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**COMPARISON OF DYNAMIC ANALYSIS OF
A SCHILLING HYDRAULIC MANIPULATOR
WITH EXPERIMENTAL RESULTS**

C. P. Baker
J. Y. Lew
M. S. Evans
D. P. Magee^(a)

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Pacific Northwest Laboratory
Richland, Washington 99352

(a) Georgia Institute of Technology
Atlanta, Georgia 30332

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COMPARISON OF DYNAMIC ANALYSIS OF A SCHILLING HYDRAULIC MANIPULATOR WITH EXPERIMENTAL RESULTS

C.P. Baker, J.Y. Lew, and M.S. Evans

Pacific Northwest Laboratory¹, P.O. Box 999, Richland, WA 99352

D.P. Magee

George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332

ABSTRACT

Two independent models of the dynamics of a Schilling Titan II hydraulic manipulator were developed and compared in order to obtain an accurate model of the manipulator dynamics. These models will be used in the development of feedback control laws and active damping algorithms. One of the model is an analytical model which was developed "by hand" with the assistance of computer symbolic manipulation. The other is a numerical model developed using a commercially available dynamics code. The data from these models were then compared with experimental data from an actual Titan II manipulator.

KEYWORDS

Robotics, Hydraulic, Dynamic, Manipulator, Experiment.

INTRODUCTION

One method of waste remediation under consideration at U.S. Department of Energy sites uses a dual-manipulator retrieval system. Structural and geometric considerations dictate a design consisting of a long-reach positioning manipulator (LRM) with a dextrous short reach manipulator (SRM) mounted on the end. The combined LRM and SRM system is referred to as the retrieval manipulator system (RMS). The LRM will be relatively compliant because of its length. A test bed representative of an RMS is shown in Figure 1, where a Schilling Titan II manipulator (representing the SRM) is mounted on the end of a compliant

FIGURE 1. Flexible Manipulator Test Bed

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fixed-free beam (representing a single-link LRM). To study vibrations induced in this system and develop active damping algorithms to annihilate these vibrations (as in Baker et al., 1993 and Evans et al., 1992), the dynamics of the end-mounted dextrous manipulator must be well understood. Two dynamic models of the dextrous manipulator were developed to assist in developing this understanding. One model was developed

using classical rigid-body dynamics methods to find a set of differential equations of motion. The other model was developed using a commercial numerical dynamics code.

FIGURE 2. Schilling Titan II Manipulator

The Schilling Titan II manipulator is a hydraulic six degree of freedom manipulator originally constructed for telerobotic undersea applications. The manipulator is largely constructed of Titanium, reaches approximately 6 feet, and has a rated payload of 250 pounds. It is controlled by a VME-based computer using a Motorola 68030 microprocessor and the VXWorks real-time operating system. A graphical representation of the computer model of the manipulator is presented in Figure 2.

DYNAMIC MODELS

One dynamic model is analytical, developed with the support of the Mathematica symbolic manipulation code, and the other is numerical, developed using a commercially available dynamic analysis package (DADS). These two modeling techniques have different advantages and disadvantages. The analytical method yields a closed-form type solution that can be used directly in to develop control laws. The equations of motion are in a compact form with rapid solution times, and it is simple to rerun the model using different initial conditions. However, complex nonlinear effects, such as hydraulic actuators and flexible members, are difficult to include. In addition, the visualization of results can be difficult. The numerical model permits the inclusion of flexible bodies (this becomes important in the long-reach manipulator control problem), hydraulic actuator effects, and ready visualization of system trajectories. However, solution times can be long, particularly when hydraulics or flexibility are included in the model, and restarting the model with a new set of initial conditions is slightly more difficult.

Both models rely on link inertia terms that were obtained from the manipulator manufacturer. The supplied terms were the mass and location of the center of mass for each link. This information was augmented using computer solid modeling to obtain additional terms of the inertia matrix.

Other modeling boundary conditions for the structural model are

- friction is neglected (except where specified)
- gravity is neglected
- the dynamics due to the three primary axis (azimuth, shoulder and elbow) of the manipulator are considered. The three wrist joints are held fixed.

Analytical (Mathematica) Model

Analytically modeling a dynamic system gives insight into system characteristics. An understanding of dynamic modeling is required to design a high-performance feedback controller for robotic manipulators. Recent developments in symbolic computation software allow the closed form dynamic model for a multiple link manipulator to be obtained analytically. The derivation of the equations of motion by the Lagrange approach is summarized below (Spong, 1989).

Let us consider a n-links manipulator. Jacobian matrices can be computed from the forward kinematics of the manipulator. Using Jacobian matrices, the expression for the system's kinetic energy is developed for

use in Lagrange equations. Then, the Lagrange formulation is used to derive the system mass matrix in a simple form, which can be expressed as:

$$M_{kj} = \left(\sum_{i=1}^n m_i J_{v_i}(q)^T J_{v_i}(q) + J_{w_i}(q)^T R_i(q) I_i R_i(q)^T J_{w_i}(q) \right)_{kj} \quad (\text{EQ 1})$$

where q =joint angles
 m_i =mass of the i -th link
 I_i =3x3 inertia matrix of the i -th link with respect to the mass center
 J_{v_i} =translational Jacobian matrix of the mass center of the i -th link
 J_{w_i} =angular Jacobian matrix of the mass center of the i -th link
 R_i =3x3 orientation matrix of the mass center of the i -th link

Similarly, nonlinear dynamic effects, such as centrifugal and Coriolis terms, can be obtained using Christoffel symbols. From Spong (1989), the nonlinear terms are represented as:

$$C_{kj} = \sum_{i=1}^n \frac{1}{2} \left(\frac{\partial M_{kj}}{\partial q_i} + \frac{\partial M_{ki}}{\partial q_j} - \frac{\partial M_{ij}}{\partial q_k} \right) \dot{q}_i \quad (\text{EQ 2})$$

The resulting equation of motion becomes:

$$M\ddot{q} + C\dot{q} = T \quad (\text{EQ 3})$$

here T represents the applied joint torques.

This nonlinear set of differential equations was solved using the O.D.E. solver built into Mathematica. This solver automatically selects between the backward differentiation (or Gear) method for stiff problems and the Adams predictor-corrector method for nonstiff problems (Keiper, 1992).

Numerical Model

The numerical code can include a variety of complex nonlinear effects. However, when comparing it with the analytical model, the numerical model includes only the structural elements of the manipulator and the forces required to move them.

When using the numerical code, model formulation consists of describing the rigid bodies that make up the device, the joints which connect them, and the loads to be applied. The description of the rigid bodies consists of inertia values and the location in space of each body. The visualization geometry for each body is added to the model later and is independent of the system dynamics. Once the bodies are all in place, they are connected by joints; other types of constraints (such as joint torques, external forces, and hydraulic actuators) can also be added. The model is then solved using Kane's method to extract the equations of motion, which are then solved numerically. The user has several solvers available, including Runge-Kutta, the Adams-Bashforth predictor-corrector, and the Gear backward differentiation.

Comparison of Model Results

Both models were run to obtain results for three different types of boundary conditions. The initial condition for all runs corresponds to that shown in Figure 2 – the arm is in a horizontal configuration with all joint axis intersecting a horizontal line. No gravity terms were included in these models. The three different types of runs were:

1. step input torque applied to a single joint (all others are fixed)
2. simultaneous step torque input to all three major axis joints
3. simultaneous harmonic torque applied at a frequency of 0.2 Hz to all three major axis joints.

For the runs with step torque inputs to individual joints, no gravity or friction were included in the models. These models allowed verified that the link length, mass, and primary moment of inertia terms were correct in both models. An example plot comparing the analytical and numerical results for the azimuth (first) joint of the manipulator is shown in Figure 3. The results are essentially indistinguishable.

The analysis performed with simultaneous step inputs to all three main joints also produced indistinguishable results, as shown in Figure 4, which depicts the percent error for each of the three main joints for the model in which all three main joints are driven by a step torque.

For the harmonically applied torque model, substantial damping was added to both models; the intent was to rapidly drive the response to a limit cycle. This limit cycle behavior was then plotted in a phase plot of joint velocity versus position for each joint. Using these phase plots, each model's accuracy with respect to nonlinearities, such as the coriolis terms and the "secondary" inertia terms were compared. Phase plots for the azimuth joint (joint 1) and the shoulder joint (joint 2), with a 0.2 Hz driving frequency are shown in Figures 5 and 6.

EXPERIMENTAL SETUP

To validate the analytical models, comparisons were made between model results and experimental results. Because it was not feasible to isolate the motion of the manipulator from the actuator dynamics, the comparison was made between an improved numerical model (which includes the actuator dynamics and control logic) and the experiment. To simplify the modeling process and the robot control inputs, simple test motions were used. Each test motion began at the joint zero position (see Figure 2), where a step input was applied to the control system for the joint under study. Although the interaction between motions of different joints when simultaneously subjected to this type of step input is of interest, this type of test was not performed. This test would have lead to starvation in the hydraulic pump, causing the sys-

tem operating pressure to drop. While the pressure drop effect is of interest in this problem, investigation of this effect is beyond the scope of this paper.

Numerical Model Extensions

Hydraulics, controls, and actuator-type improvements were added to the numerical model to allow comparison with the experimental results. Rather than simply applying torques at each joint, a complete hydraulic system model, including valves, lines, actuators, and fluid dynamics, was added. A duplicate of the low level control system on the manipulator was also incorporated into the model. In addition, the torque at the shoulder joint was provided by an off-axis linear hydraulic actuator like the actual manipulator.

Experimental Considerations

The effects of friction, which cannot be predicted a priori; hydraulic starvation; and noise and other issues affecting data quality affecting data quality hamper the model's accuracy and thus the ability to directly compare results. Although inaccurate, no friction was assumed because the development of an accurate friction model for this system is beyond the scope of the current work.

Comparison of Results

Experimental and simulated responses to step input commands for the azimuth and shoulder joints are shown in Figures 7 and 8. The results compare reasonably well. An interesting difference is the steady state offset in both experimental responses, which has several of possible sources, including the differences in friction and the possibility of error in converting experimentally measured values (measured in resolver counts) to angular or linear units. Also, the lack of gravity in the model is probably an effect in the shoulder joint model, and the lack of integral control in the joint level controllers probably has an effect. When compared, the experimental and predicted rise times for the azimuth joint are similar. However, the over-

FIGURE 7. Comparison of step command, simulation response, and experimental response (azimuth joint).

FIGURE 8. Comparison of step command, simulation response, and experimental response (shoulder joint).

shoot and recovery observed in the experiment is different in character from that observed in the model. Specifically, the experimental results present a slight overshoot at a fairly low frequency. In contrast, the numerical results rapidly settle to a high-frequency limit cycle because the implemented controller is unstable. In the experimental system, the effects of friction compensate for this inherent instability. The effect of friction in the model, however, differs from the experiment, allowing the observed limit cycle behavior. It is critical to understand the existing friction to develop an adequate model.

CONCLUSION

Both of the modeling techniques examined in this work provide powerful and useful models of the complex dynamics of robotic manipulators. When considering problems concerning only the rigid body dynamics of the system, they produce essentially indistinguishable results. However, when the actuator dynamics are complex and pertinent to the problem at hand, the numeric tool may be required.

As in many other dynamic systems, the effect of friction is extremely important and cannot be predicted in the absence of experimental testing. The importance of friction is independent of the modeling technique used.

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