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ANALYTICAL MODEL FOR DETERMINING SPACECRAFT IMPACT VELOCITY AND ORIENTATION RELATIVE TO AN IMPACT SURFACE

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16. Abstract

An analytical model which can be used to determine spacecraft impact velocity and orientation relative to an impact surface for variable dynamic conditions determined by the atmosphere, the landing system or spacecraft (or both), and the impact surface has been developed. These impact condition values can be used in the determination of impact loads.

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ANALYTICAL MODEL FOR DETERMINING SPACECRAFT IMPACT VELOCITY AND ORIENTATION RELATIVE TO AN IMPACT SURFACE

By David B. Howes and Arthur M. Whitnah
Manned Spacecraft Center

SUMMARY

An assessment of the potential loads encountered by a spacecraft during landing impact requires comprehensive knowledge of the spacecraft velocity and orientation at impact. An analytical model which determines the impact parameters (i. e., normal and tangential velocities and roll and pitch angles of the spacecraft relative to the impact surface) as functions of the dynamic conditions determined by the atmosphere, the landing system or spacecraft (or both), and the impact surface has been developed and is described in this report. The coordinate systems for the various components of the model, the Euler angles, and the mathematical expressions pertaining to the velocity and angular relationships are described. A computer program developed from this model is also described. This computer program can be used to determine the impact conditions for a single spacecraft landing or for a parametric study of a large number of landings. The computer program can also be used in a statistical analysis to determine the magnitude and frequency of occurrence of impact parameters.

INTRODUCTION

The development of design criteria which will assure adequate structural capability for a given space vehicle requires the consideration of loads peculiar to each phase of the flight. To design a reentry spacecraft which will sustain the loads encountered during the landing or impact phase of a flight, it is necessary to predict both the magnitude of the expected loads and their location on the body of the spacecraft. These data are usually determined by drop tests of scaled models with discrete impact conditions or, more recently, through the use of computer-simulated impacts (ref. 1).

Knowledge of spacecraft velocity and orientation relative to the impact surface at the time of impact is required in determining spacecraft landing loads. The dynamic conditions determined by the atmosphere, the landing system or spacecraft (or both), and the impact surface combine to vary spacecraft velocity and attitude parameters to an extent that precludes a comprehensive load analysis based on drop tests alone. Similarly, to conduct computer-simulated impacts, a means of determining the effect of these varying dynamic conditions on spacecraft impact parameters is required. An analytical model which describes the angular and velocity relationships of the spacecraft with respect to the impact surface as a function of the dynamic conditions determined by the atmosphere, the spacecraft or landing system (or both), and the impact surface has been developed and is described in this report. A computer program (developed from the analytical model) which is adapted to computer landing simulations is also described.

The computer program and the Monte Carlo statistical technique were used conjunctively to determine the distribution of impact conditions for a sampling of 100 000 simulated Apollo command module landings. This distribution of impact parameters for water landings was used in assessing the structural capability of the Apollo command module because of weight growth prior to the Apollo 7 mission. An example of the use of the computer program in this assessment is presented in the appendix to this report.

SYMBOLS

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Systemè International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

IP	impact point
$\{i\}$	unit vector in the X_{SC} direction
$\{k'\}$	unit vector in the Z_{TP} direction
$\{\underline{k}'\}$	unit vector in the Z_{TP} direction transformed into the spacecraft axis system
ℓ, m, n	direction cosines of a line
ℓ_E, m_E, n_E	direction cosines of the line E on the spacecraft
ℓ_F, m_F, n_F	direction cosines of the line F on the impact tangent plane
u, v, w	velocity components, m/sec (ft/sec)
V	velocity, m/sec (ft/sec)
$\vec{V}$	velocity vector, m/sec (ft/sec)
X, Y, Z	coordinate system reference axes
γ	included angle between the impact tangent plane and the local horizontal, deg

γ_c	angle between Y_H and its projection in the impact tangent plane, deg
γ_{ud}	angle between X_H and its projection in the impact tangent plane, deg
ϵ	angle between the direction of impact-tangent-plane motion and the projection of X_{TP} into the horizontal plane
θ	pitch angle, rotation about Y_{TP}, deg
θ'	complement of θ, deg
λ	angle between the wind direction and the vertical plane containing the riser center line, deg
μ	angle between the wind direction and the horizontal component of impact-tangent-plane movement, deg
μ'	sum of ϵ and μ, deg
TH2R, $\left[a_{ij}\right]$	transformation matrix describing the relation of the local horizontal axis system to the riser axis system
TH2TP, $\left[c_{ij}\right]$	transformation matrix describing the relation of the local horizontal axis system to the impact-tangent-plane axis system
TR2SC, $\left[b_{ij}\right]$	transformation matrix describing the relation of the riser axis system to the spacecraft axis system
TTP2SC, $\left[d_{ij}\right]$	transformation matrix describing the relation of the impact-tangent-plane axis system to the spacecraft axis system
Υ	hang angle, negative rotation about Y_{SC}, measured between X_{SC} and the riser center line, deg
Φ	roll angle, rotation about X_{SC}, deg
Φ'	rotation about X_{SC} prior to Υ rotation, deg
Ω	rotation about Y_R, describing the deviation of the riser center line from vertical, deg

Subscripts:

H	local horizontal axis system
I	impact surface velocity component

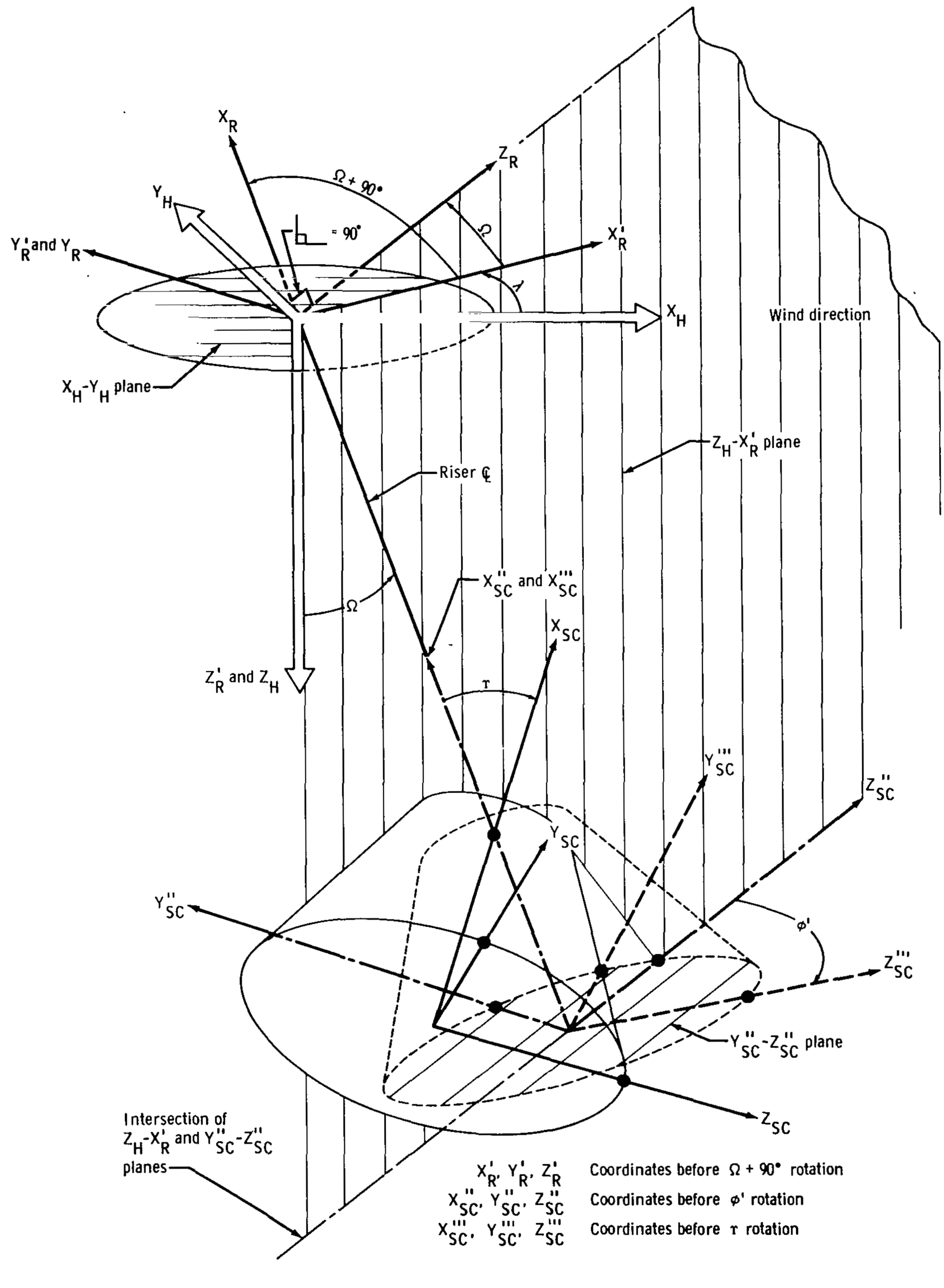
i, j	indices for matrix transformations, i, j = 1, 2, 3
N	normal
O	velocity component of the spacecraft center of gravity (c.g.) resulting from oscillatory movements of the risers with respect to the parachute canopy
R	riser axis system
SC	spacecraft axis system
T	tangential
TP	impact-tangent-plane axis system
W	velocity component of the spacecraft c.g. resulting from atmospheric forces
x, y, z	vector components

DEVELOPMENT OF ANALYTICAL MODEL

The calculation of spacecraft impact parameters for any given set of dynamic conditions determined by the atmosphere, the impact surface, and the landing system or spacecraft (or both) requires the development of an analytical model which describes the angular and velocity interrelationships of the landing system, the spacecraft, and the impact surface. In the development of this model, it is necessary to define the coordinate system and associated Euler angles for each model component. From these systems, a mathematical model of the spacecraft velocity and attitude relative to the impact surface at the moment of impact can be established. The components of this model include the local horizontal system (parachute), the riser system, the spacecraft system, and the impact-tangent-plane system. The mathematical equations present a closed-form solution for impact parameters. Except for the riser swing angle, which produces an angular rate, translational velocity relationships with no angular rates or accelerations are assumed to exist between all components.

Coordinate Systems

Local horizontal axis system. - The local horizontal axis system is used as a reference frame for the parachute velocity. The parachute is assumed to be in a steady-state condition, moving in the direction of the wind at the same velocity as the wind and downward at terminal velocity. In the local horizontal axis system, the X-axis X_H is in the horizontal plane, positive along the direction of the wind; the Z-axis Z_H is positive toward the geodetic center of the earth; and the Y-axis Y_H completes a standard right-hand orthogonal system. This system is illustrated in figure 1(a).



(a) Local horizontal, riser, and spacecraft axis systems.

Figure 1. - Coordinate systems and Euler angle relationships.

Riser axis system. - The origin of the riser axis system is coincident to the origin of the local horizontal axis system. The axes of the riser axis system are designated as X_R, Y_R, and Z_R. The transformation matrix which describes the relation of the local horizontal axis system to the riser axis system is based on two Euler angles λ and Ω, as shown in the matrix equation

$$TH2R = \left[a_{ij}\right] = \begin{bmatrix} -\sin \Omega \cos \lambda & -\sin \Omega \sin \lambda & -\cos \Omega \\ -\sin \lambda & \cos \lambda & 0 \\ \cos \Omega \cos \lambda & \cos \Omega \sin \lambda & -\sin \Omega \end{bmatrix} \tag{1}$$

where (1) λ describes the rotation about Z_H and (2) $\Omega + 90^\circ$ describes the subsequent rotation about Y_R needed to establish colinearity between X_R and the riser center line.

Spacecraft axis system. - The spacecraft Z-axis Z_{SC} is initially in the plane formed by Z_R and Z_H and is positive in a direction that is generally pointing outward from Z_H. The spacecraft X-axis X_{SC} coincides with the spacecraft center line and is positive in a generally upward direction. The spacecraft Y-axis Y_{SC} completes a standard right-hand orthogonal system. The riser axis system is related to the spacecraft axis system by a transformation matrix based on two Euler angles Φ' and Υ, as shown in the matrix equation

$$TR2SC = \left[b_{ij}\right] = \begin{bmatrix} \cos \Upsilon & -\sin \Upsilon \sin \Phi' & \sin \Upsilon \cos \Phi' \\ 0 & \cos \Phi' & \sin \Phi' \\ -\sin \Upsilon & -\cos \Upsilon \sin \Phi' & \cos \Upsilon \cos \Phi' \end{bmatrix} \tag{2}$$

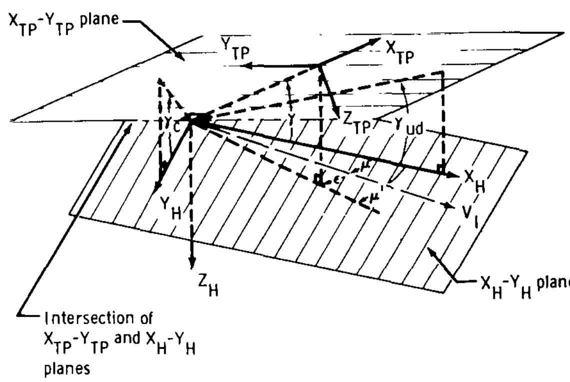
where (1) Φ' describes the rotation about X_{SC} with X_{SC} assumed to point upward along X_R and Z_{SC} assumed to be initially in the vertical plane formed by Z_H and X_R and parallel to Z_R, and (2) the angle Υ (the hang angle) describes the subsequent negative rotation about Y_{SC} which displaces X_{SC} from the riser center line. The spacecraft axis system and its relationship to the riser system are shown in figure 1(a).

Impact-tangent-plane axis system. - The impact tangent plane is established tangent to the spacecraft and the impact surface at the point of spacecraft contact. The impact-tangent-plane Z-axis Z_{TP} is normal to the impact tangent plane and is positive downward. The X-axis X_{TP} lies in the impact tangent plane, normal to the line formed by the intersection of the impact tangent plane with the local horizontal, and is positive in the upslope direction. The Y-axis Y_{TP} completes a standard right-hand orthogonal system.

The transformation matrix which describes the relationship of the local horizontal axis system to the impact-tangent-plane axis system is based on two Euler angles μ' and γ, as shown in the matrix equation

$$\mathrm{TH2TP} = \left[c_{ij}\right] = \begin{bmatrix} \cos\gamma\cos\mu' & \cos\gamma\sin\mu' & -\sin\gamma \\ -\sin\mu' & \cos\mu' & 0 \\ \sin\gamma\cos\mu' & \sin\gamma\sin\mu' & \cos\gamma \end{bmatrix} \tag{3}$$

where, assuming the two axis systems to be initially coincident in all three axes, (1) the angle μ' describes the initial rotation about Z_H needed to place X_{TP} in its proper heading with respect to X_H and (2) the angle γ describes the subsequent rotation about Y_{TP} which establishes the slope of the impact tangent plane. Figure 1(b) illustrates the relation between the impact-tangent-plane and the local horizontal axis systems.



(b) Local horizontal and impact-tangent-plane axis systems.

Figure 1. - Concluded.

Velocity Relationship

The analytical model must provide a representation of a dynamic system such that the relative motions of the spacecraft, the riser system, and the impact surface are summed into a resultant velocity vector from which velocity components relative to the spacecraft or the impact surface can be resolved. In a conventional structural analysis of a spacecraft, velocity components relative to the spacecraft axis system are desired. However, because of the complexity of the hydrodynamic analysis associated with landing, velocity components relative to the impact-tangent-plane axis system are a necessity. Because current landing system or spacecraft configurations (or both) are designed for water landings, the analytical model is designed to provide velocity components V_N and V_T normal and coincident to the impact tangent plane, respectively.

The resultant velocity vector which describes the motion of the spacecraft relative to the impact surface, as measured in the local horizontal axis system, can be developed in the equation

$$\{\vec{V}\}_H = \begin{Bmatrix} u \\ v \\ w \end{Bmatrix}_H = \begin{Bmatrix} u_W \\ v_W \\ w_W \end{Bmatrix}_H + (TH2R)^{-1} \begin{Bmatrix} u_O \\ v_O \\ w_O \end{Bmatrix}_R - \begin{Bmatrix} u_I \\ v_I \\ w_I \end{Bmatrix}_H \tag{4}$$

where the downwind and crosswind spacecraft velocity components (u_W and v_W, respectively); the spacecraft descent velocity w_W; the transformation matrix TH2R from the local horizontal axis system to the riser axis system as developed in equation (1); the tangential velocity components u_O, v_O, and w_O of the spacecraft as a result of parachute riser oscillations; and the impact surface velocity components u_I, v_I, and w_I are known in terms of defined variables and where all these components are assumed to be directed away from the spacecraft.

The resultant velocity vector can be transformed from the local horizontal axis system to the impact-tangent-plane axis system by the equation

$$\{\vec{V}\}_{TP} = \begin{Bmatrix} u \\ v \\ w \end{Bmatrix}_{TP} = (TH2TP)\{\vec{V}\}_H \tag{5}$$

where TH2TP as developed in equation (3) represents the required transformation matrix. By definition, w_{TP} is V_N, the required velocity component normal to the impact tangent plane, and the equation

$$V_T = \sqrt{u_{TP}^{\ 2} + v_{TP}^{\ 2}} \tag{6}$$

provides the required velocity component V_T coincident to the impact tangent plane. A more direct and facile method of developing V_T is possible by equating the vector moduli for both systems, as in the equation

$$\left| \{\vec{V}\}_{TP} \right| = \left| \{\vec{V}\}_{H} \right| \tag{7}$$

Therefore, since $\{\vec{V}\}_H$ is known in terms of defined variables and V_N has been solved for, V_T can be determined by the expression

$$V_T = \sqrt{u_H^2 + v_H^2 + w_H^2 - V_N^2} \tag{8}$$

Angular Relationship

The analytical model must also provide a means of determining the orientation of the spacecraft relative to the impact tangent plane. This orientation is described by the Euler angles θ and Φ, as shown in figure 2. Assuming the spacecraft and impact-tangent-plane axis systems to be initially coincident in all three axes, $90^\circ - \theta$ describes the rotation about Y_{TP} which displaces X_{SC} from its coincidence with X_{TP}. This angle may also be defined as the included angle between the Z_{SC}-Y_{SC} plane and the impact tangent plane (the X_{TP}-Y_{TP} plane). The angle Φ is the rotation about X_{SC} which describes the relationship between the X_{SC}-Z_{SC} plane and the plane formed by X_{SC} and the impact point (the X_{SC}-IP plane). The determination of these angles can be accomplished by the use of unit vectors in a vector analysis, based on the spacecraft and impact-tangent-plane axis systems. Given the respective axis systems and the transformation matrix TTP2SC defined as

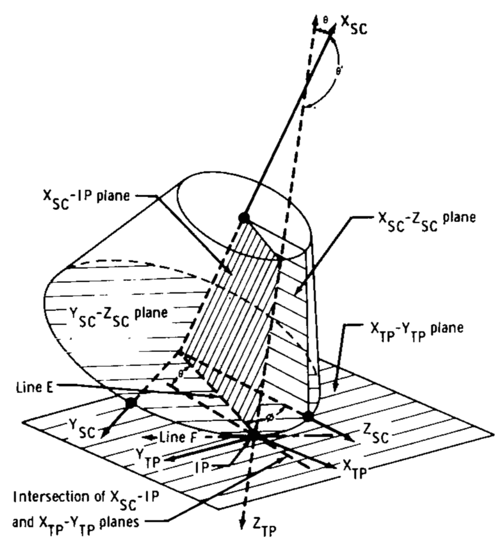


Figure 2. - Angular relation of the spacecraft to the impact tangent plane.

$$\text{TTP2SC} = \left[d_{ij}\right] = (\text{TR2SC})(\text{TH2R})(\text{TH2TP})^{-1} = \left[b_{ij}\right] \cdot \left[a_{ij}\right] \cdot \left[c_{ij}\right]^{-1} \tag{9}$$

the vector analysis technique can be used to solve for θ and Φ, as shown in the following.

In this analysis, θ is defined as the included angle between the Y_{SC}-Z_{SC} and X_{TP}-Y_{TP} planes, and as stated in reference 2, the cosine of the included angle (such as θ) between two planes can be determined in the relation

$$\cos \theta = \left[\ell_1\ell_2 + m_1m_2 + n_1n_2\right] \tag{10}$$

where $\ell_1: m_1: n_1$ and $\ell_2: m_2: n_2$ are the direction cosines of lines normal to the respective planes. Then, if the unit vector $\{i\}$ in the X_{SC} direction has direction cosines of 1: 0: 0, if the unit vector $\{k'\}$ in the Z_{TP} direction has direction cosines of 0: 0:1, and if $\{k'\}$ is transformed into the spacecraft coordinate system in the relation

$$\{\underline{k}'\} \equiv \{k'\}_{SC} = \mathrm{TTP2SC}\{k'\} \tag{11}$$

the angle between the normals to the Y_{SC}-Z_{SC} and X_{TP}-Y_{TP} planes (θ' as shown in fig. 2) can be obtained directly from the relation

$$\cos \theta' = i_x\underline{k}'_x + i_y\underline{k}'_y + i_z\underline{k}'_z = \underline{k}'_x \tag{12}$$

The angle θ can then be obtained through the relation

$$\theta = 180^\circ - \theta' = 180^\circ - \cos^{-1}\left(\underline{k}'_x\right) \tag{13}$$

As stated previously, the angle Φ is defined as the included angle between the X_{SC}-Z_{SC} plane and the plane formed by X_{SC} and the impact point (the X_{SC}-IP plane). This angle can be more specifically described as the angle between Z_{SC} and a line E formed by the intersection of the Y_{SC}-Z_{SC} plane and the X_{SC}-IP plane. The direction cosines of a line of intersection between two planes can be determined in the general relation

$$\ell : m : n = \begin{vmatrix} m_1 & n_1 \\ m_2 & n_2 \end{vmatrix} : \begin{vmatrix} n_1 & \ell_1 \\ n_2 & \ell_2 \end{vmatrix} : \begin{vmatrix} \ell_1 & m_1 \\ \ell_2 & m_2 \end{vmatrix} \tag{14}$$

where the direction cosines $\ell_1 : m_1 : n_1$ and $\ell_2 : m_2 : n_2$ describe lines normal to the respective planes (ref. 2).

The relation in equation (14) can be used to obtain the direction cosines of the line of intersection (line F) between the Y_{SC}-Z_{SC} and X_{TP}-Y_{TP} planes; that is

$$\ell_F : m_F : n_F = \begin{vmatrix} \underline{k}'_y & \underline{k}'_z \\ 0 & 0 \end{vmatrix} : \begin{vmatrix} \underline{k}'_z & \underline{k}'_x \\ 0 & 1 \end{vmatrix} : \begin{vmatrix} \underline{k}'_x & \underline{k}'_y \\ 1 & 0 \end{vmatrix} \tag{15}$$

Inasmuch as line F is normal to the X_{SC}-IP plane, the direction cosines $0 : \underline{k}'_z : -\underline{k}'_y$ of line F and the direction cosines 1:0:0 of the line normal to the Y_{SC}-Z_{SC} plane can then be substituted into the same relation to provide the direction cosines of line E as follows.

$$\ell_E : m_E : n_E = \begin{vmatrix} 0 & 0 \\ \underline{k}'_z & -\underline{k}'_y \end{vmatrix} : \begin{vmatrix} 0 & 1 \\ -\underline{k}'_y & 0 \end{vmatrix} : \begin{vmatrix} 1 & 0 \\ 0 & \underline{k}'_z \end{vmatrix}$$

$$= 0 : \underline{k}'_y : \underline{k}'_z \tag{16}$$

The angle Φ can then be obtained from the relation

$$\Phi = \tan^{-1}\left(\frac{\underline{k}'_y}{\underline{k}'_z}\right) \tag{17}$$

COMPUTER PROGRAM FOR SIMULATED IMPACTS

The preceding section was devoted to the development of the analytical expressions required in order to determine the velocity and orientation of a spacecraft relative to an impact surface at the instant of impact. These expressions are functions of the following input parameters: (1) the Euler angles λ, Ω, Φ', and Υ which describe spacecraft orientation; (2) the velocity vectors $\vec{V}_W$, $\vec{V}_O$, and $\vec{V}_I$ which describe wind and descent velocity, riser oscillation, and impact-tangent-plane velocity (in the event of water landings), respectively; and (3) the Euler angles μ' and γ which describe the orientation of the impact tangent plane. From these analytical expressions, a computer program has been developed which simulates a spacecraft impact and provides a means of determining impact velocity and orientation for a given set of input parameters. (The exact location of the impact point on the body of the spacecraft is a function of spacecraft configuration and can be determined geometrically from the orientation angles.) A flow diagram illustrating this computer program is presented in figure 3. The program can be used to determine the impact conditions for a single spacecraft landing or for a parametric study of a large number of landings. If the available data are sufficient to prepare a cumulative frequency distribution for each required input parameter, the computer program can be used to perform a statistical analysis which will provide an insight into the probability of occurrence of the various landing impact conditions (i.e., θ, Φ, V_N, and V_T).

Calculate the transformation matrix required in order to go from the local horizontal axis system to the riser axis system.

$$TH2R = \left[a_{ij}\right]$$

Input:
λ, Ω

↓

Calculate the transformation matrix required in order to go from the riser axis system to the spacecraft axis system.

$$TR2SC = \left[b_{ij}\right]$$

Input:
Φ', Υ

(a) Impact angle.

Figure 3. - Landing simulation flow diagram.

Calculate the transformation matrix required in order to go from the local horizontal axis system to the impact-tangent-plane axis system.

$$\mathrm{TH2TP} = \left[c_{ij}\right]$$

Input:
μ', γ

Calculate the transformation matrix required in order to go from the impact-tangent-plane axis system to the spacecraft axis system.

$$\mathrm{TTP2SC} = \left[d_{ij}\right] = (\mathrm{TR2SC})(\mathrm{TH2R})(\mathrm{TH2TP})^{-1}$$

Determine the components of the unit vector in the spacecraft axis system.

$$\begin{Bmatrix} \underline{k}'_x \\ \underline{k}'_y \\ \underline{k}'_z \end{Bmatrix} = \begin{Bmatrix} d_{13} \\ d_{23} \\ d_{33} \end{Bmatrix}_{TP} = \mathrm{TTP2SC} \begin{Bmatrix} 0 \\ 0 \\ 1 \end{Bmatrix}_{TP}$$

Calculate the impact pitch angle

$$\theta = 180^\circ - \cos^{-1}\left(\underline{k}'_x\right)_{SC}$$

and the impact roll angle

$$\Phi = \tan^{-1}\left(\frac{\underline{k}'_y}{\underline{k}'_z}\right)_{SC}$$

(a) Concluded.
Figure 3. - Continued.

Calculate the transformation matrix required in order to go from the local horizontal axis system to the riser axis system.

$$TH2R = \left[a_{ij}\right]$$

Input: λ, Ω

Calculate the transformation matrix required in order to go from the local horizontal axis system to the impact-tangent-plane axis system.

$$TH2TP = \left[c_{ij}\right]$$

Input: μ', γ

Calculate the resultant velocity vector relative to the local horizontal axis system.

$$\{\vec{V}\}_H = \begin{Bmatrix} u \\ v \\ w \end{Bmatrix}_H = \begin{Bmatrix} u_W \\ v_W \\ w_W \end{Bmatrix}_H + (TH2R)^{-1} \begin{Bmatrix} u_O \\ v_O \\ w_O \end{Bmatrix}_R - \begin{Bmatrix} u_I \\ v_I \\ w_I \end{Bmatrix}_H$$

Input: appropriate velocity components

Calculate the normal impact velocity

$$V_N = c_{31}u_H = c_{32}v_H + c_{33}w_H$$

and the tangential impact velocity

$$V_T = \sqrt{u_H^2 + v_H^2 + w_H^2 - V_N^2}$$

(b) Impact velocity.

Figure 3. - Concluded.

These distributions can provide the range of impact parameters to be considered in determination of impact loads and could also serve as input to an analysis to assessing the structural capability of a previously defined structure in order to determine the probability of a structural failure.

CONCLUDING REMARKS

An analytical model which describes the angular and velocity interrelationships of the landing system, spacecraft, and impact surface for any given set of dynamic conditions determined by the atmosphere, the landing system or spacecraft (or both), and the impact surface has been described. A computer program developed from this model provides a means of determining the normal and tangential velocities and the roll and pitch angles of the spacecraft with relation to the impact surface at the moment of impact.

The computer program may be used to determine the impact conditions for a single spacecraft landing or for a parametric study of a large number of landings. Also, if the available data are sufficient to prepare cumulative frequency distributions for the variables which describe or affect impact surface, relative velocity, and spacecraft orientation, the computer program can be used to perform a statistical analysis of expected impact conditions. These impact conditions can in turn be used in the determination of impact loads.

Manned Spacecraft Center
National Aerounatics and Space Administration
Houston, Texas, November 10, 1970
914-50-11-09-72

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APPENDIX

STATISTICAL ANALYSIS OF POTENTIAL APOLLO COMMAND MODULE IMPACT CONDITIONS

INTRODUCTION

To demonstrate use of the computer program described in the text, a statistical analysis of Apollo command module impact conditions is presented. In the analysis, the structural capability of the Apollo command module must first be considered. Portions of the command module primary structure were designed relative to the water impact phase of the mission and relative to a recovery weight of 3628.8 kilograms (8000 pounds). However, extensive modifications increased the command module weight to such an extent that the design margin of the structure required reevaluation. To perform this reevaluation, it was necessary to determine both the range of impact conditions (velocity and attitude) which the Apollo command module might experience upon landing on the ocean surface and the relation of these conditions to landing loads. Based on this information, a determination was made of the number of times structural damage hazardous to crew survival would occur.

STATISTICAL TECHNIQUE

The impact conditions could have been determined by parametric computations; however, when the wide range of potential values for each of the several input parameters was considered, a statistical analysis which presents the results in terms of probabilities was more practical. One such statistical method is the Monte Carlo technique which, based on random numbers (computer generated), selects values from a range of possible values for each of the input parameters. The range of input values and the choice of the values used are based on the probabilities associated with the parameter rather than typical worst-case values. This type of technique had the direct effect of indicating less severe impact conditions, which in turn lessened the design loads and thus prevented further weight increase.

INITIAL CONDITIONS

The spacecraft configuration for which the statistical analysis was performed is the Apollo Block II command module which has a recovery weight (parachute and spacecraft) of 5307.1 kilograms (11 700 pounds) and a center-of-gravity and a riser attachment point which result in a 27.5° mean hang angle while the command module is on the three main parachutes. The resulting impact conditions, that is, normal velocity V_N, tangential velocity V_T, and impact angle θ measured between the Y_{SC}-Z_{SC} plane and the impact tangent plane, were determined for the current operational surface wind limit (in which mean winds are fixed and operationally constrained to a limit of

28.5 knots at the surface or 37.7 knots at an altitude of 45.7 meters (150 feet)), a 2.25-knot gust variance, a fully developed sea (described by the NASA Manned Spacecraft Center sea model), and a 1-percent two-parachute probability. Based on the previously discussed spacecraft configuration, wind condition, gust component, sea state, and 1-percent two-parachute probability, a cumulative frequency distribution was prepared for each required input parameter, that is, λ, Ω, Υ, μ, γ, w_I, v_O, u_W, and w_W. These cumulative frequency distributions are shown in figure A-1. The effects of the velocity components u_I, v_I, and v_W are negligible and, if a circular riser oscillation in the Y_R-Z_R plane is assumed, u_O and w_O are equal to zero. Therefore, these velocity components are not used as input parameters in the demonstration.

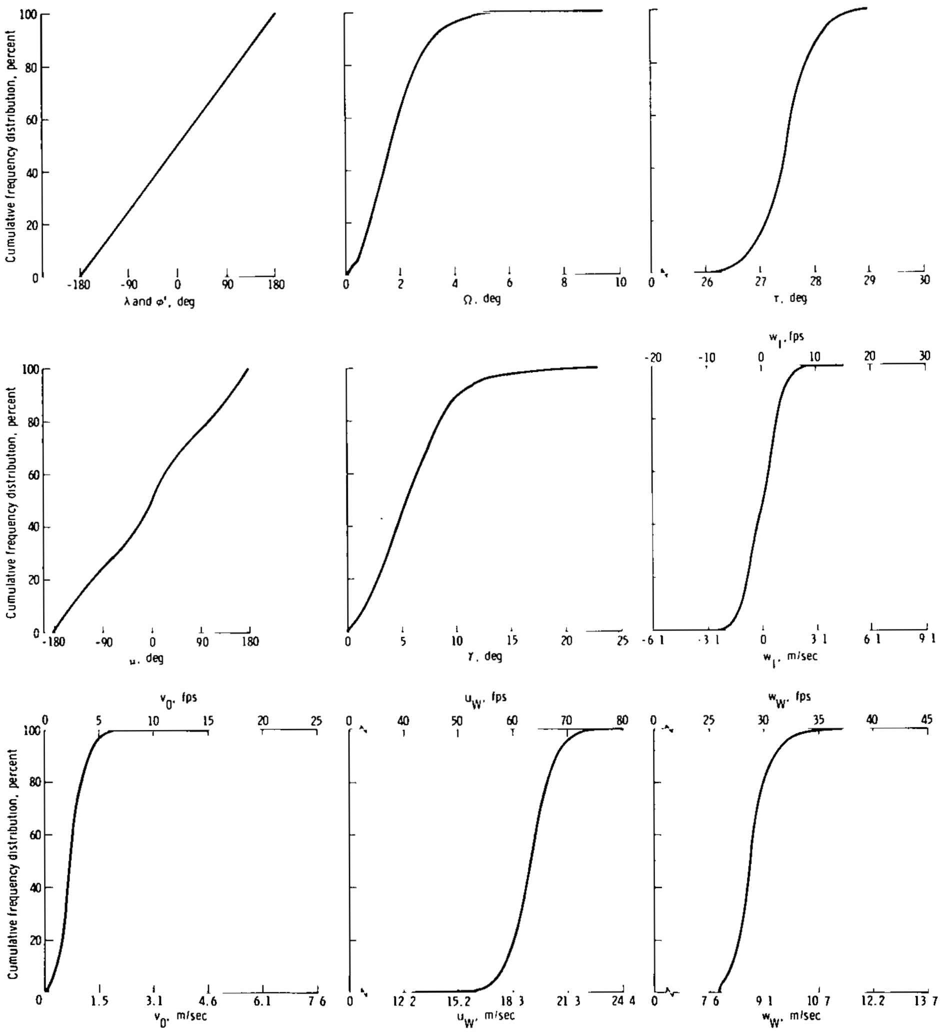


Figure A-1. - Cumulative frequency distributions of impact parameters for a fully developed sea with a 28.5-knot surface wind and a 1-percent two-parachute probability.

COMPUTER-SIMULATED LANDING IMPACTS

With the Monte Carlo statistical technique to select values randomly for each input parameter from the appropriate cumulative frequency distribution, the computer program was used to calculate impact conditions for spacecraft landings. This computer-implemented landing simulation was conducted for 100 000 samples with the previously discussed initial conditions.

RESULTS

The cumulative frequency distributions of the resulting water impact parameters for the input conditions analyzed are shown in figure A-2. This information was used for an assessment of the range of potential velocities and attitudes to be anticipated and later provided initial-condition data for testing the capability of the actual hardware.

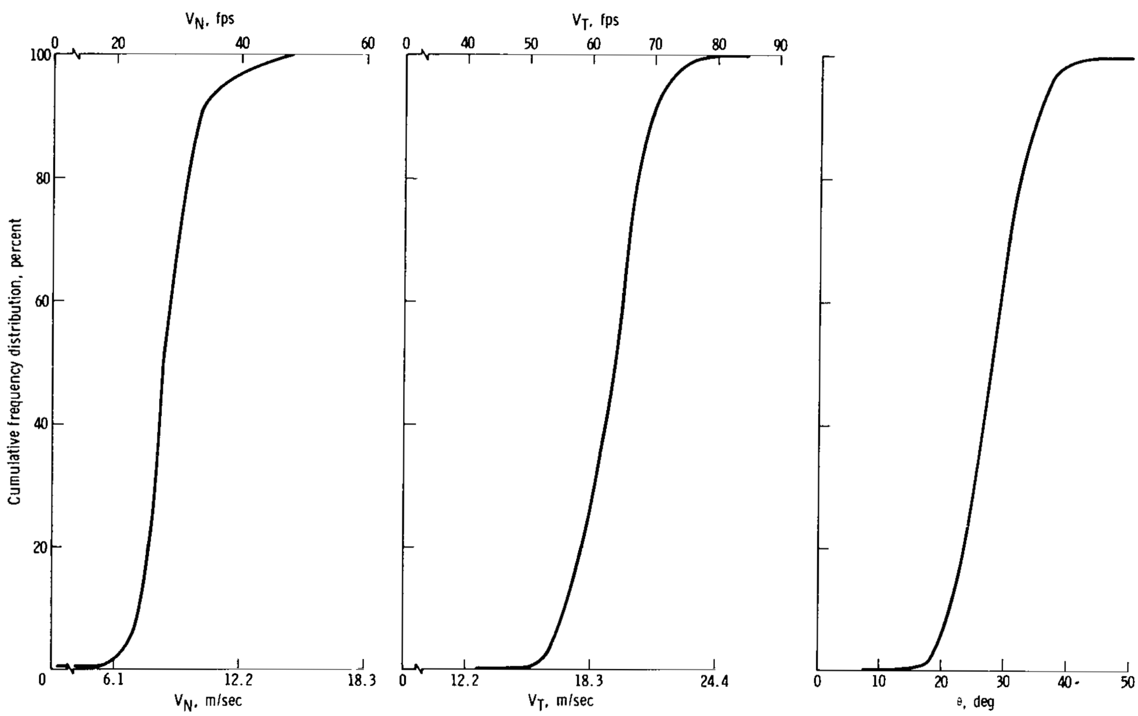
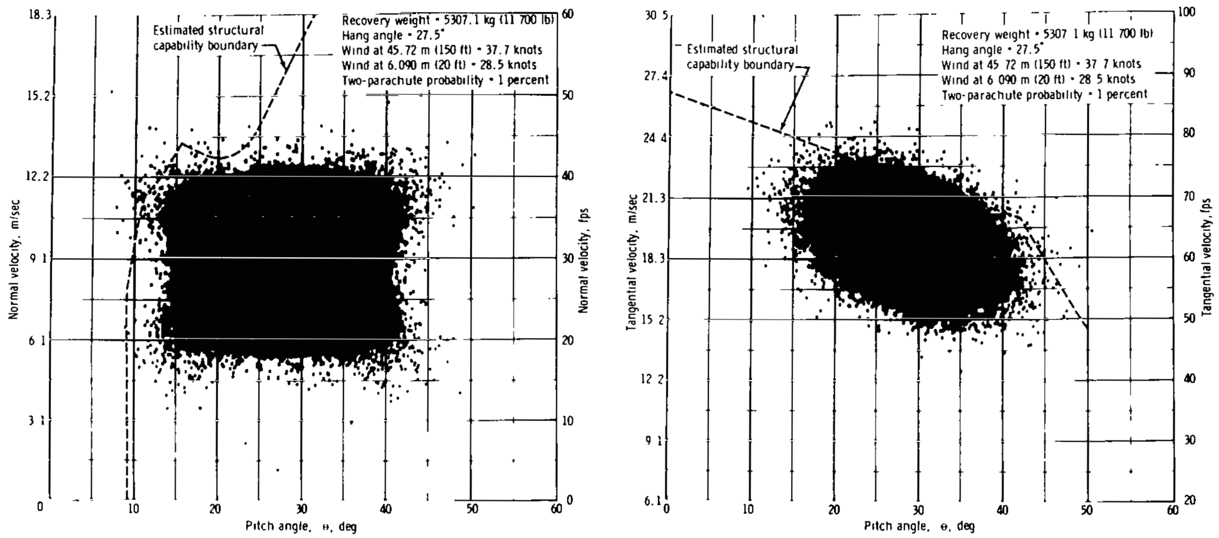


Figure A-2. - Cumulative frequency distributions of water impact conditions for a fully developed sea with a fixed 28.5-knot surface wind and a 1-percent two-parachute probability.

By comparing the impact conditions to values representing the limiting structural capability, the success or failure for each simulated landing can be determined. To demonstrate this comparison, scatter diagrams of the resulting impact conditions, together with a line representing the structural capability data, are provided in figure A-3. Figure A-3(a) illustrates V_N compared with θ for the normal structural capability line and figure A-3(b) illustrates V_T compared with θ for the tangential structural capability line. By accumulating the number of successful impacts (combining successful impacts from figures A-3(a) and A-3(b)) and dividing by the number of trails (100 000), the probability of success may be determined. By actual count of the data shown in figure A-3, there were 61 and 425 exceedences (i. e., impact conditions which exceed the design limit capability) for V_N and V_T, respectively. Consequently, the probability of success for an Apollo Block II command module water landing with a fixed surface wind of 28. 5 knots (37. 7 knots at a 45. 7-meter altitude), a 2. 25-knot gust variance, a fully developed sea, and a 1-percent two-parachute probability is 0. 99514. It should be noted, however, that the current operational surface wind as established in the Apollo mission rules represents the maximum wind speed that will be accepted at a water landing site. (An alternate site will be selected if the surface wind speed approaches 28. 5 knots.) Therefore, the results of the demonstration are based on a remote probability of wind speed and sea state.



(a) Normal velocity compared with impact angle.

(b) Tangential velocity compared with impact angle.

Figure A-3. - Distribution of water impact conditions for a fully developed sea with a fixed 28. 5-knot surface wind and a 1-percent two-parachute probability.

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