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Biodynamic Simulation of Pilot Interaction With a Helicopter Multiairbag Restraint System

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The introduction of airbags into the helicopter cockpit has raised the issue of acceptable limits on the weights of helmet-supported devices which can be tolerated safely by the aviator. It is hypothesized that, if the acceptable injury risk associated with current helmet-supported weights were reduced with the use of airbags, then an increase in the helmet weight would not necessarily increase the injury risk above what is acceptable without an airbag. To test this hypothesis, a biodynamic simulation software, Dynaman, is used. But first, the data set which describes the crash scenario must be developed. The results of the simulations are described in a separate report. This report describes the input data set required by Dynaman to simulate the interaction of a helicopter pilot with a multiairbag system during a simulated crash.

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<u>Introduction</u>

The crashworthy design of modern Army helicopters has resulted in fewer injuries from the impact acceleration in survivable crashes. The injury reduction, primarily to the spinal column, may be attributed to the energy-absorbing seat design which limits the forces transmitted to the seated pilot. Head and upper torso injuries also have been addressed with various design concepts to cockpit interior components, such as the breakaway optical relay tube used by the gunner in the AH-64 Apache helicopter. Following the introduction of these energy-absorbing devices into the Apache and Black Hawk helicopters, the injuries sustained in Army helicopter crashes due to excessive accelerations have dropped relative to other helicopters (Shanahan, 1989). Despite the success of the crashworthy design of these helicopters, contact injuries continue to occur and, in fact, outnumber acceleration injuries. Contact or flail injuries are produced in secondary collisions which result from inadequate restraints, collapsing structure, or a combination of both.

Total delethalization of U.S. Army helicopter interior systems is impossible because of operational requirements and design constraints. Further, current restraints systems are unable to prevent secondary impacts (McEntire, 1992). The use of some airbag protection for the gunner has been suggested for many years (Loushine, 1975), but no acceptable system ever was introduced into Army helicopters. More recently, the U.S. Army Aeromedical Research Laboratory (USAARL), Fort Rucker, Alabama, has demonstrated the effectiveness of airbags in reducing the severity of head injury (Alem et al., 1992), and evaluated the projected effectiveness of airbag supplemental restraint systems in Army helicopters (Shanahan, Shannon, and Bruckart, 1993). These studies and other factors convinced the Army of the need to utilize airbag technology as a method of delethalizing the cockpit interior of its new Comanche attack helicopter. Currently, the Aviation Applied Technology Directorate (AATD) is conducting a research program to reduce the likelihood that aviators will be injured seriously by cockpit strikes (Greth et al., 1992; Smith, 1993,). As part of that program, Simula, Inc. has proposed a multi-airbag system (Zimmerman, 1993) which will inflate upon a crash to protect the aviator. A prototype of the system has been developed and tested in mockup crew stations.

The introduction of the airbag has raised the issue of acceptable limits on the weights of helmet-supported devices which can be tolerated safely by the aviator. It is hypothesized that, if the acceptable injury risk associated with current helmet-supported devices were reduced with the use of airbags, then an increase of head-supported weights would not necessarily increase the risk to levels above those presently acceptable without airbags. To support or reject such a hypothesis, it is necessary to conduct tests and evaluate injury parameters produced under different test conditions. A cost-effective tool to test the hypothesis is biodynamic modeling. This report describes the work done at USAARL in the summer of 1994 to develop a valid biodynamic simulation of the aviator's interaction with the inflating airbags. The results of the simulations are described in a separate report.

Objectives

Given the biodynamic simulation software available at USAARL, the immediate goal of the study was to develop the basic input data set required to simulate a multiairbag restraint system in a helicopter cockpit. This report documents the modeling strategy and the sources of the engineering constants utilized as input to the simulation. The report also is intended to provide a list of problems encountered in the simulation, to suggest alternative modeling strategies, and to recommend future software development.

Methods

The three-airbag inflatable restraint system shown in Figure 1 was modeled using the Articulated Total Body (ATB) (Obergefell et al., 1988) and the ATB-compatible DYNAMAN pre- and postprocessing software (GESAC, Inc., 1991). The inflatable restraint model has been added to an existing DYNAMAN input file in which both the occupant biodynamics and helicopter crash dynamics were modeled (Beale, Alem, and Butler, 1994).

The DYNAMAN software has two different techniques for modeling airbags: the original airbag model developed for the ATB program and the new DYNAMAN airbag model that provides more flexibility in airbag modeling.

The original airbag model is based on the assumption of a stretchless ellipsoidal-shaped airbag and the gas dynamics of choked flow through a nozzle. The airbag is assumed to have zero volume at the start of the simulation. During the simulation, the airbag is inflated by a constant volume, high pressure supply tank. The supply tank volume is the volume the gas would occupy at atmospheric pressure in the fully inflated airbag. The airbag dimensions are determined by scaling the airbag semiaxes by the cubed root of the volume. Contact forces between the airbag and intersecting segments are considered to be zero until the airbag computed volume plus the volume of the contact intersections is equal to the airbag geometric volume. The increase in pressure, after the airbag has been inflated fully, produces contact forces on the segments in contact with the airbag. Also, when the airbag has been inflated fully, it is moved dynamically similar to any other mass system (CALSPAN Corporation, 1981).

In the new DYNAMAN airbag model, the airbag may be modeled as an ellipsoidal or a cylindrical shaped airbag. The new airbag model allows the user to input the time history for the deployment volume (size) of the airbag, the mass flow into the airbag, and the temperature time history of the inflator. The thermodynamics calculations are based on a perfect gas law and adiabatic processes. During the simulation, the airbag is inflated based on the mass flow input and the airbag volume (size) is determined from the deployment time history input. The airbag deployment history has three options: none, airbag volume, and airbag semiaxes. If the deployment history of the airbag is not given, then the calculations of the airbag geometry is determined by the same procedure as the original airbag model.

If the deployment is based on the airbag volume, then pressure is calculated using the perfect gas law, and the airbag dimensions are determined by scaling with respect to the final airbag shape. If the deployment history is based on airbag semiaxes, then the volume of the airbag is determined from the dimensions of the airbag, and then the pressure is determined from the perfect gas law based on the mass flow input. The contact forces can be determined by three techniques. The first technique determines the contact force as the sum of the force due to pressure acting over the contact area and the integration of the total tension force over the contact contour. The second technique is a simplified force calculation procedure similar to that of the original airbag model. The third is a numerical procedure for calculation of contact forces similar to that of the first technique. The airbag dynamics are determined by constraining the airbag to its reference segment by the deployment point.

The three-airbag restraint system shown in Figure 1 has been modeled using the DYNA-MAN new enhanced airbag model with a cylindrical shape. The new enhanced model was chosen because of its modeling flexibility. The cylindrical shaped airbag was chosen because it better represented the actual airbags that may be used in the future airbag system. The geometry for the cylindrical shaped airbag is shown in Figure 2. The cylindrical airbag is modeled by specifying the following information in the input file via the preprocessor:

1. Bag options

    a. Airbag shape can be modeled as either an ellipsoid or a cylindrical shape.

    b. Deployment history which can be either by airbag volume or by airbag semiaxes.

    c. The reaction panels for an airbag are modeled as contact ellipsoids attached to the vehicle. One reaction panel must be defined for each airbag. The deployment point of the airbag also is defined as a point on the reaction panel. The location and orientation of the airbag reaction panel are defined with respect to the reference segment coordinate system. The reference segment is defined in the airbag geometry section. The direction of the airbag deployment also is defined using the reaction panel. The center of the airbag is defined to lie on a vector parallel to the x axis of the reaction panel but in the negative direction. Thus, the airbag deployment direction is in the minus x direction of the reaction panel (Figure 3). The size of the reaction panel for each airbag was chosen such that the projection of the reaction panel on its Y-Z plane was the same size approximately as the airbag projection on the Y-Z plane of the reaction panel. The orientation of the reaction panel was chosen so the airbag deployment was in the desired direction. The reaction panel definitions for the three airbags in Figure 1 are shown in Tables 1-3 .

Table 1.
Panel definition for the right airbag.

	x	y	z
Semiaxes	4	15	15
Mass center	12	-4	-20
Orientation	90	0	0

Table 2.
Panel definition for the left airbag.

	x	y	z
Semiaxes	4	15	15
Mass center	12	-44	-20
Orientation	-90	0	0

Table 3.
Panel definition for the front airbag.

	x	y	z
Semiaxes	4	15	15
Mass center	30	-24	-25
Orientation	0	0	0

d. The airbag geometry is defined by specifying the airbag position, size, orientation, deployment point, and the airbag reference segment. The airbag size is defined by specifying: the x and z semiaxes of the central cylinder, the semiaxes of the left and right endcaps, and the cylinder half length shown in Figure 2. The airbag position, orientation, and deployment point are defined with respect to the coordinate system of the airbag reaction panel. The reference segment defined for the airbag should be a defined segment attached to the helicopter. The program will allow an undefined reference segment to be used such as the vehicle (VEH) or ground (GRND) segments, but these may result in inappropriate results or may cause problems during program execution. The size and orientation of each airbag was chosen so that each airbag would produce the desired effects on the occupant. The size, orientation, and deployment point for the three airbags in Figure 1 are shown in Tables 4-6. The deployment point is defined with respect to the main reaction panel definition.

e. Deployment history can be either by volume or by semiaxes. The DYNAMAN manual specifies that the time for the deployment history should be input using seconds and the semiaxes input in inches. Since the deployment history for the airbag is optional, it is preferable not to supply it unless the history has been obtained by experimental analysis. The deployment history has not been used in this model.

f. The airbag thermodynamic properties:

(1) The airbag characteristics are defined by three variables: airbag density, airbag-segment friction coefficient, and the airbag stretch coefficient. The value for the airbag density was obtained from Lupker et al. (1991). The airbag-segment coefficient was estimated to be approximately 0.35. The airbag stretch coefficient of 0.2 was obtained from an original airbag example in the DYNFEM user's manual (GESAC, 1991). The values for these parameters are shown in Tables 7-8.

(2) The gas characteristics are defined by the three variables: atmospheric pressure, gas constant, and the specific heat ratio. The values for these parameters are the DYNAMAN default values and are shown in Tables 7-8.

(3) The vent characteristics are defined by the three variables: vent area, vent discharge coefficient, and the minimum vent pressure. The values for the vent area and the minimum vent pressure were obtained from Enouen et al. (1984), and the value for the vent discharge coefficient was obtained from Lupker et al. (1991). The values for these parameters are shown in Tables 7-8.

(4) The mass flow rate time history is specified using lbs/sec and the time is specified in seconds. The values for the mass flow rate for each bag was chosen so the airbags would be fully deployed in approximately 20 msec. Table 9 shows the mass flow rates for each of the airbags.

(5) The temperature time history of the inflator is specified using Rankine and the time is specified in seconds. The temperature time history can be input at specific times or can be held at a constant value. The inflator temperature for the airbags in this model is set at a constant value of 900 Rankine (Enouen et al., 1984). Modification of the temperature time history may be needed when more appropriate data has been obtained for the inflator characteristics.

Table 4.
Position and size for the right airbag.

Reference segment: HELI	x	z	Right end cap	Left end cap	Half length
Bag size	13	17	0.5	0.5	3

Bag position	x	y	z
Bag deployment	-4	0	0
Bag orientation	0	0	0

Table 5.
Position and size for the left airbag.

Reference segment: HELI	x	z	Right end cap	Left end cap	Half length
Bag size	13	17	0.5	0.5	3

Bag position	x	y	z
Bag deployment	-4	0	0
Bag orientation	0	0	0

Table 6.
Position and size for the front airbag.

Reference segment: HELI	x	z	Right end cap	Left end cap	Half length
Bag size	7	12	0.5	0.5	8

Bag position	x	y	z
Bag deployment	-4	0	0
Bag orientation	0	0	0

Table 7.
Airbag thermodynamics for the right and left airbags.

Bag density	0.023
Bag segment friction coefficient	0.200
Bag stretch coefficient	0.350
Atmospheric pressure	14.300
Gas constant	639.600
Specific heat ratio	1.400
Vent area	1.500
Vent discharge coefficient	0.625
Minimum vent pressure	24.700

Table 8.
Airbag thermodynamics for the front airbag.

Bag density	0.023
Bag segment friction coefficient	0.200
Bag stretch coefficient	0.350
Atmospheric pressure	14.300
Gas constant	639.600
Specific heat ratio	1.400
Vent area	1.500
Vent discharge coefficient	0.625
Minimum vent pressure	24.700

Table 9.
Mass flow time histories for the three airbags.

Airbag mass flow rates (lbs/s)			
Time (sec)	Left or right airbag	Time (sec)	Front airbag
0	0	0	0
0.004	5.0	0.008	5.3
0.007	9.0	0.010	8.5
0.009	10.3	0.030	6.2
0.011	9.4	0.035	3.0
0.014	6.6	0.040	1.0
0.017	3.3	0.050	0
0.020	1.1		
0.024	0.1		
0.030	0		

2. Airbag contacts are defined by specifying plane contacts and ellipsoid contacts separately for each airbag. The DYNAMAN program allows a total of 10 contacts per airbag: 4 plane contacts and 6 ellipsoid contacts.

a. Ellipsoid contacts are specified by defining the following five parameters.

(1) The number associated with the airbag.

(2) The segment that will contact the airbag. The segment may be chosen by typing in the number associated with a particular segment.

(3) The ellipsoid number of the segment that will contact the airbag.

(4) The function number defined for the airbag-segment contact. The DYNAMAN program has three options for the function parameter. If the function number is specified as zero, a numerical procedure will be used to estimate the force due to airbag penetration, assuming the segment contact is rigid. If the function number is negative, an approximate procedure will be used to determine the force due to bag penetration, assuming the segment contact is rigid. If the function number is greater than zero, a numerical procedure will be used to determine the force due to airbag penetration without the assumption of rigidity. The force deflection characteristic of the segment will be described by the force function defined in the force function section. The function number of -1 has been used for each airbag-segment contacts in this model.

(5) The friction coefficient number is the number of the force function the user has defined for the friction between the airbag and each segment that will contact the airbag. The default is zero in which the sliding friction coefficient specified for the airbag will be used for the friction function. The default value of zero has been used for all airbag-segment contacts in this model.

b. Plane contacts are defined in the same fashion as ellipsoid contacts, but the first contact plane must be the reference segment used in the airbag geometry definition. Shown in Table 10 are the ellipsoid contacts defined for each airbag and shown in Table 11 are the plane contacts for each of the airbags. The segment contacts were chosen so the most likely segments that would contact each airbag have been defined.

Results

An input data set for a multi-airbag restraint system has been developed for the DYNAMAN software. Airbag positions, orientation, deployment directions, and sizes were chosen to approximate the possible configuration for a multiairbag constraint system for a helicopter. Figure 4 is a diagram showing the three-airbag configuration and the deployment directions for each airbag. Shown in Figure 5 is a possible variation of the deployment directions for the two side airbags, and given in Tables 12-13 are the parameters that must be changed in the input file to produce this variation.

Table 10.
Ellipse segment contacts for each airbag.

Bag	Segment	Ellipse	Function	Friction
Left airbag	LT	1	-1	0
Left airbag	CT	2	-1	0
Left airbag	UT	3	-1	0
Left airbag	LUA	15	-1	0
Left airbag	LLA	16	-1	0
Left airbag	H	5	-1	0
Right airbag	LT	1	-1	0
Right airbag	CT	2	-1	0
Right airbag	UT	3	-1	0
Right airbag	RUA	12	-1	0
Right airbag	RLA	13	-1	0
Right airbag	H	5	-1	0
Front airbag	LT	1	-1	0
Front airbag	CT	2	-1	0
Front airbag	UT	3	-1	0
Front airbag	N	4	-1	0
Front airbag	H	5	-1	0

Table 11.
Plane segment contacts for each airbag.

Bag	Segment	Plane	Function	Friction
Left airbag	HELI	16	-1	0
Right airbag	HELI	16	-1	0
Front airbag	HELI	16	-1	0

Table 12.
Right airbag panel definition
for deployment variation.

	x	y	z
Semiaxes	4	4	15
Mass center	-5	-11	-20
Orientation	180	0	0

Table 13.
Left airbag panel definition
for deployment variation.

	x	y	z
Semiaxes	4	4	15
Mass center	-5	-36	-20
Orientation	-180	0	0

Discussion

The airbag parameters used in the model have come from different sources and from approximations. Thus, the airbag parameters used are rough approximations to that of a realistic airbag and may not produce the appropriate effects on the crewman during simulations. As a result, one should run simulations of the input file with and without the airbags to determine what effects the airbag will have on the crewmember, and modify the input parameters for the airbags to minimize the adverse and undesirable effects caused by the airbags.

The adverse effects that may be caused are: rebound of body segments, airbag-slap, high forces and moments, and high linear and angular accelerations. Body segments should not rebound off the airbags and should impact the airbags approximately the same time, especially the head, torso, and neck segments. If the head were to impact the airbag and rebound before the impact of the torso, the body segments would be moving in opposite directions and produce high moments in the neck, and possible injuries. Changes to the input parameters if rebound effects occur would be to: increase the vent area, reduce the mass flow rates, and reduce the minimum exhaust pressure. Changes in the position, orientation, and size of the airbags will help make body segments impact the airbag at approximately the same time. The airbag parameters have been set up so the airbags are deployed fully before impact occurs. Modifications to the mass flow rates, vent area, and vent pressure may be necessary if the impact velocities are too high. The maximum contact pressure on the head segment should be around 10 to 15 psi, which would produce forces around 1000 to 1500 lbs. This also can be changed by modifying mass flow rates, vent area, and vent pressure.

Conclusions

The objective of developing an input data set has been obtained. The airbag parameters used are rough estimates of real airbag characteristics and modifications will be necessary. The process in which an airbag model is set up and the rationale for the airbag parameters values used in the model have been discussed. The problems setting up the input data set and possible bugs in the DYNAMAN software are mentioned in Appendix B.

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Appendix A.

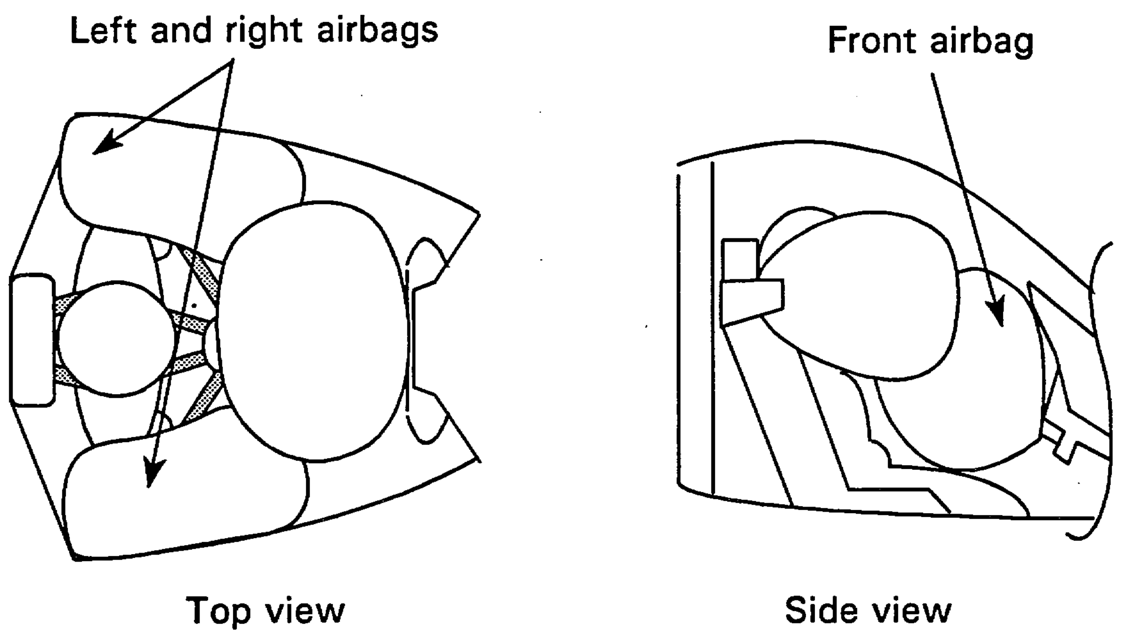

Figure A-1. Diagram of a multi-inflatable restraint system.

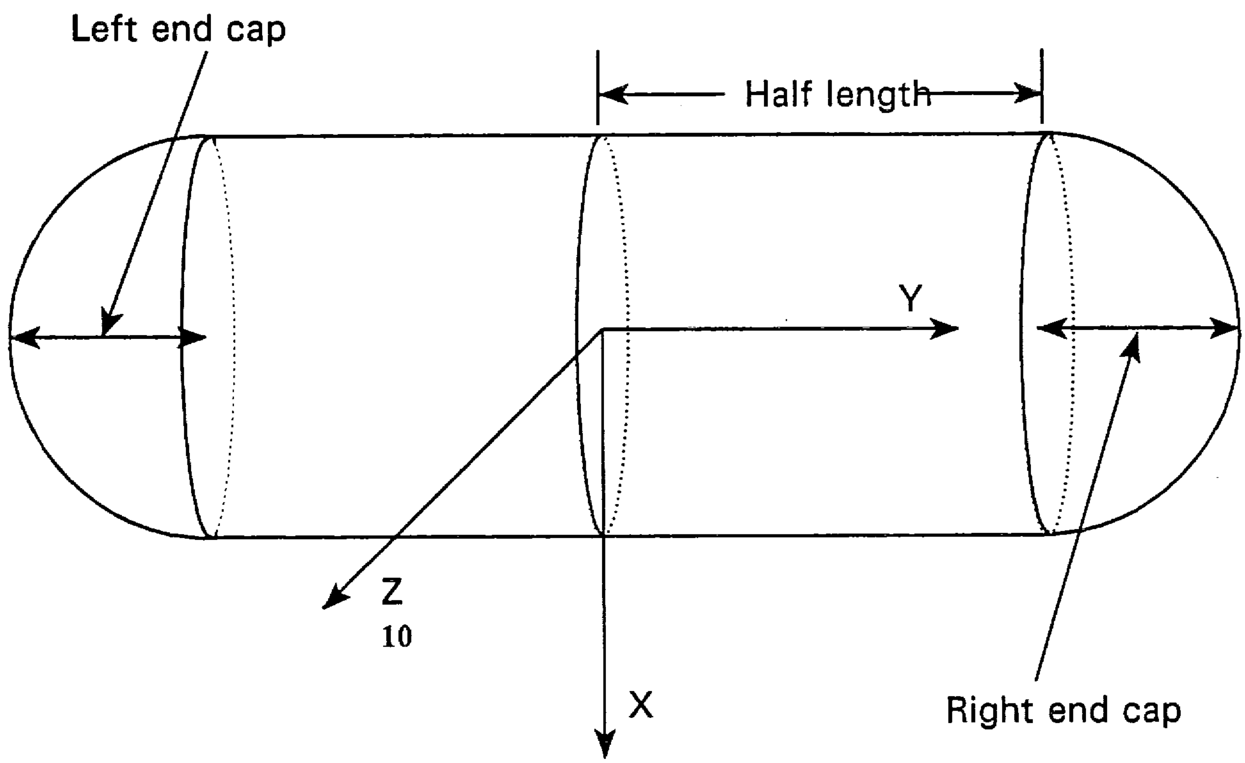

Figure A-2. Cylindrical airbag geometry.

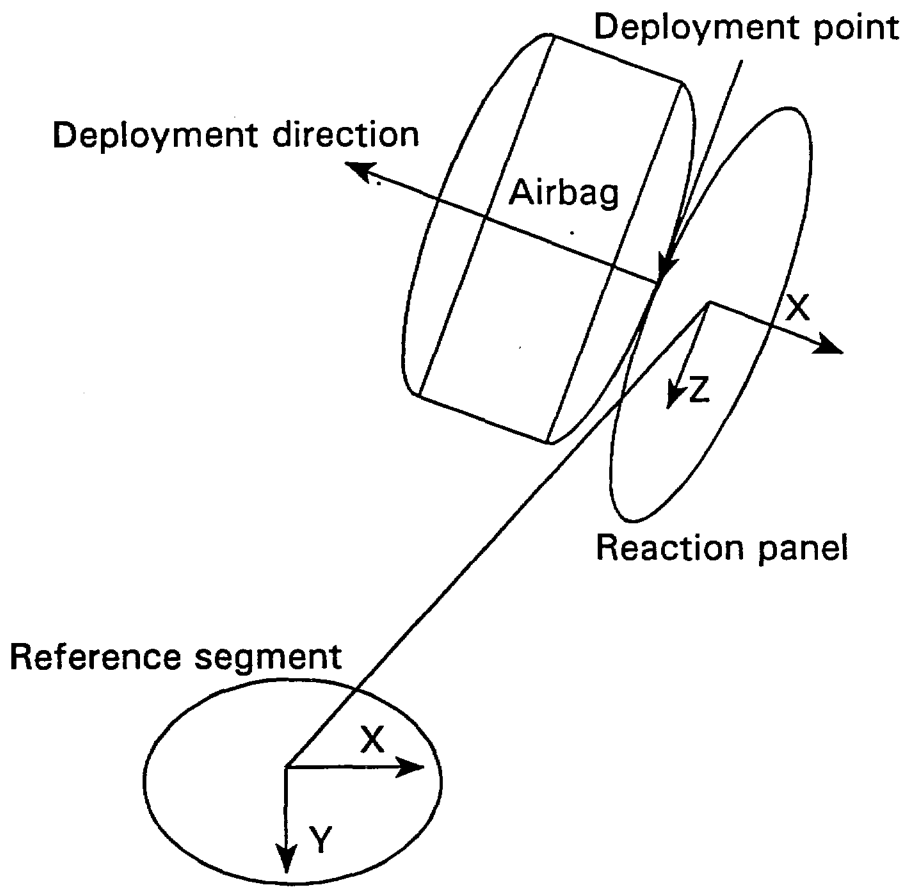

Figure A-3. Airbag deployment geometry.

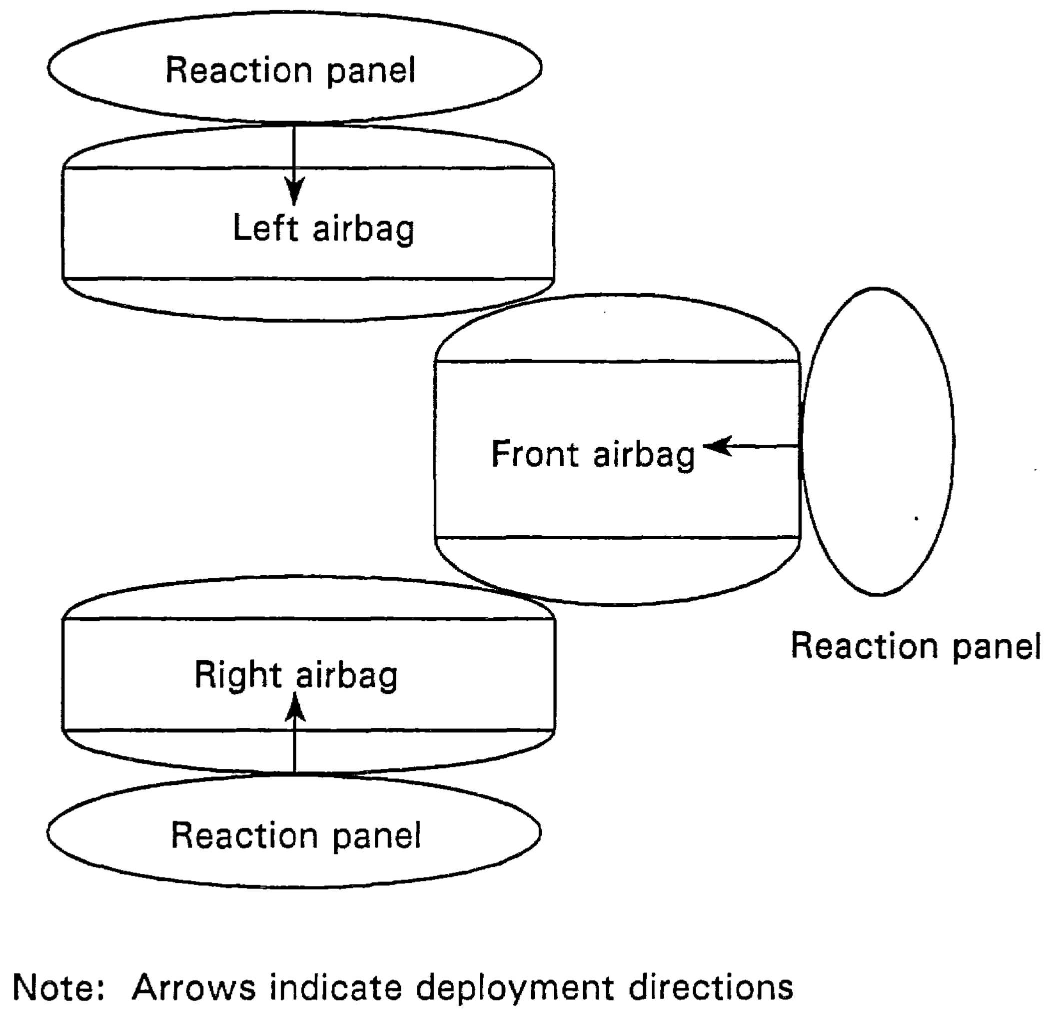

Figure A-4. Diagram of multiairbag model and deployment directions.

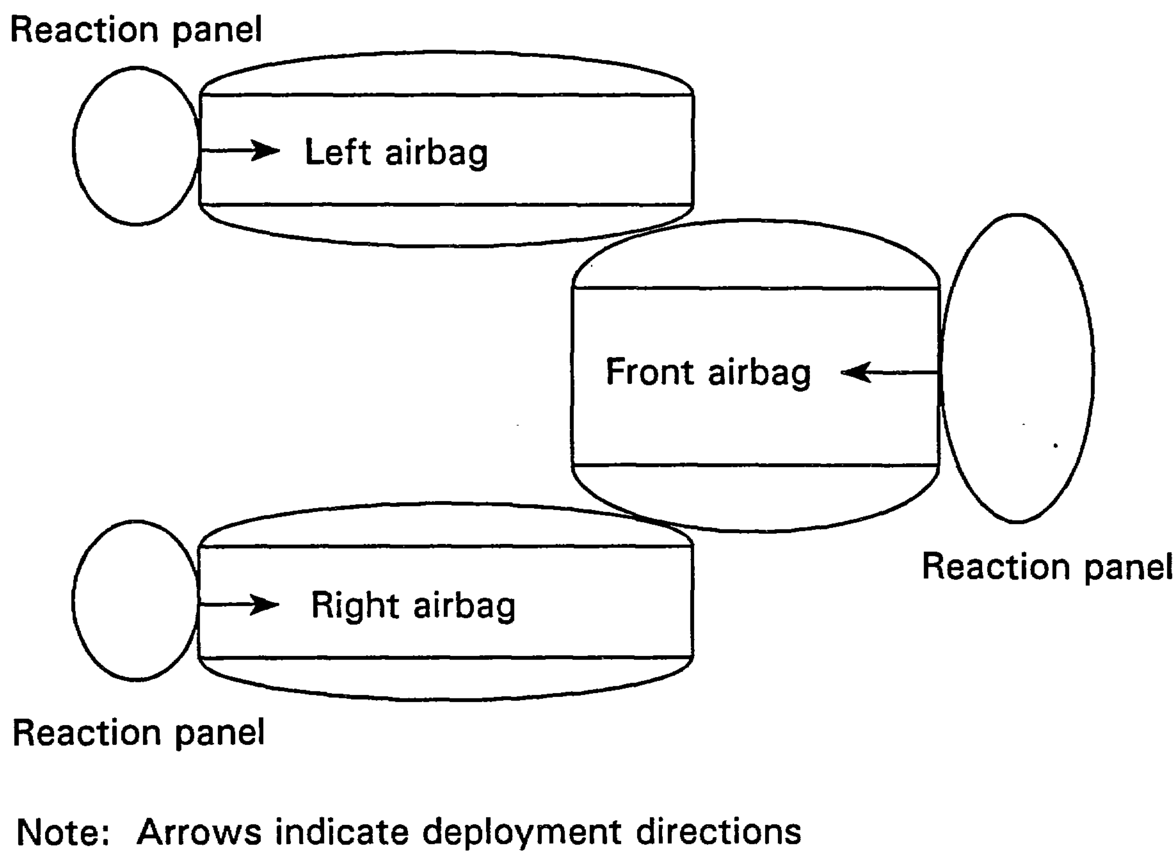

Figure A-5. Diagram of side airbag deployment direction variation.

Appendix B.

Problems and possible bugs in DYNAMAN software

DYNAMAN preprocessor

1. When defining airbag-segment contacts, the "F3" key is defined so the user may choose the segment he/she wishes to contact from a list of the defined segments. When pressing the "F3" key, a list of the defined segments appear to the right of the contact menu. Using the arrow keys, the user is allowed to select the desired segment from the list. This option does not work properly and the segment must be chosen by typing in the number associated with the desired segment.

2. The "F10" key is used to save the information the user has typed for the segment contacts, and returns to the previous window. The window does not have a choice for exit and the "F10" key will not work to return to the previous window. The "Esc" key must be used to return to the previous window.

3. The airbag deployment option does not work. The time should be input using seconds but the program will not accept the time values in seconds. (This problem has been fixed by GESAC, Inc.)

4. Specifying the segment reference for the airbag. The reference segment used for the airbag should be one of the reference segments defined under the environment menu. Here also, the program has the "F4" key to allow the user to display a list of segments that may be chosen. The list of segments shows the segment VEH and the segment GRND to be viable options for the reference segment. These segments actually are undefined segments and should not be chosen as an airbag reference segment. The program will allow these two segments to be chosen but may yield poor results or problems in simulation of the input file. The reference segment should be a segment defined in the helicopter or the helicopter segment itself.

DYNAMAN simulation

1. The following error will occur when a total of three contacts have been defined for the side airbags and having more than two contacts for the front airbag. When less than three airbags are used, the error will not occur:

> STOP in AIRBAG: number of airbag parameters to be saved in the BAGSF array exceeded the maximum allowed, 20 for airbag.
> Error Code: 701.

2. The following error occurs depending on the orientation and the deployment direction of the airbag.

EDEPTH: Singular Matrix ITER, T, DL, DU: 12 0.999109E+00 -0.1620077+115 0.
Error Code: 720

EDEPTH is a FORTRAN subroutine that determines the depth of penetration of two ellipsoids. The EDEPTH routine uses the DSMOL routine to solve a set of linear simultaneous equations of the form $A \mathbf{x} = \mathbf{b}$. Since the A matrix is singular, the set of equations is not linearly independent.

3. The following error occurs sometimes when trying to save modifications for the *.dyn, *.001, *.006, and *.008 files.

FORTRAN run time error: external file "*.*" (5)
I/O Error

It also occurs sometimes at the end of a simulation. This problem is due to not having enough memory to write the files. In order to prevent this from happening, keep track of how many files have accumulated and how much available memory is left. If this happens at the end of a simulation, you will have to do the simulation again.

DYNAMAN postprocessor

1. Problem in obtaining the correct output for airbag-segment contacts. The output displayed by the postprocessor does not agree with the output in the *.006 file.

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