COMPUTER-AIDED DESIGN AND ANALYSIS OF MECHANISMS

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SUMMARY

This paper presents a short introduction to the computer programs which have been developed to assist in the design and analysis of mechanisms. A survey of the various types of programs which are available is given, and the most widely used programs are compared. The way in which the programs are used is discussed, and demonstrated with an example.

INTRODUCTION

Traditional mechanism design methods, both graphical and analytical, can be very complex and time consuming for all but the most simple mechanism systems. Computer software packages facilitate the automation of the trial-and-error process inherent in the design of mechanisms. Instead of cranking through equations by hand, the mechanism designer or analyst can specify characteristics of the mechanism and use the computer to calculate the kinematic and/or dynamic quantities of interest. Two-dimensional pin and paper models used to visualize the operation of proposed designs can be replaced by two- or three-dimensional dynamic visual models shown on a graphic computer terminal. The effect of design changes can be easily seen, and so the time required to develop the desired mechanism is greatly reduced.

Since the late 1960's, many computer programs for mechanism analysis have been developed. A number of these programs have been developed within particular companies and so are proprietary and not generally available. Other programs have been developed for a very specific application and thus are not very useful for general mechanisms work. There are, however, a handful of general programs which are enjoying widespread industrial use, and are actively marketed and maintained commercially. These programs are the subject of this paper.

PROGRAM SURVEY

Table I presents a summary of the characteristics of several of the most commonly used general-purpose mechanism analysis programs. At present, the programs which appear to be in widest use for general kinematic and dynamic analysis are known as ADAMS (for Automatic Dynamic Analysis of Mechanical Systems), DRAM (Dynamic Response of Articulated Machinery) and IMP (Integrated Mechanisms Program). These and other analysis programs operate on similar, but different, analytic principles, the details of which may be found in Reference (1). Of these programs, only ADAMS and IMP have been implemented for three-dimensional systems. A "two-dimensional" package, however, does not require that all of the links of the mechanism being designed must be contained completely in a single plane, but rather that all motions of the mechanism take place in parallel planes. For a large number of mechanisms, this is not a serious restriction, and the two-dimensional formulation provides advantages in computing speed and model simplicity.

ADAMS, IMP, and DRAM are used for the analysis of a mechanical system which has already been designed. These programs are distinctly different from packages which have been developed to assist in the synthesis of mechanisms. Table II compares three of these programs, KINSYN (Kinematic Synthesis), LINCAGES (Linkage Interactive Computer Analysis and Graphically Enhanced Synthesis Package), and MECSYN (Mechanism Synthesis). These programs provide the designer with a "family" of possible solutions to a design problem involving mechanisms which may be modeled as four-bar linkages (pin and slider-jointed planar mechanisms). They do not, however, lend themselves to more general mechanism systems.

Table III is provided as a summary of other more specialized mechanism programs. While these types of programs may be very useful for particular types of analyses, they do not lend themselves to more general mechanism systems. This paper will discuss the most widely used programs, ADAMS, IMP and DRAM, in more detail.

PROGRAM COMPARISONS

In comparing mechanisms programs, one should first attempt to determine for what types of problems the program selected will eventually be used. A three-dimensional program may be necessary for some applications, but a two-dimensional analysis may be sufficient for a wide class of problems. Of course, it is important to determine whether the intended use is one of design analysis or design synthesis, since both types are available.

Beyond distinctions in type, there are other more subtle differences. The most general programs, IMP and ADAMS, offer certain advantages. IMP is less expensive, but ADAMS appears to be more powerful, especially with respect to graphic capabilities. IMP is particularly good in detecting "lock-up" configurations. Both offer a similar menu of joints which may be used to connect the system components. The languages used in IMP and ADAMS to input the geometry of the model are similar. In contrast, programs such as DYMAC use standard computer languages (e.g., FORTRAN).

A major difference in the way these programs operate is that IMP is formulated to analyze systems composed of linkages comprising "closed" kinematic loops, while ADAMS permits open loops. Dummy loops, with masses and stiffnesses equal to zero, may be used in IMP to connect free links to ground. For some types of analyses, the use of dummy loops may not be desirable because of the resulting increases in model complexity and computing time. For aerospace applications, the requirement that all components be connected to ground is particularly inconvenient.

DRAM is similar to ADAMS, mainly because these two programs were developed by the same people. DRAM is two dimensional, however, and so has considerably greater computing speed. It is also a good deal less expensive. A unique feature of DRAM is its generalized impact modeling capability.

PROGRAM USAGE

ADAMS, IMP and DRAM rely heavily on interactive graphics for presenting the results of the design session. In using programs such as these, however, it is first necessary to model the system geometry using alphanumeric program statements. This geometry is not the physical geometry of the system, but rather the kinematic geometry. The distinction is that many details of the physical geometry may be unrelated to the way the mechanism behaves kinematically. The kinematic "shape" of a linkage is defined by the points at which it is connected to other system elements and by its inertial properties. The actual physical shape of the linkage is unimportant unless the shape would cause a condition such as interference.

In addition to describing the kinematic geometry, specification of the forces and constraints which act on the system is necessary to complete the system model. This includes the types of joints which connect the system components, spring stiffnesses, damping constants, and externally applied forces and torques. A wide variety of joints may be used to connect the system components. For example, ADAMS allows the following types of connections: ball joints, U-joints, revolute (pinned) joints, translational contact, cylindrical joints, gear contact, screw joints, flat sliders, and rack-and-pinion gears. IMP offers a similar menu of joints.

Since DRAM is two dimensional, it is limited to translational and rotational contacts. Cam-and-follower-type contact is not currently available in any of the programs; however, this and other special situations may be simulated with user-written subroutines.

Forces and torques may be input as constants or as "conditional" values which only act under certain conditions. In this way, it is possible to model compliant members or simulate impact by specifying that certain forces act only when specific members are within a certain distance of each other.

The development of the system model and entering it into the computer comprises most of the work required to use the programs. The language used to describe the model is "user oriented," in that familiar terms are used to describe the system. For example, the ADAMS statement:

JOINT/3, REVOLUTE, I = 21, J = 14

defines a rotational joint, numbered 3, which connects previously defined points numbered 21 and 14. By using familiar terms such as this, it is intended to minimize the amount of computer programming experience which is required by the user. Once the system geometry is described, the program user is required to enter the initial conditions (displacements, velocities, etc.) for the mechanism, and define the time interval over which the analysis is to be performed. When the system has been fully described, the designer may run the program.

After the program has been run, the user may request a wide variety of graphical and alphanumeric outputs. The most descriptive output feature for kinematics is the computer graphics which is available; however, it will be shown that many other types of useful results can be obtained.

EXAMPLE

As an example of computer-aided mechanism analysis, consider the automobile suspension shown (without its tire or the automobile frame) in Figure 1. An ADAMS model of the suspension was created to examine the kinematic and dynamic properties of the suspension. The model consisted of five major parts with twelve degrees of freedom. Compliance effects were included by modeling the tire stiffness and damping effects, and two mechanical stops, four bushings, a spring and a shock absorber. Also included in the model were three ball joints, one universal joint and rack-and-pinion steering. Figure 2 depicts the computer graphics model created for this suspension. The graphics serve two purposes: verification of the correctness of the input model, and easier interpretation of the simulation results. By combining suspension models with a rigid body model of a truck body, it is possible to model the total vehicle, as depicted in Figure 3. Using the computer **graphics model, it is possible to determine** the response of the total vehicle without ever building a prototype.

The graphic output may be manipulated in a number of ways. The graphic model shown at various times may be superimposed on one view as in Figure 3, or each interval of time may be viewed individually. The view may be rotated, or zoomed in or out. It is also possible to show three orthographic views, either at individual time increments, or superimposed. This is demonstrated in Figure 4 with a robot arm. By using cameras which are computer controlled to take pictures of the graphics display at each time increment ("frame-by-frame"), it is possible to produce motion pictures which allow the response of the system to be viewed continuously throughout the time increment analyzed. This type of motion picture will be demonstrated at the symposium. Recently, new technology in computer graphics has made it possible to produce a similar graphic display directly on the computer terminal.

While graphic results are the most striking feature of these programs, other types of useful information may be obtained. The user may request plots or tabular listings of forces, displacement, velocities or accelerations as functions of time. An example of a plot produced by the IMP program is shown in Figure 5. These programs may also be asked to compute relative velocities, torques, static equilibrium positions, natural frequencies and the like. That these programs may be used with an alphanumeric terminal is an important economic consideration, since the cost of one of these terminals is quite a bit less than that of a graphics terminal.

While the example discussed previously is from the automotive industry, the use of mechanism analysis programs in aerospace applications is particularly advantageous since the analyst is able to simulate conditions of zero gravity. Since one can "turn off" gravity effects, simulations of mechanical systems which could not be tested on the ground can be performed. The programs have been used to analyze the performance of numerous aerospace systems such as landing gears, ailerons, airplane doors and deployable booms. The interactive nature of the programs allows the designer to quickly determine if a candidate design is able to fulfill the requirements of the desired mechanism. The kinematic properties of the system are clearly seen and the effect of design changes are immediately evident. Consequently, the time required to design a mechanism is reduced and the number of options which may be examined is greatly increased.

CONCLUSIONS

An introduction to the types of programs which are available has been given and some quick comparisons of the most widely used have been made. It has been shown that ADAMS, IMP, and DRAM are the most complete programs for mechanism work, and offer a comparatively wide range of analysis capabilities. Each of the programs offers certain advantages to the user, depending on the type of mechanism to be designed or analyzed. For more details on the programs, the reader is directed to References 1 through 15.

TABLE I

GENERAL ANALYSIS PROGRAMS

	ADAMS	DRAM	DYMAC	IMP	UCIN
Dimensionality	3-D	2-D	2-D	3-D	3-D
Capability	General mechanical systems*	General mechanical systems*	Closed-loop systems	Closed-loop systems*	Open-loop systems
Available from	Mechanical Dynamics, Inc., Ann Arbor, MI	Mechanical Dynamics, Inc., Ann Arbor, MI	B. Paul, U. of Penn. Phil., PA	Structural Dynamics Research Corp. Milford, OH	Univ. of Cincinnati
Graphics	Yes	Yes	No	Yes	No
Availability	Time-share or lease	Time-share, lease or purchase	Purchase	Time-share, lease or purchase	Purchase
Features	Large problems. Open- and closed-loops OK. Excellent graphics. Good support.	Large problems. Open- and closed-loops OK. Excellent graphics. Generalized impact. Good support.	FORTRAN language. Inexpensive	Large probs. Very accurate kinematic results, easy to learn. Excellent documentation. Good support.	Simple Inexpensive
Limitations	No generalized impact. Manual difficult to understand.	Planar mechanisms only. Manual difficult to understand.	Planar mechanisms only. Closed-loops only. No graphics.	Closed-loops only. Somewhat limited graphics. No generalized impact.	Open-loops only. No graphics.

*See text

TABLE II

PLANAR SYNTHESIS PROGRAMS

	KINSYN	LINCAGES	MECSYN
Dimensionality	2-D	2-D	2-D
Capability	Kinematics design synthesis	Kinematics design synthesis	Kinematics design synthesis, dynamics
Available from	Prof. Kaufman, George Washington, Washington, DC	Prof. Erdman, University of Minnesota, Mineapolis, Minnesota	Prof. Myklebust, Florida Atlantic University, Boca Raton, Florida
Graphics	Yes	Yes	Yes
Availability	Time-share (available Spring 1982) or purchase	Time-share or purchase	Purchase or time-share
Features	Interactive, small version to run on Apple computer being developed. Will handle 4-, 6- or 8-bar mechanisms	Interactive Device independence	Interactive Ringed data structure Can specify time-dependent properties 4-, 6- or 8-bar mechanisms
Limitations	No dynamics	No dynamics 4-bar mechanisms only	Cannot display mechanism itself

TABLE III

SPECIALIZED MECHANISM PROGRAMS

PROGRAM NAME	APPLICATION	DEVELOPER AND/OR AVAILABLE FROM
AFL	Static force analysis of four-bar linkage system	Structural Dynamics Research Corp., Cincinnati, Ohio
CAMDES	Design of disk cams	K. W. Chase, Brigham Young Univ., Provo, Utah
CAMDYN	Design of plate cams	B. Paul, University of Penn., Philadelphia, PA
CAMPAC	Synthesis, analysis, and design of cams	Prof. D. Tesar, Univ. of Florida, Gainsville, Florida
COMMENT I	Generalized mechanical design system with linkage cam, gear, spring, shaft and timing-belt design progrmas	IBM Systems, Development Division, Rochester, MN
DKINAL	Dynamic analysis of machinery	Prof. B. Paul, Dept. of Mech. Eng., University of Penn., Philadelphia, PA
DYREC	Dynamic analysis of reciprocating machines with multiple sliders	Prof. B. Paul, University of Penn., Philadelphia, PA
FLYLOOP	Flywheel design	Prof. B. Paul, University of Penn., Philadelphia, PA
FORBAR	Kinematic and dynamic analysis of four-bar linkage systems	Structural Dynamics Research Corp., Cincinnati, Ohio
GODAS	Design of parallel axis gears	D. Hughson, Ford Motor Co., Dearborn, Michigan
IMAGE	Design and analysis of planar mechanisms	Reed and Garrett, University of Texas, Austin, Texas
ISD-FORSS	Force system structural synthesis of four-bar mechanism	Prof. Carson, University of Missouri-Columbia, Columbia, MO
KINAL	Kinematic analysis of planar multiple-loop mechanisms	Prof. B. Paul, University of Penn., Philadelphia, PA
SLIDER	Static and dynamic analysis of slider crank systems	Structural Dynamics Research Corp., Cincinnati, Ohio
STATMAC	Static analysis of planar machines	Prof. B. Paul, University of Penn., Philadelphia, PA

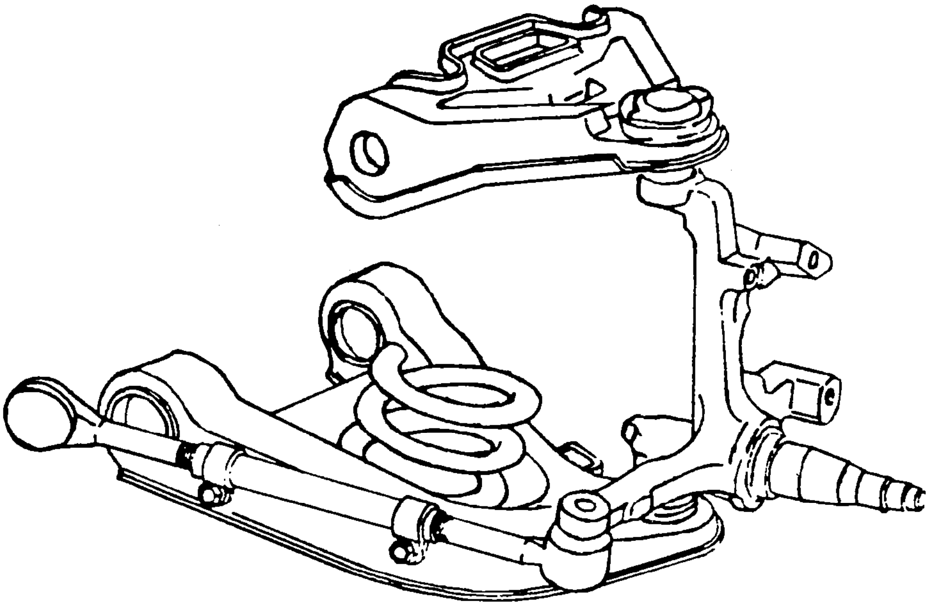

FIGURE 1 - SCHEMATIC OF AUTOMOBILE SUSPENSION
(WHEEL AND TIRE NOT SHOWN)

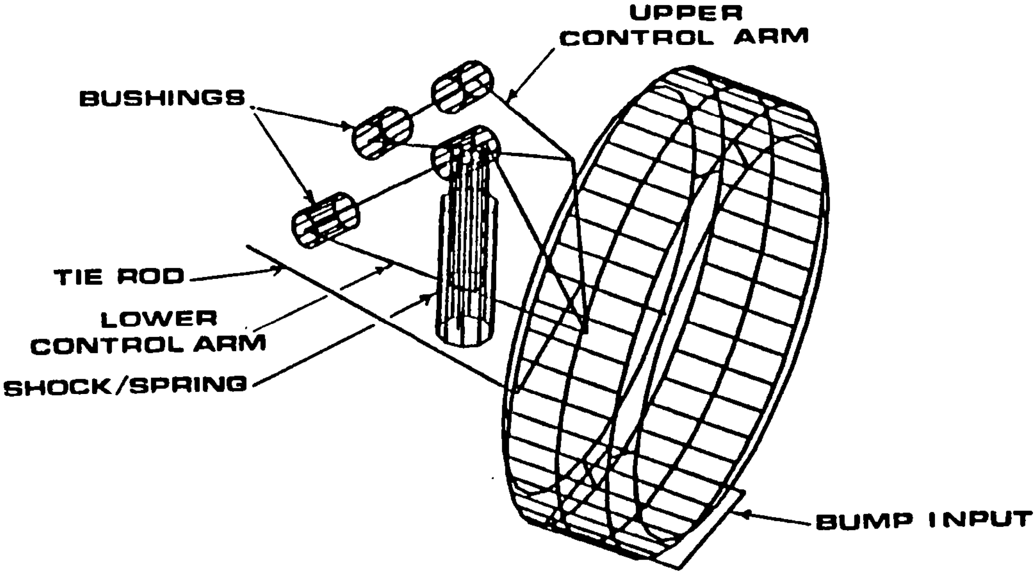

FIGURE 2 - ADAMS GRAPHICS MODEL OF SUSPENSION

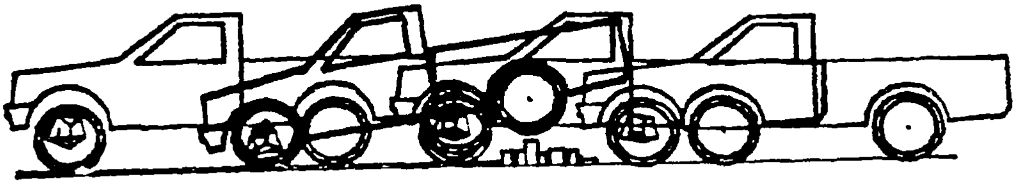

FIGURE 3 - TOTAL VEHICLE SIMULATION

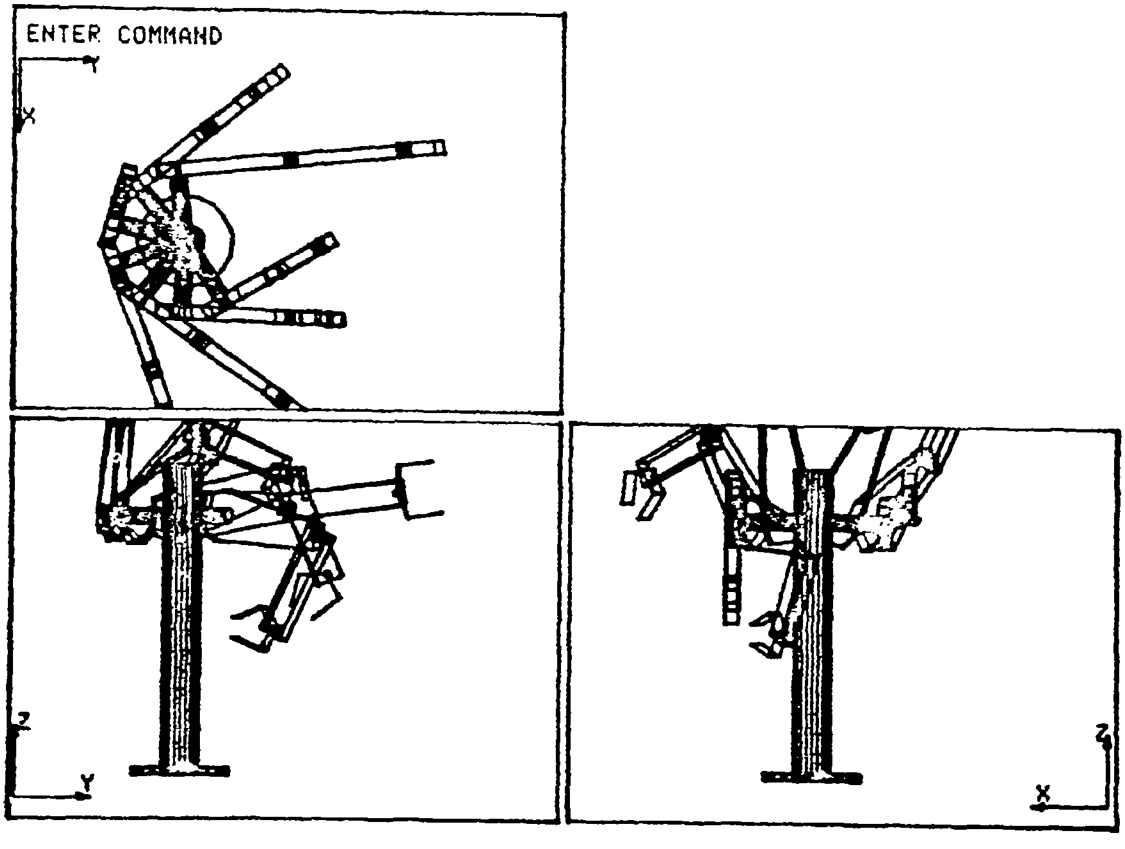

FIGURE 4 - SUPERIMPOSED ORTHOGRAPHIC VIEWS
OF A ROBOT ARM

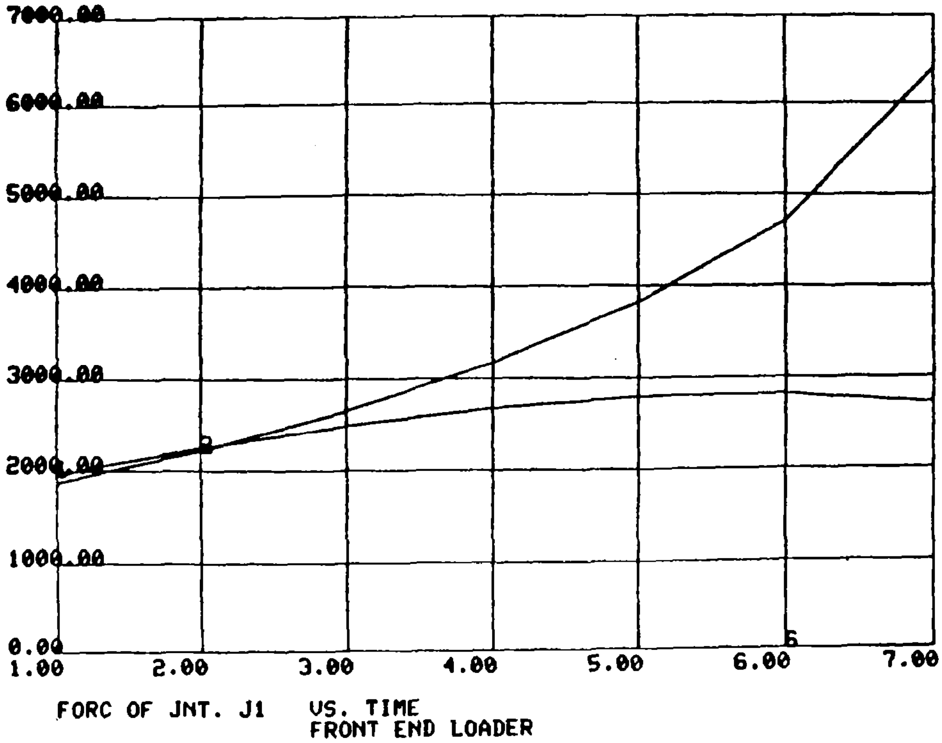

FIGURE 5 - IMP FORCE PLOT

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