

Control Design and Simulation of Systems Modeled Using ADAMS

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ABSTRACT

This paper presents a technique for control design and simulation using the ADAMS software and a control design software package. For design of control systems ADAMS generates a minimum realization linear time invariant (LTI), state space representation of multi-body models. This LTI representation can be produced in formats for input to several commercial control design packages. The user can exercise various design strategies in the control design software to arrive at a suitable compensator. The resulting closed loop model can then be simulated using ADAMS. This procedure is illustrated with two examples.

1. INTRODUCTION

Due to decreasing cost and increasing reliability of computing hardware, there is increasing interest in control of complex multi-body systems. Before any such systems can be implemented in hardware, it has to be designed using computer software. ADAMS[1] is a commercial software package for modeling and large displacement simulation of non-linear multi-body dynamical systems. It has been successfully used for modeling multi-body systems such as on and off road ground vehicles, aerospace mechanisms and structures and general machinery amongst others. Control design software packages such as Matrixx[2], Pro-Matlab[3] and others have implementations of commonly used control design methodologies. Most popular control design methods require a linear time invariant (LTI) representation of the multi-body system. This LTI representation for a multi-body system can be obtained automatically from ADAMS, in a format suitable for direct input to control design packages.

The paper begins with an introduction to the ADAMS software, followed by a brief review of one of the commonly used state space control methods. The methodology being introduced in this paper is then presented. Two examples are used to illustrate this methodology.

2. OVERVIEW OF ADAMS

ADAMS is a multi-body dynamics software package[4]. As input ADAMS requires a system description, consisting of the mass and inertia data of all bodies in the systems and connections between various bodies. Others data such as environmental effects and simulation parameters have also to be specified. Once a user specifies the analysis mode for the system, ADAMS automatically constructs the governing equations for the system and solves these equations. Bodies can be connected by kinematic or force connections. Kinematic connections represent joints between bodies. These connections are typically represented by algebraic equations. Force connections represent compliant elements in the multi-body system.

2.2 Kinematic connections - Joint Types : Some of the joints allowed by ADAMS are

- (1) Revolute - allows for relative rotation about 1 axis.
- (2) Translational - allows for relative translation along 1 axis.
- (3) Spherical - allows relative rotation about 3 axes.
- (4) Universal - allows for relative rotation about 2 axes.
- (4) Cylindrical - allows relative rotation about 1 axis and translation about the same axis.
- (5) Several types of gear joints are permitted.

- (6) Joint primitives - allow for joints to be constructed that represent motions that cannot be represented by one of the joint types stated above.
- (7) User can also introduce non-standard kinematic connections through user supplied subroutines.

2.3 Force Connections: Standard forces in ADAMS include

- (1) Translational forces - these apply forces along an axis
- (2) Rotational forces - apply a torque about an axis
- (3) Bushings - apply 3 forces and 3 torques between the two bodies that are connected by this element.
- (4) Fields - allow for a user supplied stiffness matrix to be applied between two bodies connected by this element.
- (5) Beams - apply a beam element stiffness matrix between the two bodies being connected by this element.

Force elements can have linear as well as non-linear characteristics. Non-standard forces can be introduced via user-supplied subroutines.

2.4 Analysis Modes

ADAMS allows the following analysis modes

- (1) Static and Quasi-static : For a dynamical systems this mode computes the equilibrium position of the systems.
- (2) Kinematic: This mode only applies for systems with no dynamical degrees of freedom. In this mode displacement, velocity, accelerations and forces for the multi-body system are computed in response to motion inputs.
- (3) Transient dynamics: The time response of a dynamical system is computed in this analysis mode.
- (4) Eigensolution: The generalized eigenvalue problem for the ADAMS model is solved for eigenvalues and eigenvectors of the model.
- (5) State Matrices Computation: LTI representation of the ADAMS model is computed and output in the form of (A, B, C and D) matrices.

2.5 Governing Equations

Given the elements that make up the multi-body system, ADAMS automatically generates the non-linear governing equations for the model. In the ADAMS modeling methodology these governing equations are written in a surplus set of coordinates[4], resulting in a system of implicit first order differential-algebraic equations given as,

$$g(Y, \dot{Y}, t) = 0 \tag{1}$$

where

Y = vector of solution variables.
t = independent variable time.

These equations can be linearized about a suitable operating point $Y^* = (Y_0, \dot{Y}_0, t_0)$ to give

$$\left(\frac{\partial g}{\partial Y} \right)_{Y^*} \Delta Y + \left(\frac{\partial g}{\partial \dot{Y}} \right)_{Y^*} \Delta \dot{Y} = 0 \tag{2}$$

where

Δ indicates small perturbations in the respective variables about their nominal values at Y^*

subscript Y^* indicates that the matrix is being evaluated about the reference position.

Defining inputs **u**, to and outputs **y** from the plant, it is possible to express the plant model as a LTI form given as,

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{3}$$

where

x = state vector for the plant
y = vector of outputs from the plant
u = vector of inputs to the plant
A, B, C and D = Constant state matrices

Equation (3) is in a minimum realization form. A condensation procedure is used for reducing equation (2) which is in a surplus coordinates sets to a the minimum realization form of equation (3) [5, 6]. Some of the variables in ΔY are retained in **x**, while others (dependant variables) are condensed out algebraically.

3. CONTROL DESIGN METHODS

Several classical (root locus, Bode plots...) and modern methods (pole placement, LQG, LQG/LTR, H_∞ ,...) are available for control design[7,8]. Most commercial control design packages have procedures that implement these design methods. The commonly used LQR design methodology states the optimal control problem as

Determine gains k for a state feedback of the form $u = -kx$ to

$$\text{Minimize the functional } J = \frac{1}{2} \int_0^{\infty} (x' Q x + u' R u) dt$$

Subject to the state equations

$$\begin{aligned} \dot{x} &= A x + B u \\ y &= C x + D u \end{aligned}$$

where

Q and R are square weighting matrices

By applying different weighting coefficients in the Q and R matrices the control designer can exercise different control design options. The solution to the steady state optimal control problem is obtained by solving the algebraic Riccati equation[7].

The essential element of this methodology from the perspective of the control design for multi-body dynamical systems is the need for a LTI representation of the plant model.

4. PROPOSED METHODOLOGY

The methodology being proposed in this paper begins with the an open loop model of the multi-body system created using the ADAMS language elements.

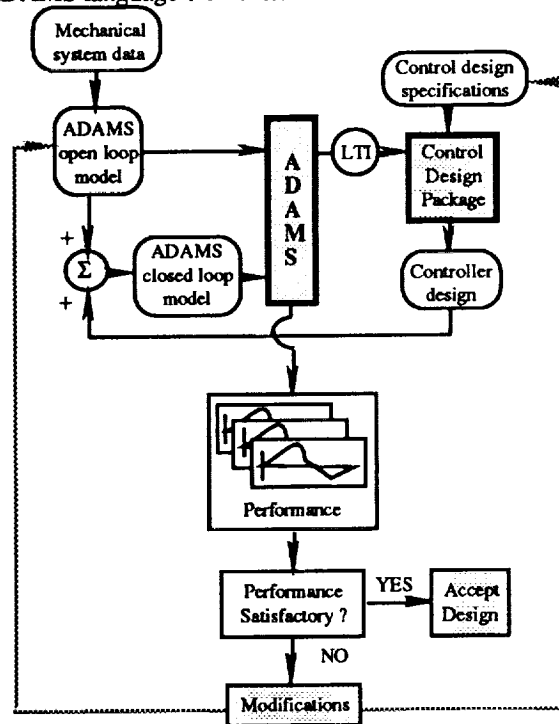


Figure 1. Schematic of Proposed Methodology

This non-linear model can be placed in a nominal position Y^* and linearized to obtain its LTI representation as in equation (3). Presently this LTI representation can be obtained from ADAMS in the Matrixx and Pro-Matlab formats. Translation into any other data format can be easily performed. Once the plant model has been read into the control design package, the control design problem can be defined and a compensator designed using any one of the control design methods stated earlier. This compensator is then implemented using ADAMS language elements. Combining the open loop ADAMS model and the ADAMS representation of the compensator gives the closed loop model. A non-linear time domain

simulation of the closed-loop ADAMS model is performed to evaluate its performance. If the closed-loop model performs as expected, the compensator design is accepted. On the other hand if the closed loop system does not perform as desired, the open loop model may have to be modified or the control design problem specifications adjusted. More often than not adjusting the control design specification is sufficient to achieve the desired closed loop performance. This design and simulation process is repeated till a satisfactory compensator design is obtained.

5. EXAMPLES

In this section two examples for control design for multi-body systems will be demonstrated using the methodology presented in earlier sections.

5.1 Balancer 1 Model

The first example considered is a mechanical balancer shown in figure 2. This device consists of a frame that is pivoted in ground. At its reference position this frame is in the vertical position. The frame includes a cross member, on which is located a sliding mass. By applying actuation forces between the slider and the frame it is possible to move the slider on the cross member in a controlled manner.

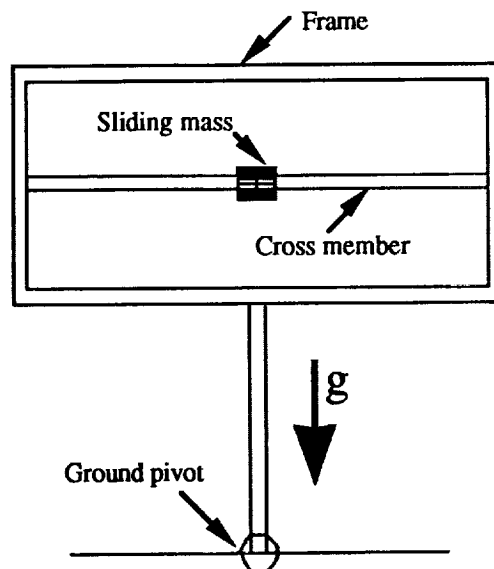


Figure 2 Initial Configuration of Balancer 1 model

From the open loop poles for this system shown in figure 3 it can be seen this system is unstable because of a pole in the right half plane. The control design objective for this system is to stabilize the frame at a position 2.5 degrees from the vertical.

The control inputs to the plant are actuation forces applied on the sliding mass. Outputs from the plant are the angle and velocity of inclination of the frame from the vertical and the position and velocity of the slider on the cross member. Since there is a constant external disturbance, i.e. gravity, integral of the inclination of the frame is also used as an output. This permits a PID control law to be devised for this model. These input/output descriptions are implemented using ADAMS data elements.

The open loop ADAMS model was placed in the vertical position and linearized. The state matrices for the model were read into $Matrix_x$ as being the plant model description. The LQR control design methodology was used to design a static compensator. Different weighting coefficients were tried in the Q and R matrices till an acceptable compensator design was obtained. When the final compensator design was incorporated into the open loop model, the resulting closed loop model has a pole pattern shown by circles in figure 3. As is evident the compensated model is stable about its nominal position.

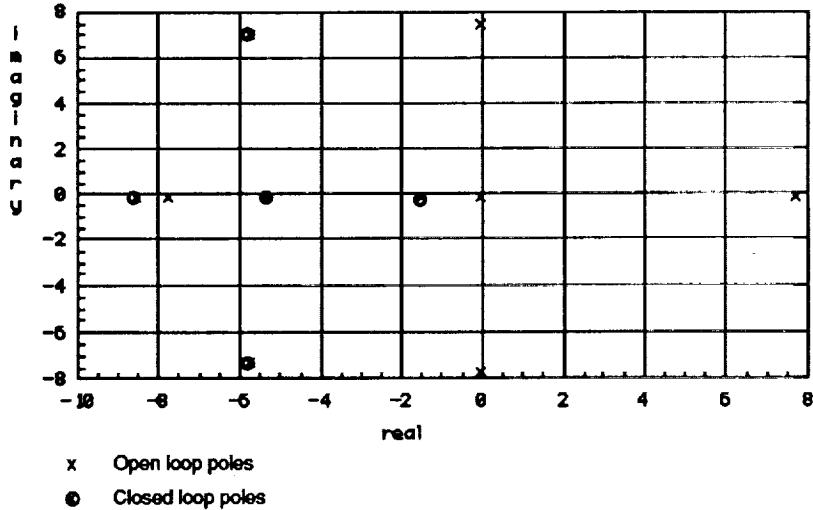


Figure 3 Open and Closed Loop Poles for Balancer 1 Model

To assess the time response of the closed loop systems a command is initiated at 0.5 seconds. This command to orient the frame at 2.5 degrees from the vertical, is ramped in over a period of 2 seconds from initiation. As is shown in figure 4 the frame tilts more than the desired angle of inclination, before stabilizing at the desired position. In the final position the orientation of the frame is as shown in figure 5.

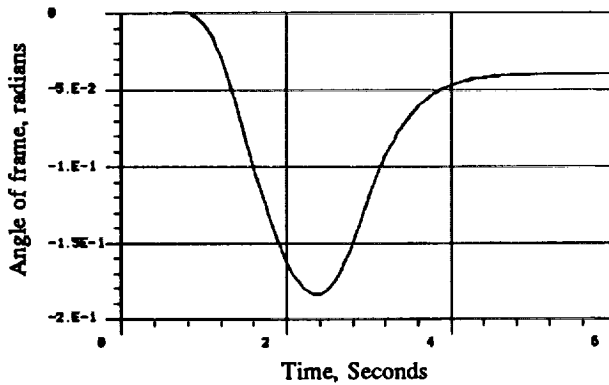


Figure 4 Time Response of frame to command

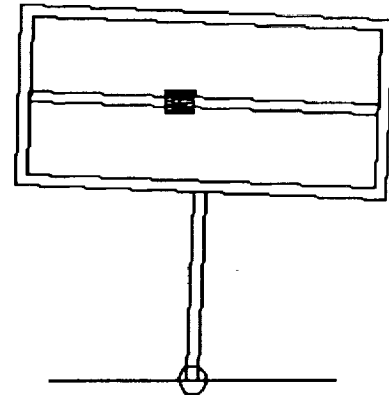


Figure 5. Final Position of balancer frame at time=6 seconds

5.2 Balancer 2 Model

The second model considered is similar to the previous model. This balancer model, as shown in figure 6, differs from the previous example in the respect that the frame cross member axis passes through the pivot axis. In the previous example these two were offset by some distance. The frame pivots in a base and a slider can slide along the axis of a cross member. The slider in this case is a solenoid. By applying appropriate voltage to this solenoid, the slider can be positioned on the cross member. There is one sensor on the base, that is able to measure the angular rotation of the frame with respect to the base. A reduced order filter is used to estimate the angular orientation of the frame. This is a single input single output system. The ADAMS model is linearized about its nominal position, ie, the frame is horizontal and the sliding mass is in the center of its travel. The root locus design methodology in Matrix_x was used to design a feedback control for this model. As shown in figure 7, this systems has 7 poles. Due to a pole in the right half plane, the open loop systems is unstable. As the feedback gain magnitude is increased from 0 (open loop) to -1.0 the poles move as indicated on figure 7. For purpose of this example a gain of -1.0 was chosen. This gain was used to create the compensated model and the model simulated in the time domain in

ADAMS. For simulation purposes a perturbation force is applied to the frame at time 1.0 second. As can be seen, from figure 8, the frame returns to its original position after about 2.5 seconds have elapsed.

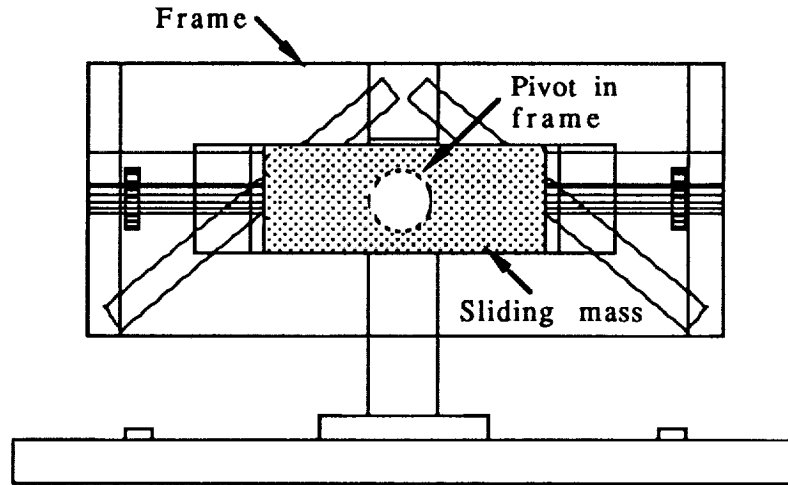


Figure 6 Balancer 2 Model

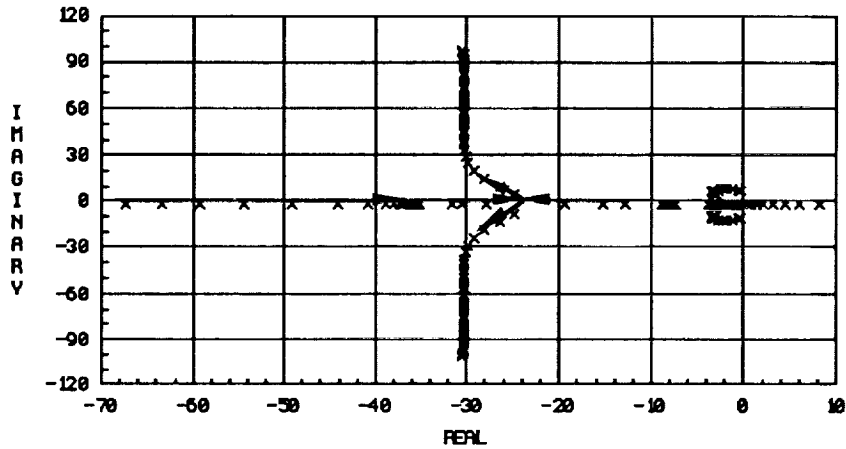


Figure 7 Root locus for balancer 2 model

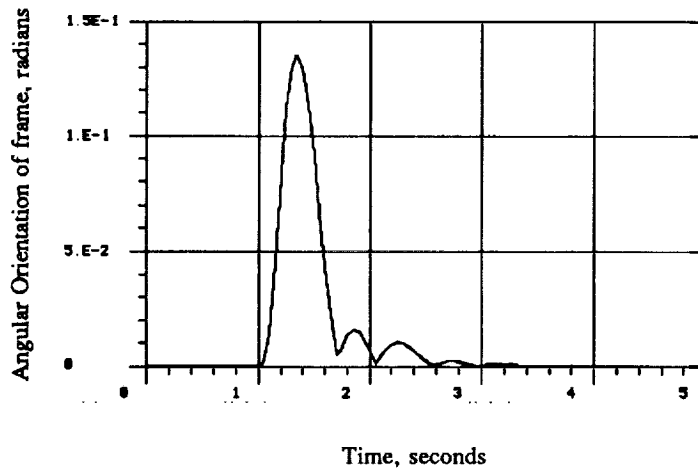


Figure 8 Time Response of Frame to a perturbation force

6. SUMMARY

This paper presented a general methodology for combining the powerful physical modeling features of the ADAMS multi-body dynamics software with the advanced control design methodologies in commercial controls software. Application of this methodology for control design of 2 multi-body dynamical systems was demonstrated. In general this technique can be applied to wide variety of complex multi-body dynamical system.

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