Model Based Development Using Hardware-in-the-Loop Simulation for Drive System in Industrial Machine

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***Abstract*— This paper presents a proposal of a model-based development method for industrial machinery drive systems using Hardware-in-the-loop Simulation system that can accommodate combined phenomena in mechanical, electrical, and control fields. The proposed method is applied to the development and verification of a speed control pattern that does not excites mechanical vibration in a stacker crane. And its effectiveness was confirmed.**

***Index Terms*— model based development, hardware-in-the-loop (HIL), drive system, factory automation**

I. INTRODUCTION

Model-Based Development (MBD), a development / design method for control systems, performs development processes such as planning, designing, prototyping, and testing based on a mathematical theory. In recent years, MBD has shown diffusion and expansion mainly in the automotive fields [1]-[7].

The drive system of industrial machinery mainly comprises controllers, drives, and motors. A controller generates commands for the angular position and speed of motors. A drive controls the electric power of motors so that they operate following commands. The action of motors that drive each part of a machine following commands authentically implements the desired operation of the whole machine.

One increasingly popular procedure is the method of validating the propriety of generated commands in which the waveform of each part is verified using a dedicated simulator on a PC. A procedure is also proposed to check for the presence of the interference or collision of mechanics using linkage with 3D-CAD data. Such a validation methodology is useful for and necessary for verification of the control logic of command patterns. However, these verification procedures treat a drive, a motor, and mechanics as an ideal system that operates authentically, following a command. Therefore, occasionally problems such as mechanical vibration are not detected until the stage of a real machine examination. A real machine examination, which comprises various tests with actual controllers, drives, motors, and mechanics combined, is usually conducted in the final stage of development when the machine system prototype is completed. Problems detected in a real system examination involve phenomena in the electrical, mechanical, and control fields mutually correlated. Countermeasures to these problems might take time and labor, and might consequently cause a severe delay in development. Additionally, large machinery entails various problems such as time-consuming preconditioning, difficulty in securing an installation location, and restrictions in operating conditions because of safety considerations.

This paper presents a proposal of an MBD method using Hardware-In-the-Loop Simulation (HILS), which can accommodate phenomena in the electrical, mechanical, and control fields for the problems described above, encountered during the development of a drive system for industrial machinery. Mounting the models of mechanics, a motor, and an electrical circuit into a real-time simulator and connecting them to a controller and

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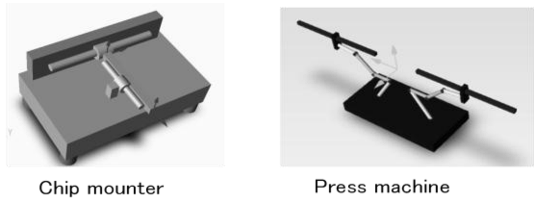
drives implements the optimization of command generation to various operating conditions. The proposed system was applied to develop evaluation of the drive system of actual industrial machinery. Its effectiveness was verified.

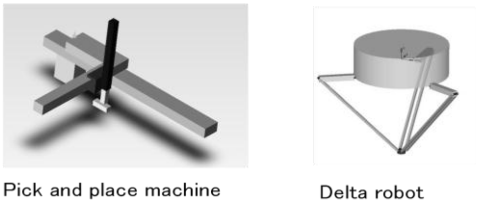
II. CONVETIONAL DESIGN VERIFICATION METHODS AND PROBLEMS

Various modes exist in the structure of industrial machinery as shown in Fig. 1. Industrial machinery is driven with multiple servo motors. The positions of a machine end and the servo motor of each axis generally do not have a linear relation. Accordingly, the control parameters of each drive should be tuned on a trial-and-error basis, so that satisfaction of the required specifications is time-consuming. Interference of two axes because of mechanical imbalance makes the control design and parameter tuning of a drive still more difficult. In addition, the measurement of various data takes time. The data include the position, velocity, and acceleration of each part of a machine, the synchronous accuracy between each axis, DC link voltage, motor current, torque, and power consumption. A coasting test at an emergency stop also requires time. In short, the design and verification of the servo control of industrial machinery is not efficient because they are conducted with a real system.

Consequently, an MBD method suitable for the drive system of industrial machinery is necessary, which reduces useless time in preparation or measurement to the greatest degree possible, and which allocates more time to the optimization of control design or parameters.



Chip mounter Press machine



Pick and place machine Delta robot

Figure 1. Various industry machines.

Fig. 2 shows a typical configuration of the drive system of the industrial machinery as the target of this study. This system comprises a programmable logic controller (PLC) as a controller, a servo drive and an inverter as a drive, a servomotor and three-phase AC motor connected with machinery, a converter that converts an AC current from an AC power supply into DC current to supply electric power to the servo systems and the inverter, human machine interface (HMI) as an indicator, and a network that connects each instrument. A converter also has a function to regenerate kinetic energy to electric power at the time of slowdown and stoppage of a machine for energy conservation.

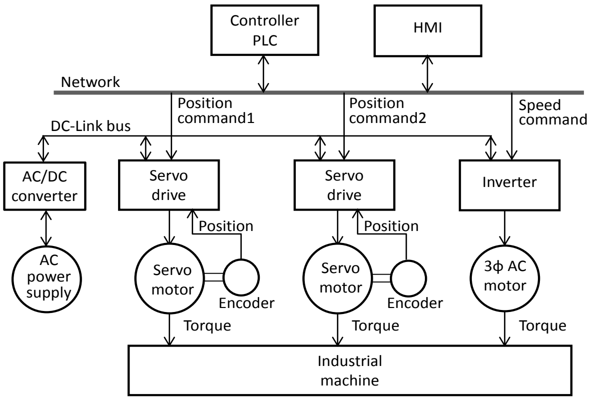


Figure 2. Drive system of industrial machine.

A controller (PLC) sets the angle of rotation according to the mechanism of each part and converts the units between rotational motion and linear motion so that the whole machine performs a designated operation. Then it generates commands for the angular position and speed of each motor. Command generation procedures by a controller include a method to output command patterns that had been generated and memorized in advance according to an external operation signal at a certain interval, and a method to generate commands one-by-one by calculation based on an outside operation signal and the machine state.

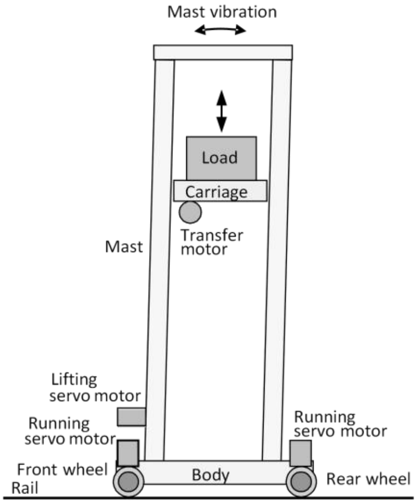


Figure 3. Stacker crane.

Fig. 3 shows the structure of a stacker crane used in an automated warehouse. A stacker crane is composed of a body, a mast, and a carriage, travels on the rail using the front and rear drive wheels, and raises and lowers the carriage along the mast. Packages on the carriage are transferred to the shelf by a transfer device installed on the carriage. The above operation is performed using motors. The running speed is up to 300 m / min, the lifting speed is up to 100 m / min, and the height of the mast is 5 m to 45 meters. The loading range is about 100 to 3000kg.

In order to increase the conveying efficiency of the stacker crane, it is necessary to increase the maximum speed and shorten the acceleration / deceleration time in each operation. However, in that case, vibration of the mast at the time of stoppage increases and a waiting time until the vibration falls is generated, so the conveying efficiency decreases. In addition, due to fluctuations in wheel loads caused by the mast vibration, slipping of the wheels is likely to occur, which may accelerate wear of the wheels and rails.

In the drive control system of the stacker crane, the speed command patterns of the servo drives and the inverter driving each of motors are given from PLC. Verification by the simulator on the personal computer described above is aimed at logic verification of the PLC control program, and it is assumed that the machine moves according to the command, so phenomena such as vibration and slip are not considered. Therefore, since problems of vibration and slip are carried out by actual machine verification which is the final stage of development, it takes time to countermeasure and development delay occurs.

III. PROPOSED MBD METHOD USING HILS

A. *System Configuration and Operation*

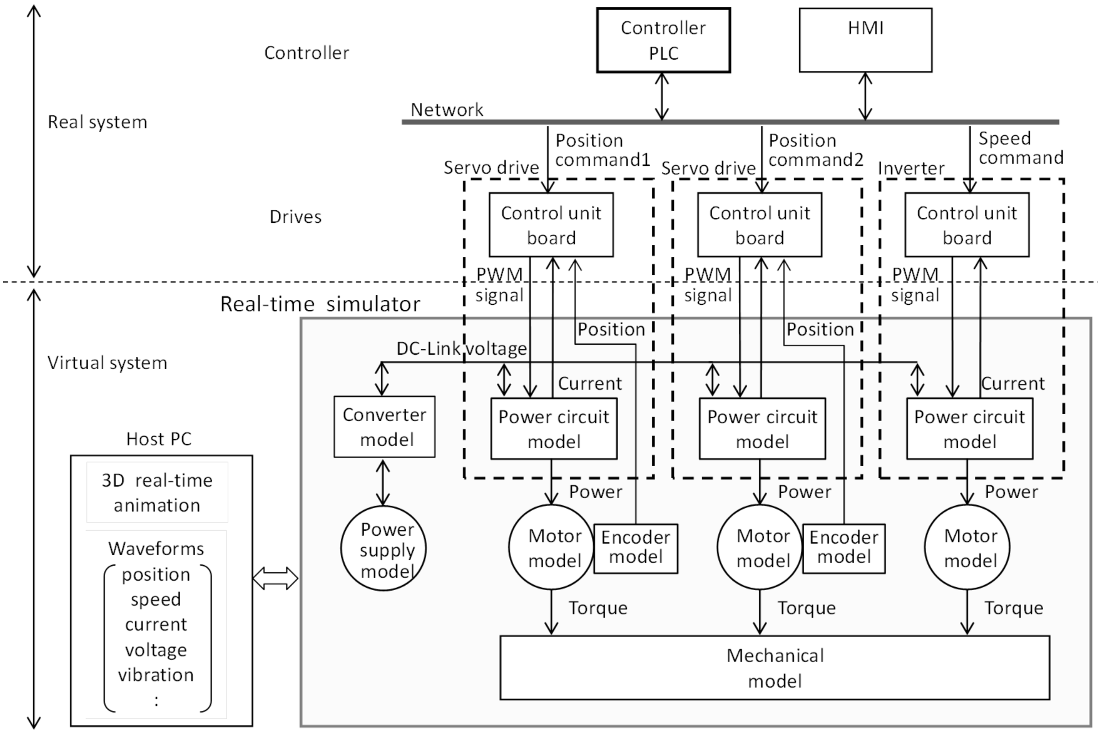


Figure 4. Constitution of HILS verification system for drive system of industrial machine.

Fig. 4 presents the configuration of a HILS test system as a solution to problems described above. Here are described the features of this system. A real-time simulator is furnished by the mathematical models of a power circuit consisting of a servo drive and an inverter, a converter, an AC power supply, a motor, and mechanics. Switching operation of the power circuit model is conducted by a PWM switching signal from the control unit boards of the servo drive and inverter. Then motor current is applied to the motor model, which generates motor torque that drives the machine. Electric signals equivalent to the output signal of an actual current detector and encoder are generated respectively for the motor current and motor angle. Then they are fed back to the control unit board. Thereby, the control unit boards of the servo drive and inverter perform behavior equivalent to controlling of an actual power circuit and motor, respectively. A machine model can carry oscillation and other characteristics to simulate actual mechanics by the combination of masses, inertia elements, spring elements, etc. This system uses no actual machinery, motor, and power circuit, so it requires a small footprint.

Next, operation of mathematical models installed on the real-time simulator is described.

(1) Inverter model: This model converts the PWM signal from the servo drive into an average voltage over 10 µs of the computation period of the real-time simulator using a FPGA. Switching of the PWM signal occurs asynchronously with the computation period of the real-time simulator. Therefore the signal is sampled with a FPGA at a cycle of 20 ns and is converted into the average voltage over a period of 10 µs. The carrier frequency of PWM signal is 9 kHz.

(2) Motor model: This model generates a current and torque based on the average voltage over 10 µs from the inverter model.

(3) Encoder model: This model simulates an encoder signal based on a motor position signal using the FPGA and outputs it to the servo drive.

(4) Current sensor model: This model simulates a current detecting signal with a D/A converter and outputs it to the servo drive.

(5) Power-source model: This model simulates the operation of a power supply system, a converter, and a brake chopper.

(6) Machine model: This model simulates the operation of each part of a machine to motor torque or disturbance.

B. Preparation of the Electrical Model

The previously described electrical system models (1)–(5) simulate a servo system. The electrical engineers of an appliance manufacturer create those models and register them into an electrical system model library. The electrical library is generally registered in the data base of the appliance manufacturer. Table I presents tools used for model preparation and the simulation time step. These electrical system models are installed to the real-time simulator by converting a Simulink model into an execution code.

C. Preparation of the Machine Model

(a) This proposal assumes that the mechanical engineers of an appliance manufacturer prepare a representative machine model and register it to a machine model library. A control engineer configures machine constants such as length, mass, and a spring modulus to the model to establish a machine model applicable to a real machine. Multi-domain modeling tool SimulationX [8] is used for preparation of a machine model. Consequently, the engineers of an appliance manufacturer can efficiently prepare a different machine model for each machinery manufacturer.

(b) Fig. 5 shows a procedure of the mechanical engineers of an appliance manufacturer to create the template model of a machine. First, a model of typical mechanisms of industrial machinery is prepared by multiple connections of standard machine elements of SimulationX on the block diagram editor, and is registered in the mechanism model library. The machine elements of SimulationX include distributed mass, various joints, springs, friction, and gears, etc. The mechanical engineers establish a library of machine models by modeling model not included in the library by combining mechanism models and standard elements, and contributes to reduce time substantially rather than newly developing a machine model.

(c) Because a Simulink model must be converted into an execution code to install a model to a real-time simulator, the machine model library on SimulationX is converted into a Simulink model using the conversion function of SimulationX. A machine model corresponding to each machine is completed by inputting length, mass, and inertia moment determined by mechanical specifications into the machine model on Simulink as parameters.

(d) The HILS verification system in Fig. 4 as a substitute for real system verification is completed by converting main circuit, motor, and mechanical models selected from the model library on Simulink into execution codes and installing them in the real time simulator.

TABLE I. ELECTRICAL MODELING TOOL AND SIMULATION TIME STEP

Models		Modeling tools	Time step
Power circuit models	Inverters	MATLAB/Simulink	10 µs
	Converters		
	Brake choppers		
Motor models	SPM motors IPM motors	MATLAB/Simulink or JMAG-RT [9]	10 µs

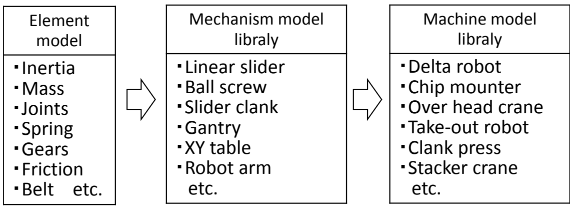


Figure 5. Procedure of creating the template model of a machine

IV. PROPOSED MBD METHOD USING HILS

In this section, we describe a case where the proposed method is applied to the development of the speed command patterns for suppressing the mast vibration generated at the time of acceleration / deceleration of the stacker crane.

A. The Machanical Model of the Stacker Crane

The mechanical model of the stacker crane can simulate the vibration of the mast and the slip of the wheel in addition to basic actions such as running, elevating, and transferring. The stacker crane model is based on the mass and dimensions of the main parts of the machine, and the specifications of the motor, gears, wheels, etc. The spring constant of the model is adjusted so that the mast vibration frequency becomes the same as the actual value. In addition, the slip characteristics of the wheel adopt the slip model of the car tire. This model is implemented in the mechanical model part in the real-time simulator shown in Fig. 4.

B. Speed Pattern for Vibration Suppression

The control unit board of the servo drive for running receives a speed command from the PLC and controls so that the speed of the servo motor follows the speed command. Several methods are conceivable to suppress the vibration of the mast. In this paper, the PLC generates a speed command that does not include the frequency component that excites vibration of the mast, and gives it to the servo drive. Fig. 6 shows the block diagram of the proposed speed command generation. First, a trapezoidal wave pattern in which the top speed and the acceleration / deceleration time are set according to the moving distance is created. Next, when this pattern is input to the vibration suppression filter for removing the natural vibration frequency component of the mast, the output becomes a new speed command signal. Here, since the vibration frequency of the mast varies depending on the height of the carriage, the characteristics of the vibration suppression filter can be adjusted according to the height of the carriage. On the control program of the PLC, it is implemented as a vibration suppression filter function after the conventional trapezoidal wave pattern generation function.

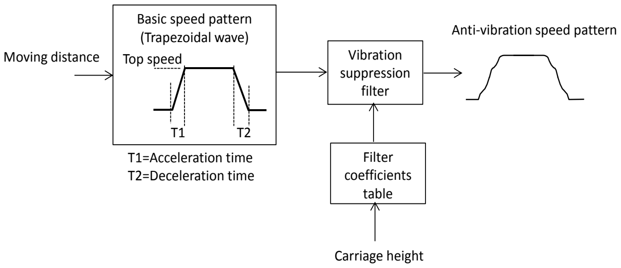


Figure 6. Block diagram of anti-vibration speed pattern generation part.

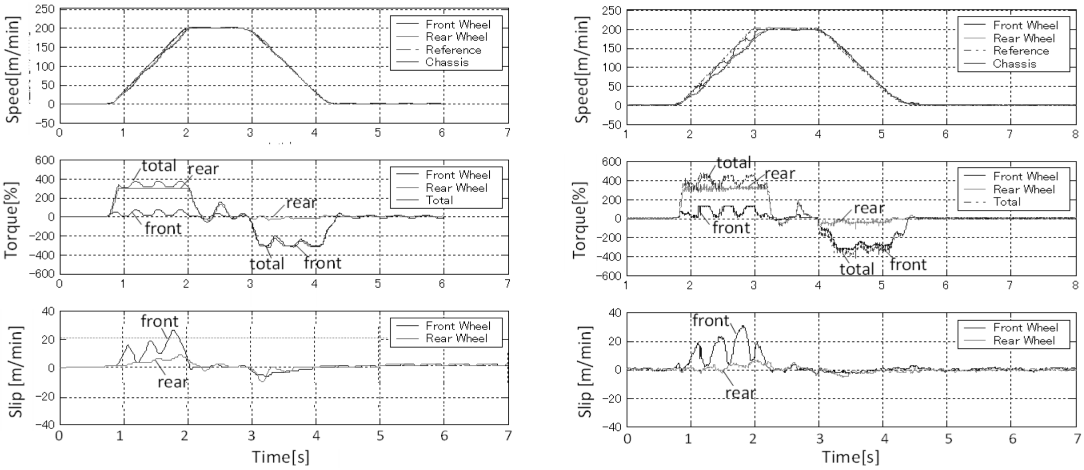
C. Verification Using HILS

A verification method of the vibration suppression filter using the HILS verification system of Fig. 4 will be described. Those prepared as the actual devices are PLC, HMI, the control unit boards of the servo drives and the inverter, the real time simulator and its host PC. Those prepared as the models are power supply, the power circuits of the servo drives and the inverter, the servo motors, the three-phase motor, the sensors related to motor control, and the proximity sensors installed in the running path. When the instructions of traveling, elevating and transfer are given from the HMI, the PLC generates speed commands. At that time, the parameters of the vibration suppression filter are adjusted based on the response waveform of the servo motor and the crane on the screen of the host PC. The parameters of the vibration suppression filter can be easily adjusted according to the vibration frequency of the mast and the height of the carriage. In addition, it is possible to evaluate under various conditions such as change of instructions on the way and emergency stop.

D. Experimental Work

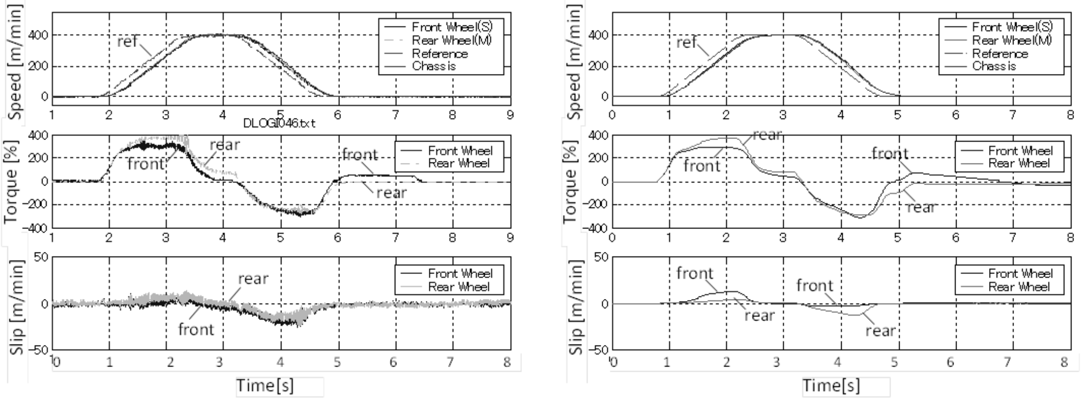
Figs. 7 and 8 show the response waveforms of the HILS verification system and the actual machine. Fig. 7 shows a case when the vibration suppression speed pattern is not used, motor torque and slip is large. Fig. 8 shows the waveform when using the vibration suppression speed and due to the vibration of the mast, the vibration of the pattern, since the mast vibration is suppressed, vibration does not appear in the motor torque and slip. The acceleration / deceleration rate in Fig. 8 is 0.4G which is twice that in Fig. 7. Also, it can be said that the waveforms of HILS and the actual machine are very similar.

From the above, the effectiveness of the proposed HILS verification system and vibration suppression filter can be confirmed.



(a) HILS verification. (b) Experimental result.

Figure 7. Without vibration suppression speed pattern. (acceleration/deceleration rate **0.2G**)



(a) HILS verification. (b) Experimental result.

Figure 8. With vibration suppression speed pattern. (acceleration/deceleration rate **0.4G**)

V. CONCLUSION

The proposed method, constituted as described above, enables us to verify the control system of even large machinery employing a high-voltage, large-capacity motor without using actual power circuits, motors, and machines, so that even a software engineer and a control engineer can accommodate it easily. No restriction in the power source environment, installation location, or safety aspects allows desktop verification. Moreover, the effect of the communication period and communications delay between instruments on control performance can be evaluated also for use with high accuracy such as synchronous control. Consequently, as described above, applying the proposed method to development of a drive system of industrial machinery enables us to ascertain, in advance, possible difficulties related to real system examination and to take countermeasures against them during upstream development.

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