Mechatronics System Dynamics Simulator

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Abstract In the development and design of a mechatronics, or electromechanical product, the key for faster speed and higher performance is optimization of its electric motor, drive and control. We have developed a software system, the "Mechatronics System Dynamics Simulator" to test the operation characteristics of mechatronics products. It significantly reduces time for selection of a motor matching the mechanics and optimization of control parameters. Its precise modeling of real products enables the designer to examine the envelope of operation performance, and devise improvements of mechanics and control schemes. Although this development is for industrial use, the authors believe its concept and approach can be applied to other areas.

While the inertia ratio of load over electric motor is increasing and the rigidity of mechanics decreasing, the market requires faster speed and higher performance of mechatronics products. To achieve this goal, it is important to not only improve performance of mechanics, electric motor and control respectively, but also balance and optimize their combination. It is vital to simulate the total operation performance of mechanics and controls combined.

There has been no software system to simulate the whole operation of mechanics and controls combined, although quite a few software packages for a single functionality such as mechanical analysis or control analysis are available on the market.

The Mechatronics System Dynamics Simulator that we have developed simulates the behavior of a mechatronics product as a whole system in real operation.
The software system has the capability of not only analyzing the mechanics and controls combined but also modeling the mechanical components in a unique manner. The goal is to offer the designer an optimization of his or her design.

This paper describes the capability and configuration of the system and its applications to a linear motor drive mechanism and a ball-screw drive mechanism.

1. INTRODUCTION

It is becoming essential to optimize the combination of the mechanism, electric motor, and controller in mechatronics systems, rather than simply relying on improvements to the individual components. This is due to the increased inertial ratio of the electric motor over the load, and decreased mechanism rigidity.

To optimize the combination it is indispensable to simulate the operational performance of mechanism and control combined. To investigate the operational performance of mechatronics products, we have developed "Mechatronics System Dynamics Simulator," hereafter MSDS, which models each mechanical system component and precisely simulates the actual behavior.
With the MSDS, our objective as a supplier of electric motor and control is to improve the performance of mechatronics products including our users' mechanisms.

To improve calculation precision in the dynamics simulation of mechatronics products, precise modeling of machine in addition to control is necessary.
Particularly with linear motor and ball-screw drive mechanisms popular in mechatronics products, it is vital for controller design to take their vibration characteristics into account. We have studied the vibration characteristics of these drive mechanisms, and have included a resulting vibration model in MSDS for use in simulations.

This paper describes the machine modeling capabilities of MSDS, and the results from the simulation of operational performance of a linear motor driven table (stage).

2. CAPABILITY AND CONFIGURATION OF THE MSDS

2.1 Capability of the MSDS

The objective of the MSDS is to precisely simulate the behavior of mechatronics products. The capabilities of the developed simulator system are as follows:

- Combined analysis of machine and control
- All the system factors from command to control to machine are modeled on the MSDS. Figure 1 show the simulation model.
- Mechanical modeling with multiple axes (multiple freedom) using spring factor
- Automatic tuning of control gain with reverse problem analysis method
- Animated display of machine behavior at any point in place with any magnification

As new capabilities we have added the following:

- Ball-screw drive mechanism to be used in mechatronics products
- Linear motor drive mechanism database as standard
- Windows 95 based GUI including controller modeling input Figures 2 and 3 show the GUI screens for mechanical modeling and controller modeling respectively.

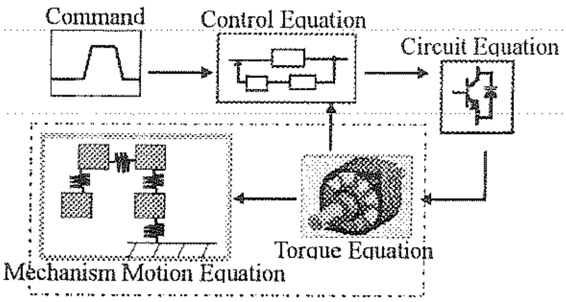


Figure 1 Simulation model

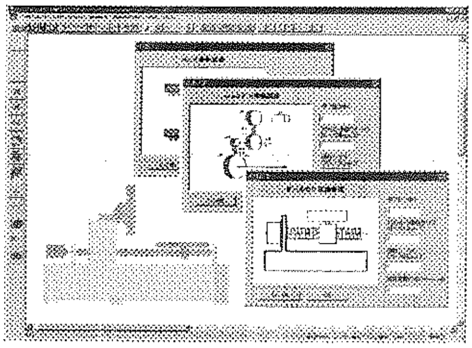


Figure 2 Screen for mechanical modeling

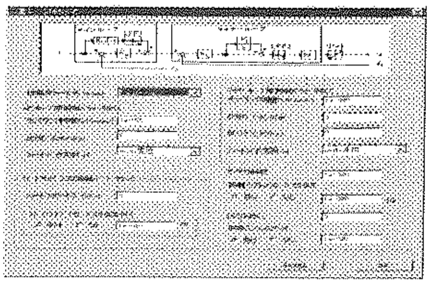


Figure 3 Screen for controller modeling

- Evaluation of torque ripple and speed ripple with circuit equation and torque equation

With the above capabilities, selecting an electric motor matched with a mechanism and determining an optimum parameter for a controller are an automatic and quick process. It is possible to examine the limits of operational performance of a mechatronics product with its precise model and propose an improvement of the machine and/or control scheme.

2.2 Configuration of the MSDS

The MSDS system comprises the three steps of machine modeling, generation of control system and command, and machine control solver. Figure 4 shows the system flow diagram.

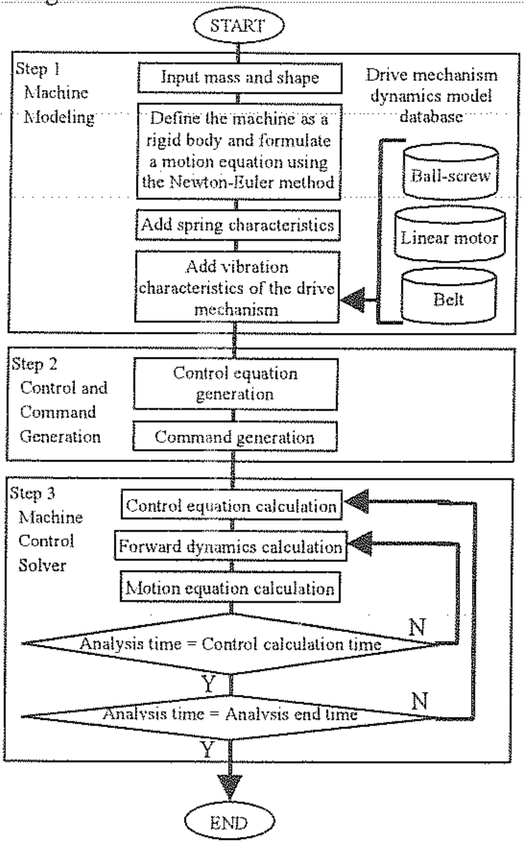


Figure 4 System flow of MSDS

Step 1 Machine Modeling

Machine modeling is done through the GUI. Machine modeling defines each mechanical component as a rigid body and connects them to each other with joint, spring or damper elements. Drive mechanisms are selected from the database and incorporated in the model. As described above, a multiple freedom axis machine model is created. This step first defines the machine as a rigid body and formulates a motion equation using the Newton-Euler method based on mass and shape information. It then adds equations of spring characteristics and drive mechanism dynamics to complete the motion equation. Expression (1) shows the motion equation.

$$M\ddot{x} + Cx + Kx + Fc = T \qquad (1)$$

where
x: position vector M: mass matrix
K: rigidity matrix C: damping matrix
Fc: friction vector T: force vector

The fidelity of the machine model is a big factor in the simulation precision. Particularly, since the drive mechanism is directly connected with the electric motor, taking the vibration characteristics into account is important in controller design. The system is designed to take into account each vibration characteristic inherent in ball-screw, linear motor, belt, etc. as drive mechanisms. In the ball-screw drive mechanism, the table sliding mode can be considered based on supporting bearing rigidity, nut rigidity, ball-screw elastic direction rigidity, and twist rigidity.

In the linear motor drive mechanism, the yawing and pitching mode based on linear guide rigidity can be considered. In the belt drive mechanism, the rotational vibration mode based on the rigidity of belt and speed-down gear can be considered. The MSDS, which is equipped with a database of these drive mechanism dynamics models, enables the user without machine modeling know-how to precisely model an actual machine.

Step 2 Generation of control and command

At this step of control system, select one of the control schemes provided as a menu and set the control gain. The resolution of sensor, calculation delay and the torque limit of electric motor can also be considered. Any control equation for more complex control scheme can also be incorporated through external functions coded in the C language. The command can be set as a function of an arbitrary waveform. It can also be imported from an external file in a specified format.

Step 3 Machine Control Solver

The solver calculates the control equation with the command and machine position information to draw the force to be applied to the electric motor. It obtains the position, speed and acceleration through forward dynamics calculation and motion equation calculation. The numerical solution is the Euler method. To improve calculation precision, the forward dynamics calculation is performed every 1us.

The MSDS is a packaged software system with the capabilities, features and configurations described above.

3. OPERATIONAL PERFORMANCE SIMULATION

The MSDS was applied to a linear motor driven table (stage) to simulate the operational performance for a higher speed and precision. Since a linear motor comprises a full closed loop control system, the machine vibration directly affects the control system. It is necessary to optimize sensor position, table mass and center of gravity. A two axis linear motor driven table mechanism was optimized through the operational simulation.
Figure 5 shows the structure of the linear motor driven table.

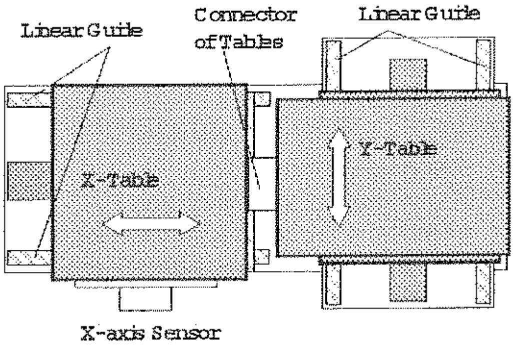


Figure5 Structure of linear slider

There are springs in the linear guides and in their connection to this mechanism. Figure 6 shows the dynamics model of the linear motor driven table. Expression (2) shows the motion equation of the X axis table.

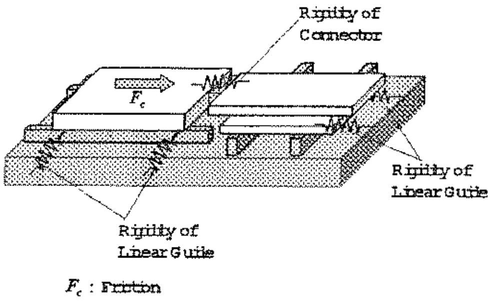


Figure 6 Dynamics model of linear slider

$$F = M\ddot{X} + C\dot{X} + KX + Fc \qquad (2)$$

Where

$$F=[Fx,0,Fx\,\Delta y]^T,\quad X=[x,y,\theta z]^T$$

$$M=\begin{bmatrix} m_1+m_2 & 0 & 0 \\ 0 & m_1+m_2 & 0 \\ 0 & 0 & I \end{bmatrix},$$

$$K=\begin{bmatrix} 0 & 0 & 0 \\ 0 & 4k_1 & \Sigma k_1 d \\ 0 & \Sigma k_1 d & \Sigma k_1 d^2 \end{bmatrix},$$

$$C=\begin{bmatrix} c_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$Fc=\begin{bmatrix} k_2(p_1-p_2)+\mathrm{sgn}(x) \\ 0 \\ 0 \end{bmatrix}$$

where

Fx: propulsion force [N]
dy: distance between working point and center of gravity [m]
m_1, m_2: masses of X axis table and Y axis table [kg]
I: inertial moment around Z axis of X axis table [kg*m2]
k_1: rigidity in the Y direction of the linear guide [N/m]
k_2: rigidity in the x direction of the connection part [N/m]
d: X coordinate of the linear guide in reference to the center of gravity [m]
$c1$: viscosity friction of the table [N*s/m]
p_1, p_2: X coordinates of the connection part [m]

The position of X axis sensor is:

$$\cos\theta z\cdot L_1 - \sin\theta z\cdot L_2 + x$$

where

L_1 is the X coordinate and L_2 the Y coordinate from the center of gravity.

Based on the above dynamics model, we made a machine model on the MSDS and drew a transmission function. Figure 7 shows the transmission function with different positions of the Y table. The vibration source is the X axis motor and the response point is the position of the X axis sensor.

The vibration amplitude substantially varies with different positions of the Y axis table. Figure 8 shows the characteristic vibration mode in the position 1. A yawing mode results in the X axis table. The cause is the rigidity, center of gravity and inertial moment of the linear guide supporting the X axis table. The node of vibration coincides with the position of the connection part. The reason why the vibration amplitude varies with the postures in Figure 7 is because the vibration amplitude at the position of the sensor varies as the vibration node moves according to the position of the Y axis table.

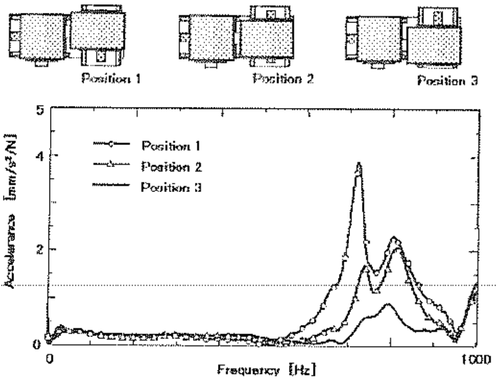


Figure 7 Bode diagram of linear slider for X-Table by MSDS

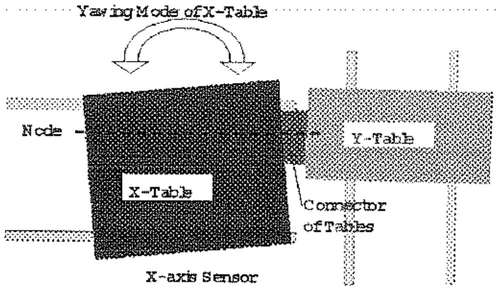
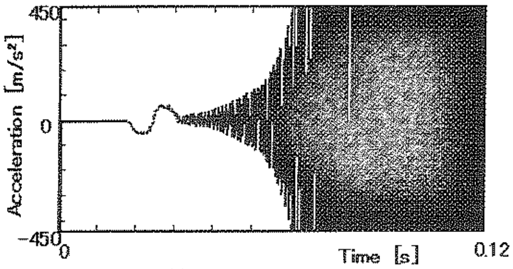
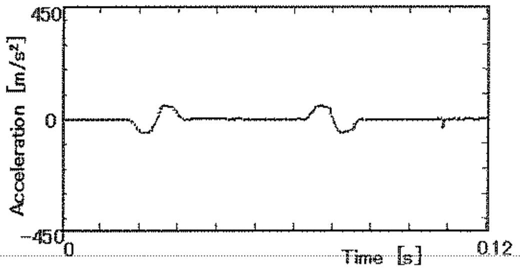


Figure 8 Natural mode for position 1 by MSDS

The control system consists of position proportional control and speed proportional integral control. Figure 9 shows the acceleration response of positioning in the posture 1 simulated on the MSDS. The chart (a) before the mechanism was changed shows an oscillation. Through simulation, an optimum reconfiguration was found: a stable operation with the same control gain was obtained as shown in Figure 9 (b). Figure 10 shows an experimental result of the acceleration response of positioning in the posture 1. Figure 10 (a) before the mechanism was changed shows an oscillation similar to the result from the MSDS. The reason why the oscillation stopped in the chart is because the controller was emergency-stopped as the vibration amplitude increased. As the results from the MSDS and the experiment matched each other, we have confirmed that the MSDS can be used to verify the total effects of the improvements in the mechanical, control and command subsystems.

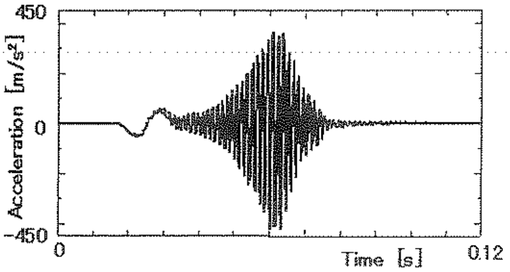


(a) Initial Design

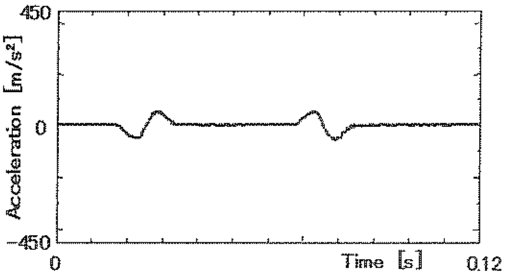


(b) Improved Design

Figure 9 Acceleration response of table for position 1 (MSDS)



(a) Initial Design



(b) Improved Design

Figure 10 Acceleration response of table for position1 (Experiment)

4. CONCLUSIONS

We have described the capabilities and configuration of the Mechatronics System Dynamics Simulator, MSDS, to examine the operational performance of mechatronics products. Its usefulness was demonstrated in the simulation of operational performance of a linear drive.

The MSDS enables the user to automatically select electric motors to match a mechanism and obtain optimum parameters for a controller according to its operational specifications. The MSDS is an indispensable development tool in the realization for higher speed and performance of mechatronics products.

References:

(1) Sumimoto, T., Miyagawa, H., et al., "Dynamics Simulator of Mechatronics System (Japanese)," *Yaskawa Denki*, Vol. 61, No. 237, pp. 250 (1997, No. 4)

(2) Miyagawa, H., Sumimoto, T., et al., "Optimal Gain Tuning for Contour Control of NC Machine Tools by Using Genetic Algorithm," *The 4th Japan-France Congress on Mechatronics*, pp. 41 (1998-10)

(3) Miyagawa, H., Yamamoto, A., et al., "Machine Control Simulator incorporated with the Drive Mechanism Dynamics Model Database (Japanese)," , No. 98-3, pp.89, (1998-10)