MADYMO - CRASH VICTIM SIMULATIONS,
A COMPUTORISED RESEARCH AND DESIGN TOOL*

by

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Abstract

MADYMO is a compact general purpose computer program package for two- or three-dimensional Crash Victim Simulations. The program predicts the kinematic and dynamic behaviour of the victim during the crash, based on data of the victim, environment, safety devices and crash conditions. The package differs from most of the existing CVS programs by its flexibility in choice of number of linkages and number of elements in each linkage. Great flexibility in the modelling of force interactions between elements and environment is assured by the fact that user-defined submodels can readily be incorporated. The program is used in basic biomechanical crash research as well as the development and optimisation of crash safety devices such as seat belts and child seats. This paper briefly discusses the theoretical basis and the use of MADYMO, with some examples of applications.

INTRODUCTION

In the field of automotive safety research, simulation of crashes to study the effects on the human body is vital in order to evaluate and improve crash safety devices and occupant environment. Most of this work is done by way of experiments, using instrumented dummies, cadavers, and occasionally animals or volunteers.
In the sixties, fast digital computers together with advanced mathematical techniques led to a new method i.e. simulation with mathematical models. These models have the advantage that a great number of simulation results can be

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obtained easily, for there is no practical limit on the number of sensors and there are no other measurement problems as occur with experiments. Based on the complete reproducibility of computer simulations, sensitivity studies to establish the relative importance of system parameters can be easily carried out. Mathematical models in conjunction with experiments can effectively reduce the number of tests with cadavers, animals or volunteers which are sometimes controversial.
This paper describes the MADYMO general purpose computer program package for Crash Victim Simulations.

EXISTING CRASH VICTIM SIMULATION MODELS

Mathematical models to simulate automobile crash victims have been developed during the past seventeen years. Such models are either 2- or 3-dimensional with a number of mass-carrying elements representing the human body ranging from 3 up to 15 (variable for the CAL-3D-CVS model).
In general, models have provisions to simulate realistic joint characteristics by elastic springs, viscous damping, coulomb friction and joint stops. The exterior body geometry is primarily presented by contact-sensing ellipses and the environment of the victim by sections of lines or planes. Resulting contact forces are calculated from tabular force-deformation curves together with provisions for viscous damping and coulomb friction. Restraint belt forces are calculated by simple or more sophisticated submodels.
The crash energy input is the acceleration time histories for almost all models. A detailed review and comparisons of existing models are given by King |1|, Robbins |2| and Huston |3|.
The MADYMO Crash Victim Simulation program package offers a choice of either 2- or 3-dimensional simulation and complete freedom of selection of the number of linkage systems, each with a variable number of elements. In addition, the package is arranged to be easy to use and compact in program size and memory storage needs, and therefore intermediate sized computers can be used for most simulations.

THEORETICAL BASIS OF MADYMO

Most existing computer models used to study the highly variable gross motion of the human body during a car crash are based on tree-structured linkages of rigid elements connected by joints. The motion of these systems is a result of externally applied forces, force interactions between elements and environment and of torques in the joints. Those forces and torques during the simulation are calculated by submodels using geometric and kinematic data in the system. These submodels are called "force interaction models" and will be described in the next chapter.

In order to perform a time-history simulation of the motion it is necessary to derive the equations of motion for the systems. These equations calculate the accelerations of the elements for each time-point using the external forces and torques from the force interaction models. The accelerations are then used for an integration procedure to predict the positions and velocities of the elements for the next time-point. The equations of motion are non-linear and have time-dependent coefficients due to the widely varying geometry of the systems.

Basically, there are two methods of deriving the equations of motion for systems of rigid bodies connected by pinned or ball and socket joints. One is the Newton-Euler and the other is the Lagrange method. Other authors advocate a combination of these methods known as Lagrange's form of d'Alembert's principle |4,5|.

For MADYMO the Lagrange method is used to establish a formalism for computer generation of the equations of motion. The advantage of this method is that the exact number of governing equations is directly obtained, without any need to eliminate constraint forces in the joints.

The position of each element with respect to time is expressed in an arbitrarily chosen, rectangular, absolute reference frame. A local rectangular frame with its origin in one of the joints is rigidly connected to each element. The angular orientation of each element with respect to the absolute reference frame is defined by three independent Bryant angles |6| or a single rotation angle for 2-dimensional simulations. These rotations together with rectangular coordinates in the absolute reference frame of one selected reference joint of the linkage form the generalised coordinates.

The mass distribution of a rigid element is represented by an arbitrarily located concentrated mass and by 3 principal moments of rotational inertia. For each element an arbitrarily number of joints can be defined representing the connections with adjacent elements (fig. 1).

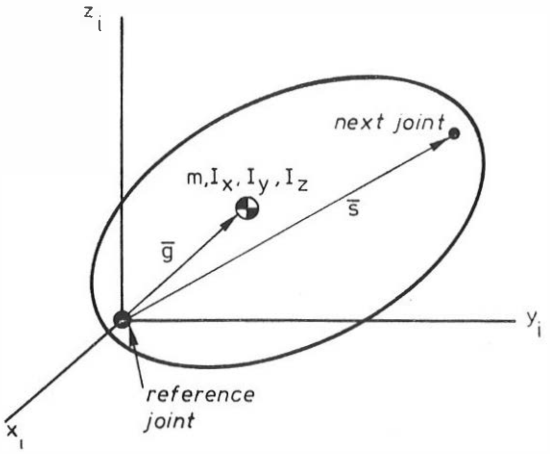

fig. 1 rigid element

m = concentrated mass

I_x =
I_y = {principal moments of rotational inertia
I_z =

$\bar{g}$ = vector defining centre of gravity

$\bar{s}$ = vector(s) defining the joint(s) with adjacement element(s)

Lagrange's equation (1) is applied to a single chain of n successive numbered elements:

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{q}_k} - \frac{\partial T}{\partial q_k} = Q_k(\dot{q}_i, q_i) \quad (k = 1, 3(n+1)) \tag{1}$$

where: T = total system kinetic energy

q_k = k-th generalised coordinate

Q_k = k-th generalised force

Splicing and regrouping of these equations, together with the introduction of partition matrices to break down the local coordinate systems transformations, leads to the final form (2):

$$S\ddot{\bar{q}} = \bar{r}_s + \bar{r}_k \tag{2}$$

where: S = symmetrical system matrix; it contains mass, inertia and dimensions;

$\ddot{\bar{q}}$ = column matrix with the elements of the generalised accelerations $\ddot{q}_k$ (k=1,3(n+1));

$\bar{r}_s$ = column matrix with the generalised forces due to velocity effects (pseudo forces: centrifugal and coriolis);

$\bar{r}_k$ = column matrix with the generalised forces due to external forces and torques on the system.

This set of 3(n+1) coupled second order differential equations with non-linear first order terms and non-constant coefficients for a chain of n successively numbered elements is programmed for the computer. Those equations form the base for a formalism that automatically generates the complete set of equations of motion for multiple topological tree-structures of linked rigid elements (fig.2).

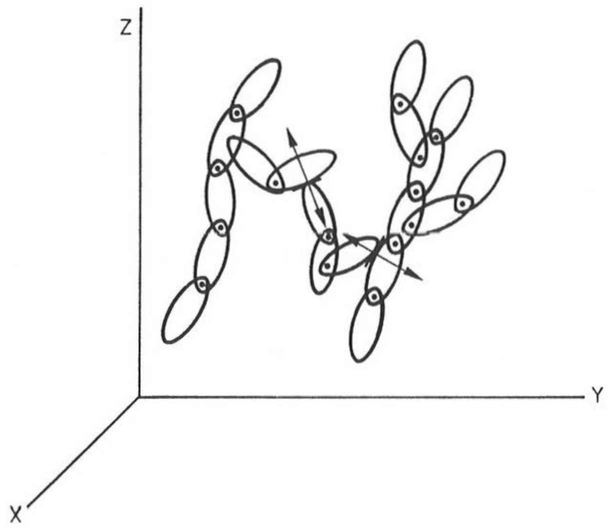

fig. 2 Tree structures of elements in force interaction.

FORCE INTERACTIONS MODELS

The equations of motion in the preceding chapter give an exact description of the dynamics of the linkages of elements. For most practical simulations however, the externally applied forces and torques in the joints cannot be calculated exactly and submodels based on simplifications of the complex physical reality then have to be used. These so-called "force-interaction models" are in principle not a part of the MADYMO program package, because their nature is greatly dependent of the kind of simulation that the user wants to perform.

The program package architecture is modular, so that the user can easily incorporate his own defined force interaction models. Any such submodels do not interfere with the basic program and no detailed knowledge of the theory is necessary.

The most common application of MADYMO is for automotive crash research with cars or deceleration sleds. For these applications the necessary force interaction models are defined and are incorporated in the program as "standard force interaction models" and are described below.

1. Joint torque model

This submodel calculates the resistive torques in the joints between two connected elements. For each relative rotation (one for 2-dimensional and three for 3-dimensional) a separate torque is defined. These torques may consist of elastic, viscous damping and coulomb friction components. The elastic torque is dependent on a tabular torque-relative angle function which represents any continuous curve. This curve may also be used to model "soft elastic" joint stops by giving the curve a steep slope at the end of the joint range of motion.

2. Acceleration forces model

This model calculates accelerative (decelerative) forces on the centre of gravity of each element. These forces are dependent on tabular acceleration-time functions representing the continuous acceleration history curves.

3. Contact forces model

This submodel calculates forces for contacts detected during the simulation between an ellipsoid and a plane. Each ellipsoid and each plane may be connected to any element of any system or to the laboratory fixed absolute reference frame.
The calculated force may consist of elastic, viscous damping and coulomb friction components. The elastic force is dependent on a tabular force-perpendicular penetration function representing any continuous curve.

4. Belt forces model

This submodel calculates belt forces for belts between two elements or belts between an element and any location in the fixed absolute reference frame.
The belt force is dependent on a tabular force-relative elongation function representing any continuous curve. This routine also has an option for initial belt slack or pretension.

MADYMO CRASH VICTIM SIMULATION PROGRAM PACKAGE

The MADYMO package is based on the FORTRAN source code to make adaptions easy. All tables with input and simulation parameters are contained in common area's for shared use of those by MADYMO and the user-defined routines. The package contains a standard output print option of all input and simulation data. For most simulations the user is interested in only a small portion of the output data, which can be obtained by a simple user-defined subroutine for printing these data. This same routine may be used to produce datafiles with relevant information for user-written, post-processing plotprograms to produce stick-figures for the kinematics and graphs of the dynamics.

The size of the standard program files of MADYMO version 1 are 1450 cards for 2-dimensional and 2200 cards for 3-dimensional simulations (these numbers include the cards with explanatory comment lines). The memory storage needs and the computer run times are dependent on the specific simulation data, such as number of modelled elements, number of contacts allowed etc.

In principle, MADYMO can be used for other problems in the field of dynamics of systems of rigid bodies, because the package readily allows all kind of sub-models for force calculation to be incorporated.

VALIDATION OF MODELS

In general, the results of simulations with mathematical models must be compared with physical reality.
For some simulations a theoretical solution to the problem exists, examples being vibrating spring mass systems and swinging pendulums. In those cases the model results can be directly compared with the theoretical solution. This process can be denominated as an ANALYTICAL VALIDATION of the model and may be used for a check of correctness of algorithms and programming. For most simulations, however, no theoretical solution exists and validation has to be based on comparison with experimental results. The dicision that the model predictions correlate acceptably with observed facts can be denominated as EXPERIMENTAL VALIDATION.
In practice, this means that a subset out of the model results must be selected and a criterion must be found to determine whether or not the correlation with the experimental results is acceptable. This problem of establishing a method for validation has not yet been solved completely, so the only way to approach this problem now is to follow common practice and good engineering judgement |7|.

HOW TO USE THE PROGRAM PACKAGE

The use of the MADYMO program package is illustrated with an example of a simplified planer simulation of a car crash with a child dummy sitting in a child restraint seat (see fig. 3).

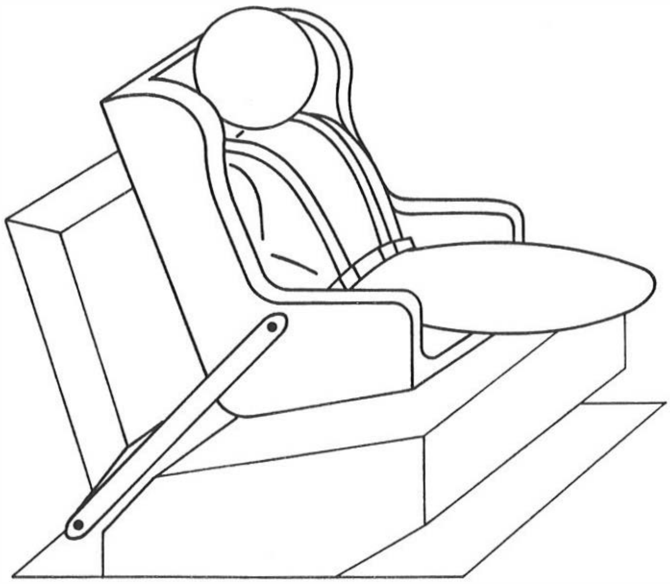

fig. 3 Simulation example

A first step towards a simulation is to make a set-up drawing for definition of relevant elements, geometry, contacts, belts, reference frames etc. (see fig.4).

The geometrical values from the drawing together with selected data for the masses, location of centres of gravity, moments of inertia, joint properties, contact properties, belt properties and car deceleration pulse are grouped into tables to form the input data set. These data may be obtained from measurements on the dummy, child seat, car seat belts etc. or selected from literature and estimations.

For the simulation defined by this input data set, the selected 2- or 3-dimensional standard program file is exactly dimensioned to obtain minimum program memory storage requirements. This dimensioning is simply effected through the user's local computer editing facilities by replacing symbolic array declarations with the relevant numbers.

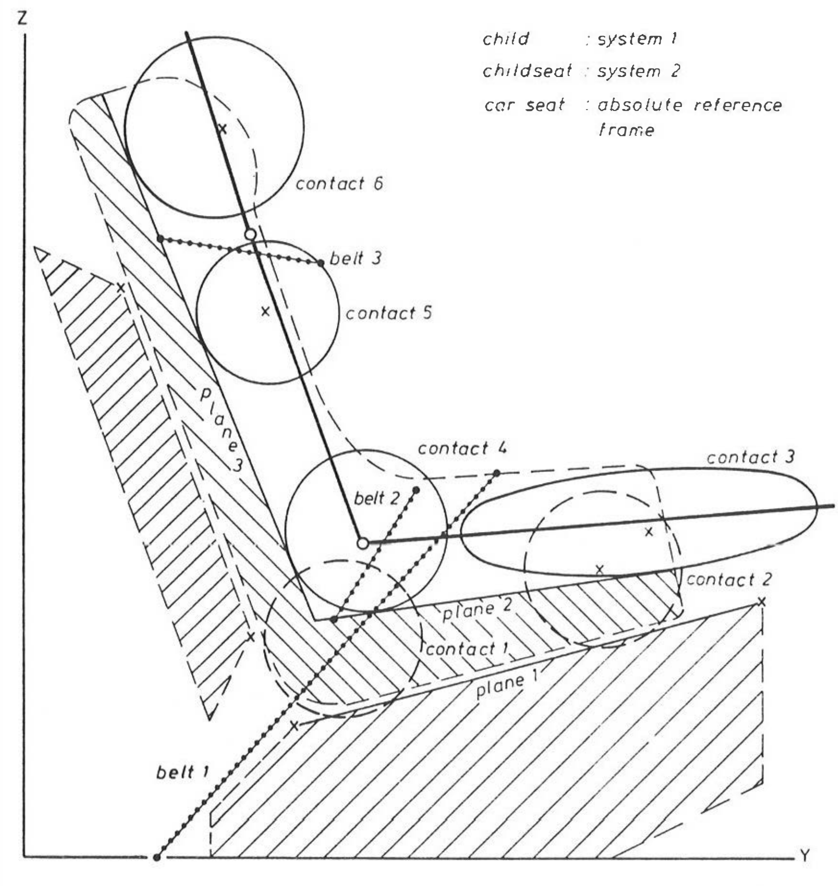

fig. 4 Set-up drawing for mathematical simulation

Finally, the program file is completed by an additional user-written subroutine for printing a table with time functions of some selected variables (fig. 5).

TIME (SEC)	LAPBELT FORCE(N)	CONTACT 2 FORCE(N)	RES. HEAD ACC. (M/S**2)	HEAD EXC. (M)
0.000	0.	0.	0.	0.000
.002	0.	0.	0.	0.000
.004	0.	0.	0.	0.000
.006	0.	0.	0.	0.000
.008	0.	0.	0.	0.000
.010	0.	0.	0.	0.000
.012	0.	1.	40.	.000
.014	0.	5.	80.	.000
.016	1.	12.	118.	.001
.018	3.	21.	158.	.002
.020	7.	34.	198.	.003
.022	12.	49.	195.	.006
.024	19.	66.	197.	.009
.026	29.	83.	194.	.013
.028	38.	105.	191.	.018
.030	47.	183.	190.	.023

fig. 5 Output table with time functions of some user-selected variables

This routine may also be used to produce files with time functions of some coordinates, forces, accelerations etc. which are used as input for user-made, post-processing programs to plot simulation, kinematics and dynamics (fig. 6).

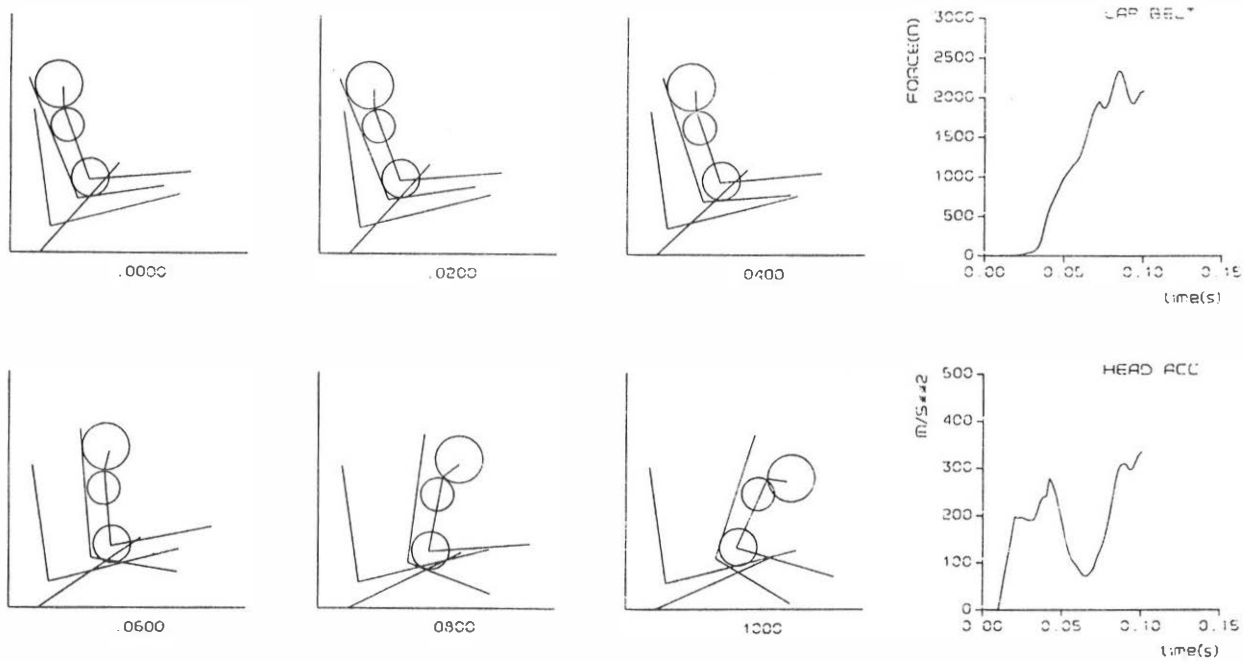

fig. 6 Example of user-made plots

The optional standard printed output of the complete simulation data is in practice only used for diagnosis of errors due to mistakes in the input data or poor modelling assumptions.

EXAMPLES OF APPLICATIONS

The versatility of the MADYMO program package for a wide variation of applications is shown by a selection of plotfigures showing kinematics of different simulations (fig. 7, 8, 9, 10, 11, 12).

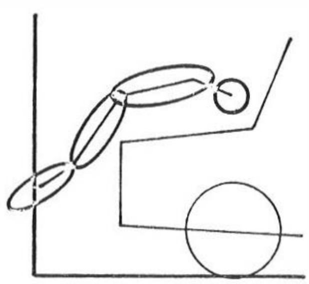

fig. 7 Pedestrian-car collision

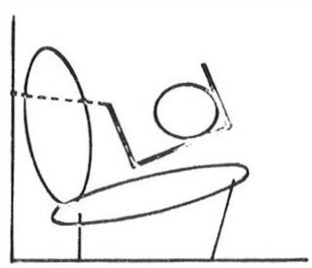

fig. 8 Baby carrycot on rear seat

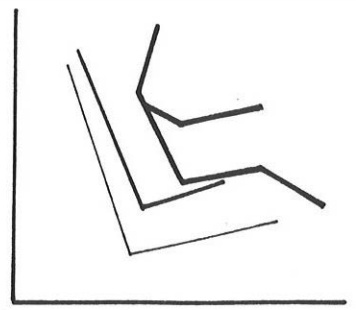

fig. 9 Child restraint seat evaluation

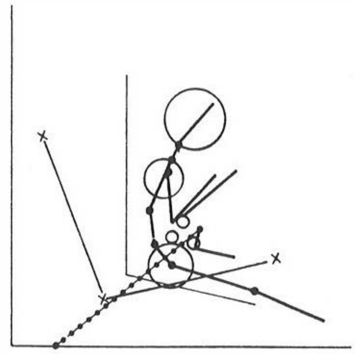

fig. 10 Design study on dynamic-acting child-restraint seat

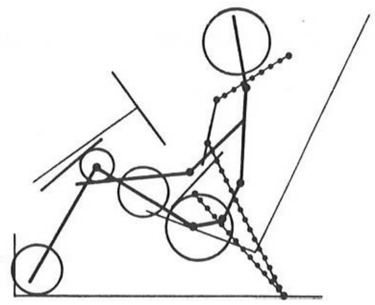

fig. 11 Mathematical reconstruction of frontal collision

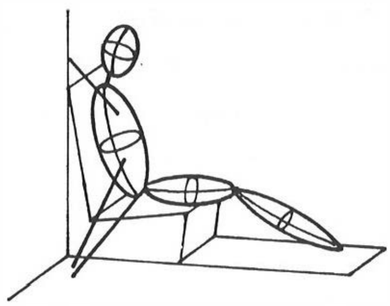

fig. 12 Deceleration sled test for belt approval

MADYMO was used successfully in a combined study of experimental and mathematical evaluation of a child restraint system. This study showed that the mathematical model of the child gives a better representation of cadaver kinematics than a dummy does |8|. The package is now used for mathematical reconstruction of a real frontal collision |9| and for a computer-aided design study of a dynamic-acting, child restraint seat |10|.

STANDARD DATA SETS

Mathematical CVS models are potentially a powerful tool for research and design studies. The widespread use of this tool has been held back because CVS models are not always easy to use and sometimes have complex input data structures. In addition, there is a lack of reliable input parameters. Some of the input data are easily obtainable, e.g. geometrical values, but others, like dynamical joint and contact properties, must be established by complicated measurements.

A great deal of effort is now being invested in MADYMO to standardize input data sets for representation of existing car crash dummies. These could considerably reduce the set-up costs and time spent on a particular simulation. The user then simply selects the data set and only provides additional data for the environment, restraint systems and crash conditions.

In a way this can raise mathematical modelling to a level comparable with experimental crash research. For realiable data sets of dummies, cadavers and real victim, cooperation between laboratories using the CVS models, and basic researchers working on anthropometric data banks, is essential.

CONCLUSIONS

- MADYMO is a useful tool in crash research projects and design optimization.
- MADYMO offers the user a choice of either 2- or 3-dimensional simulation of multiple tree-structured linkages of rigid elements. Each tree-structure may have any number of elements.
- The program package readily allows user-defined submodels for force interaction calculation to be incorporated.
- Mathematical simulations can be used for sensitivity studies of systems parameters and reduce the number of necessary experiments.
- Standard input data sets can reduce the set-up costs and time for a simulation considerably.

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