Mathematical Simulation for Crashworthy Aircraft Seat Design

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A three-dimensional mathematical model of an aircraft seat, occupant, and restraint system has been developed for use in the analysis of light aircraft crashworthiness. The occupant model consists of 12 rigid mass segments whose dimensions and inertial properties have been determined from studies of human body anthropometry and kinematics and from measurements of a production anthropomorphic test dummy. Because of the significant role played by the seat in overall system crashworthiness, a detailed finite-element model of the seat structure is included. The input data are structured so that any aircraft seat can be modeled by providing only nodal coordinates, element cross-sectional dimensions, and material properties. Plastic behavior is simulated by plastic hinges at the beam ends. Comparisons of model predictions with measured data for a dynamic test of an energy-absorbing seat are included.

Nomenclature

A	= inertia matrix
B	= velocity-dependent vector derived from kinetic energy
C	= rate coefficient
F	= force on occupant
P	= force vector derived from potential energy
q_j	= generalized coordinate
R	= vector of generalized joint resistance forces
T	= kinetic energy
V	= potential energy
X,Y,Z	= absolute position
x,y,z	= position in segment-fixed coordinate system
X_H	= heel position in aircraft coordinate system
γ	= initial position angular coordinates
$\dot{\delta}$	= rate of deformation
ψ,θ,ϕ	= Euler angles

Introduction

THERE are three major considerations in designing crashworthiness into a vehicle structure, whether it is to be used on land or in the air. The first is to insure that sufficient living space is maintained during impact. The second is to restrain the occupants to prevent injurious contact with the vehicle interior or ejection from the vehicle; implicit in this requirement is the need to retain the seat in the vehicle as well as keep the occupant in the seat. Third, the forces experienced by the occupant should be attenuated to a tolerable level.[1]

The aircraft crash environment presents problems that can make protection of occupants particularly difficult. The peak vertical acceleration present in a crash often exceeds the level that the human body can tolerate in a direction parallel to the spine. Therefore, the vertical impact forces, which are usually present, are often significant in determining occupant survivability. In light aircraft, it is seldom practical to consider designing sufficient energy-absorbing capability into the lower airframe structure to protect against these vertical forces, as the crush space is generally not available. Therefore, the seat must play an important role in the crashworthiness of an aircraft. Including some mechanism for energy absorption in the seat structure can greatly improve occupant survivability in a crash. However, not only does prediction of seat structure response to dynamic loading present a complex engineering problem, but gross overall deformation of the seat further complicates restraint system design in light aircraft, where the lap and shoulder belts are normally attached to the aircraft structure.

A number of dynamic models of the human body have been developed for use in crash survivability analysis. These models vary in complexity and possess from 1 to 40 degrees of freedom. One-dimensional models have been used in prediction of human body response to an ejection seat firing, which, with the body tightly restrained, is an essentially one-dimensional phenomenon. However, a vehicle crash generally involves a horizontal component of deceleration, which forces rotation of body segments with respect to each other. If no lateral component of deceleration is present, a two-dimensional model will suffice, provided that the restraint system is symmetric. The diagonal shoulder belt that, combined with a lap belt, forms the standard automotive restraint system and the one most likely to be used in light aircraft is asymmetric and may cause lateral motion of the occupant even in the absence of a lateral deceleration. Therefore, a model that is to be useful in restraint system evaluation must be capable of predicting three-dimensional motion, and several three-dimensional kinematic models, made up of interconnected rigid links, have been developed.[2-5] Naturally, the increase of complexity to improve the quality of simulation is accomplished at the expense of solution economy, requiring larger computers and longer execution times.

In this paper, a digital computer program developed for use in analysis and design of light aircraft seats and restraint systems is described. Additional details, particularly concerning the mathematical modeling, can be found in Ref. 6. It should be kept in mind that the goal in the development of this model has been a tool that will be useful to engineers whose function is aircraft seat and/or restraint system design. Although the program is certainly applicable to more general use, this function influenced a number of decisions during development.

Occupant Model

The aircraft occupant is modeled by 12 rigid mass segments, illustrated in Fig. 1, with rotational springs and dampers at the joints. Twelve segments are thought to represent the minimum number that will permit meaningful, accurate predictions. The two torso segments are included to simulate bending of the torso about the restraint system,

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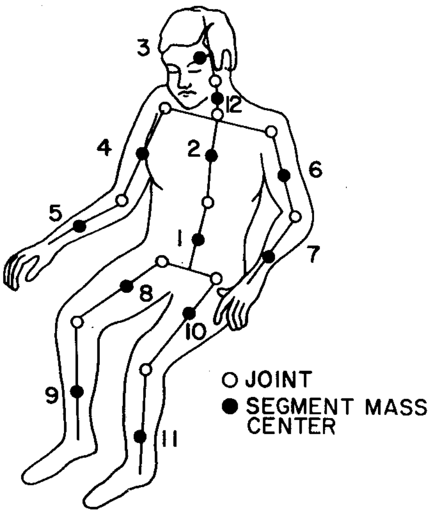

Fig. 1 Twelve-mass occupant model.

which may result in either "submarining" under the lap belt or rolling over a diagonal shoulder belt. Separate head and neck segments are intended to produce a reasonable simulation of head rotation in order to more accurately predict the head accelerations that are required for injury models. The four arm and leg segments are necessary for prediction of contact between these extremities and the aircraft interior. Whereas automobile seating positions are usually configured such that proper restraint may prevent contact between the occupant and the vehicle interior, except in side impact or very severe frontal impact, higher density seating arrangements are common in aircraft. Because contact is likely to occur, the ability to accurately determine the point of impact would facilitate design of a safer interior. Although leg and arm injuries, in themselves, may not be as serious as head or chest injuries, they may prevent escape from a stricken aircraft and the potential hazard of postcrash fire.

Each of the torso joints possesses three rotational degrees of freedom. Because of the hinge-type motion at elbow and knee joints, the position of a forearm or lower leg relative to an upper arm or thigh, respectively, is described by one additional angular coordinate. In total, the occupant model possesses 29 degrees of freedom.

Equations of Motion

The response of the occupant is described by Lagrange's equations of motion, which are written as functions of 29 independent generalized coordinates that define the position of the system. The equations are written in the form

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial T}{\partial \dot{q}_j}\right)-\frac{\partial T}{\partial q_j}+\frac{\partial V}{\partial q_j}=Q_j \qquad (j=1,2,\ldots,29) \qquad (1)$$

where T and V are the system kinetic and potential energies, Q_j are the generalized forces that are not necessarily derivable from a potential function, and q_j are the generalized coordinates.

The generalized coordinates are: the Cartesian coordinates of the mass center of the lower torso segment in the inertial system; Eulerian angles for the torso, head, upper arm, and thigh segments; and one additional angle for each of the forearm and lower leg segments and for the neck. The Euler angles (ψ_n,θ_n,ϕ_n) define the orientation of a segment-fixed coordinate system (x_n,y_n,z_n), which is assumed to be a set of principal axes fixed at the mass center of segment n, relative to the inertial (X,Y,Z) system. The orientation of each local system with respect to the segment is based on the reference position of the body, in which the occupant is seated with the torso and head upright, the upper arms and lower legs parallel to the torso, and the elbows and knees bent at right angles. The positive directions of the local axes in the reference position are x_n forward, y_n to the left, and z_n upward. Assuming that the coordinate axes are initially parallel to those of the inertial system, the Euler angles are defined according to the following sequence of rotations, illustrated in Fig. 2:

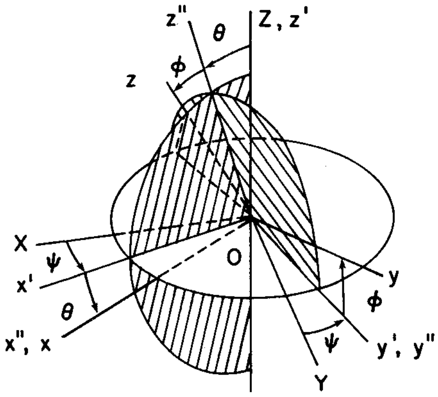

Fig. 2 The Euler angles.

1) A positive rotation ψ about the Z axis, resulting in the primed (x',y',z') system.

2) A positive rotation θ about the y' axis, resulting in the double-primed $(x'',y''z'')$ system.

3) A positive rotation ϕ about the x'' axis, resulting in the final (x,y,z) system.

For purposes of computation, the equations of motion are rewritten in the following form:

$$[A(q)]\{\ddot{q}\}=\{B(\dot{q},q)\}+\{P(q)\}+\{R(\dot{q},q)\}+\{Q(\dot{q},q)\} \qquad (2)$$

where the elements of the inertia matrix $[A]$ and the vector $\{B\}$ are obtained from the kinetic energy derivatives, and $\{P\}$ is derived from the potential energy. Both $\{R\}$ and $\{Q\}$ are vectors of generalized forces: $\{R\}$ describes the resistance of the body joints to rotation, and $\{Q\}$ is the vector of generalized external forces. Both are now discussed in further detail.

Joint Resistance

Rotation of the body joints is resisted by nonlinear torsional springs and viscous dampers. The elements of the generalized joint force vector $\{R\}$ in Eq. (2) are functions of the angular displacements of the eleven body joints from the reference position. The damping coefficient for each joint is constant in all cases. The spring moments, on the other hand, depend on the user's choice of human or dummy occupant. For simulation of a human occupant, they are zero throughout the normal range of joint rotation, but increase rapidly at the limiting angular displacements. For simulation of an anthropomorphic dummy, the spring moments are constant (nonzero) throughout the normal range of motion, and increase to higher values to limit the rotation, just as in the case of the human occupant. The constant values for the dummy model are set equal to the torques that should ideally result from the joint-tightening procedure of SAE Recommended Practice, Anthropomorphic Test Device for Dynamic Testing – J963.

External Forces

The external forces that act on the twelve body segments can be characterized as either contact forces or restraint forces. The contact forces, illustrated in Fig. 3, are the forces exerted by the cushions, the floor, and an optional inflatable restraint. Each of these forces acts at a fixed point on a body

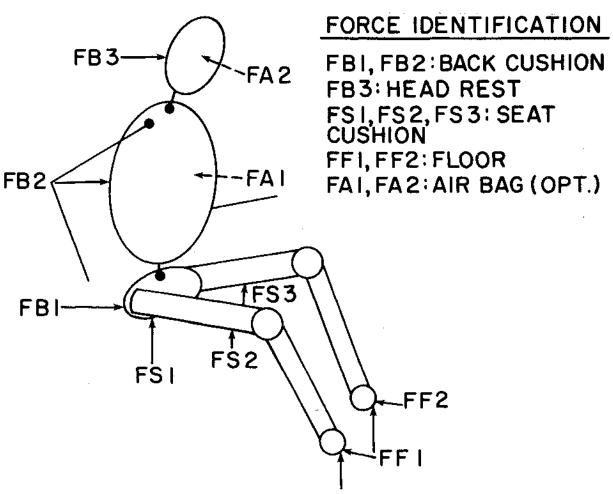

Fig. 3 Contact forces.

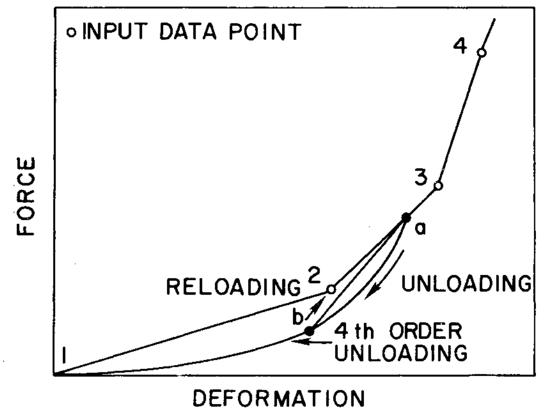

Fig. 4 Force-deformation model.

segment. In fact, they all act at segment mass centers, with the exception of the floor forces, which are applied at the feet, and the force of the seat cushion on segment 1, which acts at a point midway between the hip joints.

The forces are calculated by first determining, from occupant displacement, the penetration of a rigid contact surface fixed to a body segment into either a cushion or the floor. Using this deformation, the force is then computed using the model illustrated in Fig. 4. The actual force-deflection curve is approximated by three linear segments that are defined by input of forces and deflections. Initial loading follows the basic curve from 1 to 2 to 3. Deformation between points 1 and 2 is considered elastic, so that, should the deflection decrease prior to reaching point 2, unloading would proceed down the loading curve. However, beyond point 2, a decrease in deflection will cause the member to unload along a fourth-order curve between the point where unloading starts and the origin. If the deformation returns to zero, reloading takes place along the original loading curve, i.e., from 1 to 2, etc. However, if the deformation increases again prior to reaching zero, the member will reload along a straight line from the point where reloading starts to the point from which unloading had begun; the reloading line is followed until the original loading curve is intersected. The effect of the rate of deformation is included by use of the relationship

$$F=F_s(1+C\dot{\delta}) \tag{3}$$

where F_s is the static force computed according to the model of Fig. 4, C is a rate-sensitivity coefficient provided by input, and $\dot{\delta}$ is the rate of deformation.

The method used in calculating the forces exerted on the body by the restraint system differs somewhat from that used for the contact forces. The principal difference is that the restraint forces do not act at any fixed points on the body, but, rather, the points of application depend on current belt geometry. The four available restraint system configurations consist of a lap belt alone or combined with a single diagonal belt, over either shoulder, or a double shoulder belt. The restraint loads are transmitted to the occupant through ellipsoidal surfaces fixed to the upper and lower torso segments, shown in Fig. 5. The locations of the anchor points A_1, A_2, and A_3 on either the seat or the airframe structure and of the buckle connection B are determined by user input along with webbing properties.

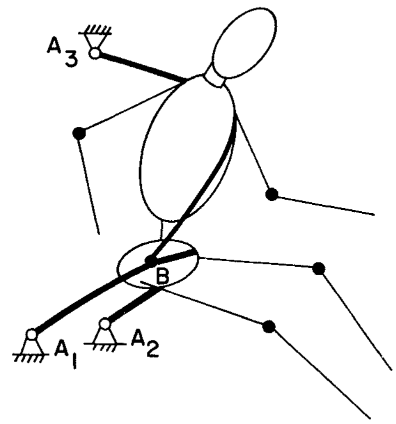

Fig. 5 Restraint system configuration (lap belt with diagonal shoulder belt).

For both the upper and lower torso restraints, the forces are determined in the same manner. First, the belt loads are calculated from the displacements of the torso surfaces relative to the anchor points. Then, the resultant force on each segment is calculated as described for the contact forces and applied at the point along the arc of contact between the belt and the ellipsoidal surface where the force is normal to the surface.

The capability of the belts to move relative to the torso surfaces allows simulation of "submarining" under the lap belt, an important consideration in design of a restraint system.

Occupant Physical Properties

Because it has been assumed that the principal user of this program is interested chiefly in the seat or restraint system, a minimum of information is required to describe the occupant. Input data include the selection of human or dummy, the main difference being the joint model, as discussed earlier. The dimensions and inertial properties for "standard" occupants, a 50th percentile civilian male and a 50th percentile anthropomorphic dummy, are included in the program. The segment lengths, masses, center-of-mass locations, and moments of inertia for the human occupant model are based on cadaver data reported in Refs. 7-9, averaged and adjusted to approximate 50th percentile values. Corresponding properties for the dummy model are based on the specifications of Federal Motor Vehicle Safety Standard 208, Part 572. Should a user wish to simulate a larger or smaller occupant, provision is made to input nonstandard properties.

For calculation of external forces exerted on the occupant by the seat cushions and restraint system and for prediction of impact between the occupant, and the aircraft interior, 23 surfaces are defined on the body. These surfaces are ellipsoids, spheres, and cylinders, as shown in Fig. 6. The dimensions of these surfaces were obtained from an anthropometric study of the U.S. civilian population.[10]

The ranges of joint rotation that are used in the program are based on the data of Dempster[7] and Glanville and Kreezer[11] for the human occupant and SAE J963 for the

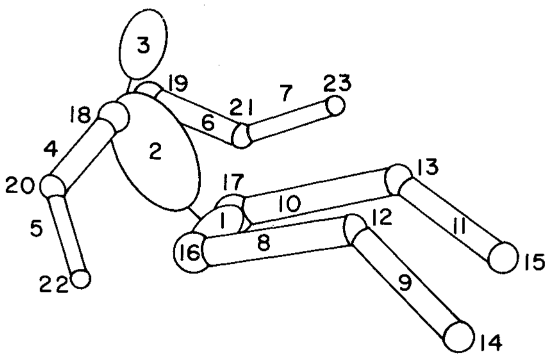

Fig. 6 Occupant model contact surfaces.

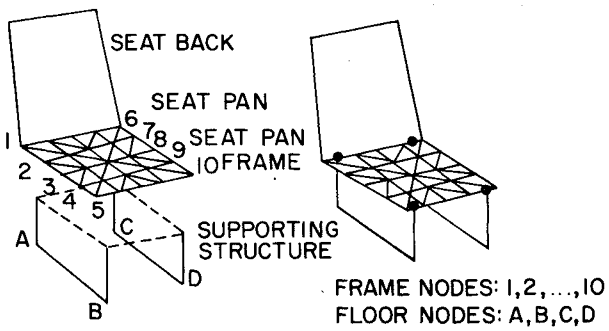

Fig. 7 Seat model components.

dummy. For the joints where the allowed range of rotation was found to depend on the axis of rotation, the rotation about the y_n axis, which would predominate in a frontal impact, was considered most important and is used as the single limiting angle in the model. As an example, Glanville and Kreezer's data for forced rotation of the head show a limit of 77 deg for dorsiflexion (backward rotation about a lateral axis), 76 deg for ventriflexion (forward rotation about a lateral axis), and 63 deg for lateral flexion (side-to-side rotation about an anterior-posterior axis). However, the angle of 76 deg is used in the model, because ventriflexion is considered the most significant of the three rotations.

Seat Model

The seat model employs conventional finite-element analysis techniques. The seat pan is composed of membrane elements, as shown in Fig. 7. The seat cushion load is distributed parabolically over nine nodes, which are selected according to the current position of the occupant on the seat. A seat pan frame formed of 16 beam elements transmits the seat pan loads to the supporting structure. Also applied to this frame are loads from the seat back, the occupant's legs, and the lap belt, should the user wish it attached to the seat. The seat back is made up of two beam elements connected at their upper ends by a rigid crossmember. The back cushion loads are distributed along the sides of the seat back and are thus transmitted to the seat pan frame. If the shoulder harness is attached to the seat, its load is applied to the crossmember.

The supporting structure is formed of beam elements, which are described by input of nodal coordinates, material properties, and cross section geometry.

Plastic deformation is simulated by introduction of plastic hinges at bar ends, should bending moments reach predetermined limiting values, which are based on yield strength data provided as input.

For use in restraint system or cabin configuration analyses, where the details of seat response may be immaterial or seat design unknown, a rigid seat model can be selected. The rigid seat consists of only the seat pan and back, which are fixed relative to the aircraft, and its use significantly reduces computer time required.

An additional feature, which may be used with any of the seat types including the rigid seat, is an energy-absorbing device. Such a device, operating in tension or compression, can be incorporated into the seat model to permit controlled relative motion between the seat pan and supporting structure. The energy absorber is described by input of its operating load and stroke limit.

Digital Computer Program

The digital computer program based on the seat and occupant models has been written entirely in FORTRAN IV to insure a high degree of compatibility with different computer systems. During development, the program has been run on CDC 6600, Univac 1108, and IBM 370 systems. The elements of the program are now discussed in terms of three general functions: input and initialization, solution, and output. Finally, a discussion of experience with resource requirements for operation is presented.

Program Input and Initialization

Input data are read by the program in the following seven categories:
1) Simulation control information
2) Cockpit description
3) Restraint system description
4) Cushion properties
5) Crash conditions
6) Seat design data
7) Occupant description.

A simulation case that utilizes the rigid seat option requires 39 cards for input data. Of these, 24 cards are used to describe the six components of aircraft acceleration as functions of time. If information concerning impact between the occupant and the aircraft interior is requested, 10 additional cards are required to define the cabin geometry. The finite-element seat analysis requires additional cards for nodal and element data, as well as material properties and cross-section geometry data.

The first block of input data contains the information required for controlling execution of the solution. The initial time step for integration of the equations of motion, upper and lower limits on the time step, the total duration of the solution, the system of units (SI or English), and identification of desired output are provided here.

Properties of the cushions and restraint system are defined by tables of forces and deflections and the rate coefficients. Additional data for the restraint system include coordinates of the anchor points, buckle location, and belt slack.

The aircraft crash conditions are defined by the initial velocity and attitude and the acceleration as a function of time. Six components of velocity are required: three translational in the aircraft coordinate directions and the yaw pitch, and roll rates. Each of the six acceleration components, which define the acceleration of the aircraft coordinate system, is computed by interpolation in a table of up to 16 points in acceleration and time. An example of input data points fitted to an acceleration pulse measured during a dynamic test is shown in Fig. 8. Although many of the higher frequency oscillations observed in measured waveforms probably contribute little to the overall response of the occupant, the use of a large number of points reduces the effect of the investigator's subjectivity in making the approximation.

The input data necessary to describe a nonrigid seat consist of dimensions, material properties, and floor attachment conditions. Input data for the rigid seat option consist only of locations of the seat pan and back.

For prediction of impact between the occupant and the aircraft interior, 10 planes are used to represent the cabin surfaces. During execution of the program, the distance between each of the 23 occupant contact surfaces and the

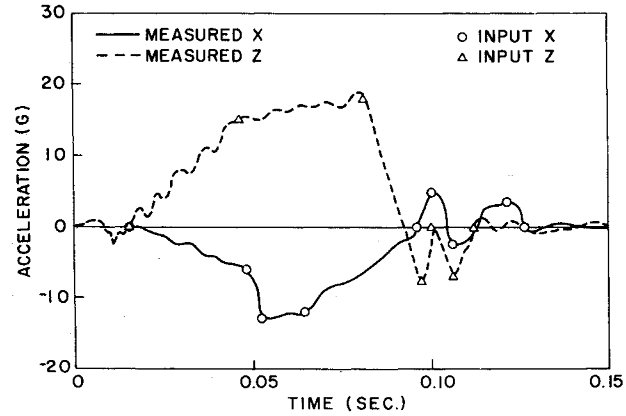

Fig. 8 Input acceleration components.

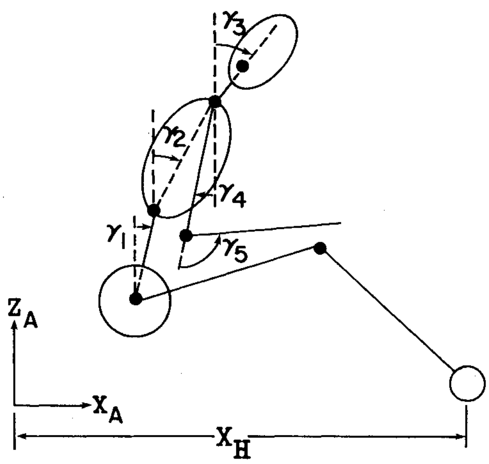

Fig. 9 Initial position input parameters.

cabin surfaces is calculated. When contact occurs, the relative velocity of impact is computed and stored for output with surface identification indices.

It is assumed that the occupant is initially positioned symmetrically with all body segments parallel to the aircraft X-Z plane, or, equivalently, so that the segment-fixed y axes are all parallel to the Y axis of the aircraft. The only input data required to specify the initial position of the occupant are five angular coordinates that describe the position of the torso and arm segments in the X-Z plane and the X coordinate of the heels, as illustrated in Fig. 9. The initialization procedure permits the weight of the occupant to load the seat cushion and floor and by means of a simple iterative procedure determines the correct initial position. The aircraft attitude is considered in this computation so that nose-down pitch will tend to elongate the restraint belts and nose-up pitch will compress the back cushion.

Solution Procedure

The first operation in each solution step includes the calculation of current values for the aircraft acceleration components and their subsequent integration to obtain aircraft velocity and displacement. If a nonrigid seat is being used, the forces exerted by the occupant on the seat are used in computation of new seat displacements. In order to reduce program solution time, the seat analysis routines are called only at certain predetermined increments of the applied loads. After yielding of the seat structure has been initiated, the force increments that determine the frequency of calls to the seat routines are reduced.

The quantities in Eq. (2) are calculated from current values of generalized coordinates and velocities. The external forces depend on the aircraft displacement, which determines the motion of the seat, floor, and restraint system anchor points.

The system of 29 equations is solved for the accelerations by first combining the vectors on the right-hand side and then solving by a direct elimination method. The resulting set of 29 second-order differential equations are rewritten as 58 first-order equations. Numerical integration is accomplished using the Adams-Moulton predictor-corrector method with variable step size, for which the starting values are provided by the classical fourth-order Runge-Kutta method.

Program Output

Output data consist of ten blocks of information that are selected for printing by user input. The data include time histories of the following variables, which are stored during solution at predetermined print intervals for output in both digital and plot form:

1) Occupant segment positions (X, Y, Z, pitch, and roll)
2) Occupant segment velocities (X, Y, and Z)
3) Occupant segment accelerations (x, y, z, and resultants)
4) Restraint system loads (tensile loads in webbing and resultant normal loads on pelvis and chest)
5) Cushion loads
6) Aircraft displacement, velocity, and acceleration
7) Seat deflections at critical points
8) Floor reactions (forces and moments)
and the following information:
9) Details of contact between the occupant and the aircraft interior
10) Injury criteria.

The injury criteria used in the program are all computed from segment accelerations. The dynamic response index (DRI) provides an indication of the probability of spinal injury due to a vertical acceleration parallel to the spine.[12] It is computed from the response of a single-degree-of-freedom, damped spring-mass model, which is driven by the component of pelvic acceleration parallel to the spine. The Severity Index[13] is calculated for the chest and head, and the Head Injury Criterion (HIC) of Federal Motor Vehicle Safety Standard 208 is also computed. Should other viable injury criteria based on occupant segment motion be developed in the future, they can be easily added to the program. Also, the predicted velocity and point of impact for contact between an occupant segment and the aircraft interior can provide information for design of energy-absorbing surface, including protective padding and collapsible structure under the padding.

Computer Resource Requirements

Execution time for the program varies somewhat from one case to another because of the variable step size integration method, but typical times can be cited for a sample case. Simulation of a 13.4 m/s longitudinal impact using a rigid seat model and carrying the solution to 0.150 s requires about 60 s of central processor time on the CDC 6600 and 90 s on the IBM 370 Model 168. The use of a nonrigid seat model increases the time for execution by five to ten times, depending on the desired level of accuracy in the seat analysis. The program requires approximately 260,000 bytes of memory on the 370/168 system. For operation on a smaller system, an overlay structure could probably be utilized quite effectively, because the occupant and seat segments of the program are about the same size and operate essentially independently of each other

Results

The response of the occupant model was optimized by adjustment of the joint damping coefficients, which are the only model parameters that cannot be directly measured, in order to achieve the best overall agreement with dynamic test data. The principal source of data for validation was a series of ten identical acceleration sled tests conducted at the FAA Civil Aeromedical Institute (CAMI) during an evaluation of

Table 1 Predicted and measured data for dynamic test of Bell 22 seat

Variable	Measured	Predicted
Maximum acceleration, *g*		
Head − *x*	14.5	6.8
Head − *y*	2.2	2.3
Head − *z*	24.3	24.0
Head − resultant	24.6	24.3
Chest − *x*	11.1	7.9
Chest − *y*	3.2	2.1
Chest − *z*	23.8	27.9
Chest − resultant	23.9	28.7
Restraint system load, N		
Right lap belt	2000.0	2450.0
Left lap belt	960.0	1340.0
Shoulder belt	2600.0	2400.0
Severity index (at 0.15 s)		
Head	88.0	85.0
Chest	79.0	107.0

several new generation anthropomorphic dummies.[14,15] The tests utilized a 50th percentile dummy in a lightly padded rigid seat, which was equipped with a lap belt and diagonal shoulder belt. The tests were conducted at an impact speed of 13.4 m/s; the longitudinal deceleration pulse was approximately a half-sine wave of amplitude 21 *g* and duration 0.1 s. Belt loads were recorded, as were the head and chest accelerations, which were subsequently used in calculation of severity indices. Reference 15 contains plotted data from individual tests along with means and standard deviations for the ten tests.

Because of the frequently serious nature of head injury and because tolerance levels for the head appear better validated than those for other parts of the body, the maximum resultant acceleration and the severity index for the head were considered the most important output quantities for validation. The objective in model optimization, therefore, was to maintain the head acceleration and severity index within ±5% of the mean of the measured data while searching for the best combination of chest response and belt loads. This objective was achieved as the final model predicted peak head acceleration within 4%, and all other quantities fell within one standard deviation of the mean, except for the peak chest acceleration whose deviation was slightly in excess of 1σ.

The model has been used to simulate a number of different seats and occupants under a range of impact conditions. The one energy-absorbing seat concept that has been simulated is a prototype lightweight helicopter crew seat developed for Bell Helicopter Textron for installation in the Bell 222 aircraft. This seat was designed to provide vertical energy absorption by crushing of a honeycomb cylinder located in the seat height adjustment mechanism. The basic design consists of a base of two L-shaped legs, the horizontal elements of which are mounted on rails for fore-and-aft adjustment. The vertical elements contain the energy absorbers and provide posts for vertical adjustment of the seat frame, which is composed of welded aluminum tubing.

Two of these seats were dynamically tested at the Civil Aeromedical Institute. The most severe test conditions consisted of an impact velocity of 9.1 m/s and an approximately trapezoidal deceleration pulse of 20 *g* magnitude. The seat was oriented on the sled so that the impact vector was directed 60 deg below the longitudinal axis, resulting in the *X* and *Z* components of acceleration shown in Fig. 8. Predictions of significant output parameters are compared with measured values in Table 1, and the complete time histories of head acceleration components are shown in Figs. 10 and 11.

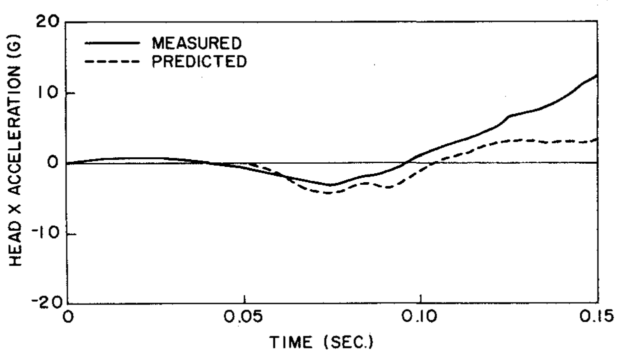

Fig. 10 *X* **component of dummy head acceleration for Bell 222 seat test.**

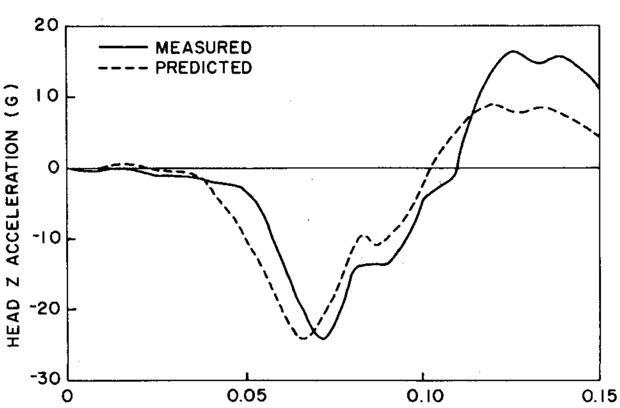

Fig. 11 *Z* **component of dummy head acceleration for Bell 222 seat test.**

Conclusions

A mathematical model of an aircraft seat and occupant has been developed for use in evaluation of the crashworthiness of seats and restraint systems in light aircraft. Program efficiency and ease of user input have been given considerable weight in development. Comparisons of model predictions with test data have produced quite favorable results. These results and its economical operation indicate that the model has significant potential in the design of crashworthy aircraft.

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