value criterion, whereas the Lyapunov indirect method is employed for the integral sliding mode controller. For both schemes, an optimization routine based on the metaheuristic particle swarm optimization mechanism is established, which adopts the robust stability conditions with

regard to each controller as the nonlinear constraints. With the proposed optimization procedure, the minimization of a desirable performance index and robust stabilization of the closed-loop system are simultaneously guaranteed in a single framework. Through both random simulation and experimental results, the integral sliding mode controller shows its superiority over the $H_\infty$ control. Hence, it is the preferable candidate for actual implementation on the real-size system in use at the harbor. A switched optimal controller is subsequently introduced to improve transport productivity. The novelty of such an approach is that we can reduce energy consumption without trading-off the sub-optimal transfer time. The basic idea is to use a binary actuator–an electromechanical clutch–to intelligently disengage the connection between the motor and the payload during the motion so that the payload can continue to rotate only with its own momentum. Two solutions, namely particular and general schemes, are proposed. Physical constraints of the actuator including bounded velocity and bounded acceleration are explicitly taken into account. Both simulation and experimental results are provided to demonstrate the effectiveness of the proposed switched optimal control system. Comparisons with no-switched time-optimal, input shaping, and integral sliding mode controllers are also presented.

Part II of the dissertation deals with swing vibration control problem of cranes. First, minimum-time zero-vibration S-curve commands for an overhead crane are established. Based on a position baseline S-curve, which is generated from a bang-off-bang acceleration profile, two approaches are proposed to build the vibration suppression capability: embedding and shaping methods. In both schemes, the baseline S-curve is parameterized to establish minimum-time optimization problems, in which maximum velocity and maximum acceleration of the actuator are explicitly taken into consideration. Minimum-time solutions are successfully obtained. Online trajectory generation can be achieved using the proposed approach. In comparison with related studies, the minimum-time S-curve commands are faster. Second, a model reference input shaping control will be formulated for a nonlinear luffing dynamics of a rotary crane system with time-varying rope length. The newly established technique is able to completely suppress the residual vibration for a highly nonlinear time-varying system. The fundamental idea is to match the real vibration of the system with a reference oscillation, by which an exact zero vibration suppression can be achieved for the actual system. Standard input shaping control designs cannot possess such a quality. Finally, a vibration excitation control scheme will be introduced for an overhead crane system in the context of bulk material transportation where the transferred materials can be dropped/discharged while in the air. In order to exploit such a unique feature, a new concept, named tossing control methodology, is introduced to enhance transportation productivity. A specific type of tossing controller is proposed, which relies on the phenomenon of linear resonance to induce oscillation in periodically increasing amplitude. It will be shown that the resonance-based tossing control can reduce the transfer time up to 26.5% compared with the well-known minimum-time swing suppression controller–the fastest member of the swing suppression control group–under similar requirements of bulk material transportation, conditions, and actuator constraints. Thus, it was found that the vibration suppression control is not always the best option in every situation.