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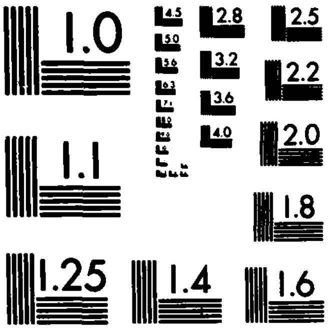
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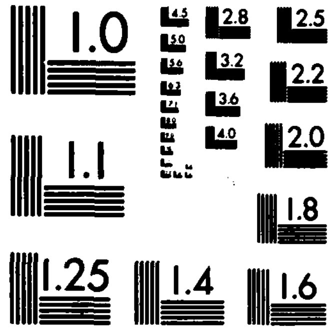

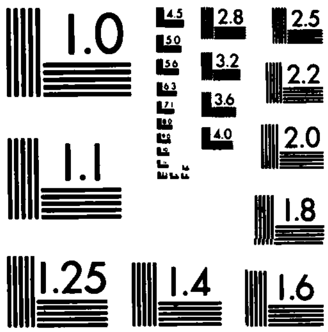

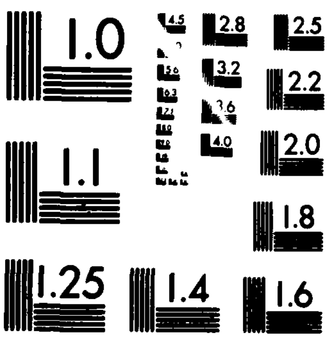

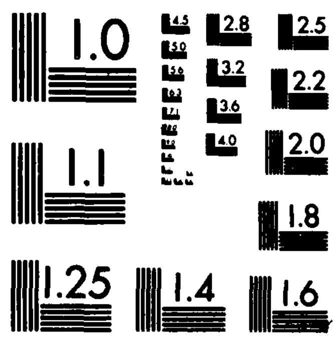

USER'S MANUAL

FOR

UCIN-EULER

A MULTIPURPOSE, MULTIBODY SYSTEMS DYNAMICS

COMPUTER PROGRAM

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A

I. SUMMARY

This is a User's Manual for the computer program UCIN-EULER. The program is designed and developed to study the dynamics of multibody systems. The multibody systems encompassed by EULER are systems of linked rigid bodies with no closed loops, as in Figure 1. Such systems are sometimes called "open-chain," "open-tree," or "general-chain" systems. Examples of such systems are robot arms, chains, antennas, manipulators, and human body models.

The manual provides instruction for using EULER to study multibody system dynamics. It also provides sample input and output data. The input procedures and the commands to EULER are expressed in terms of <u>keywords</u>. The use of keywords, as opposed to formatted FORTRAN statements, is intended to make the program useful and readily accessible to even the casual user.

II. CAPABILITIES OF EULER

EULER is designed to perform the following kinds of dynamic analyses:

1. <u>Given</u>: a) the physical data (geometry, masses, inertia properties, and the assembly configuration) of the bodies of the system; b) the external forces and moments applied to each body of the system; and c) the moments applied by adjoining bodies on each other; <u>then</u> the kinematics (positions, velocities, and accelerations) of each body of the system is determined numerically as a function of time.

2. <u>Given</u>: a) the physical data and b) the kinematics of each body of the system as a function of time, <u>then</u> the required driving forces and moments

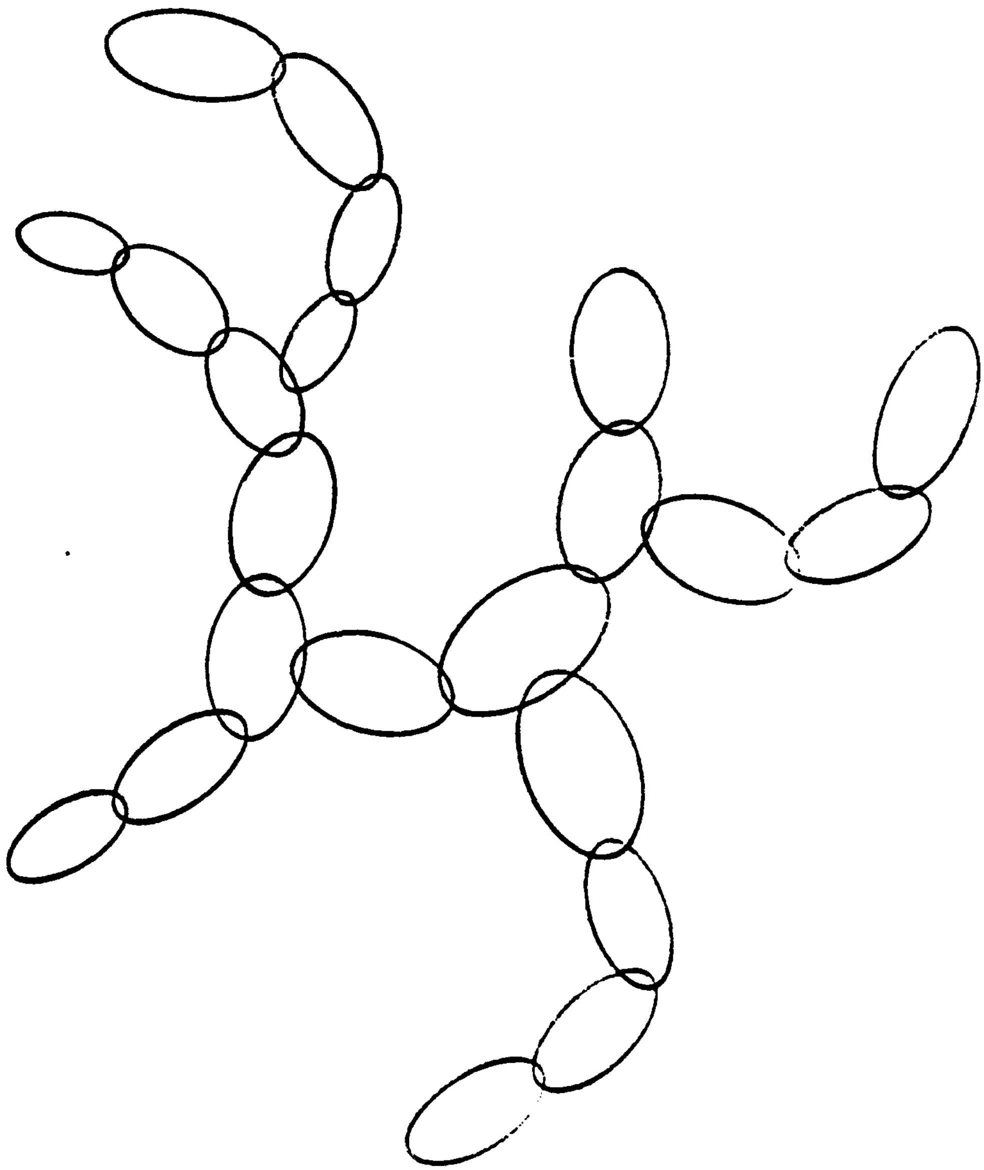


Figure 1. A Multibody System.

are determined numerically as a function of time.

3. Given: a) the physical data; b) the forces and moments exerted on some of the bodies; and c) the kinematics of the remainder of the bodies, then the kinematics of the first set of bodies is determined and the driving forces and moments on the second set of bodies is determined numerically as a function of time.

EULER has the capability for performing the above tasks in both English and metric units. The bodies of the system may be connected by either hinge or spherical joints. The hinge axes may be inclined relative to the principal inertia axes of the bodies. The bodies and joints may be given arbitrary labels. Gravity forces may be applied in six different directions. Finally, the output data may be detailed, comprehensive, or selective at the user's option.

III. THEORETICAL BASIS OF EULER

References [1-4]* provide the analytical basis of EULER. The governing differential equations are obtained by using Lagrange's form of d'Alembert's principle and Kane's equations as exposited by Kane et al. [4-8]. This procedure has distinct advantages over Newton's laws and Lagrange's equations for multi-body systems. Specifically, Kane's method provides for the automatic elimination of non-working internal constraint forces while avoiding the tedious differentiation of scalar energy functions.

In the formulation of EULER the velocities and accelerations are computed through vector derivatives which may be evaluated through vector cross products. This leads to algorithms which are readily converted into computer subroutines.

* Numbers in brackets refer to References at the end of the Manual.

The relative orientation of the bodies is defined by four Euler parameters at each joint. The use of Euler parameters, as opposed to Euler orientation angles or dextral orientation angles, provides for the avoidance of singularities which are often encountered in three-dimensional motion. (The name "EULER" comes from the use of Euler parameters.)

The use of Kane's equations and Euler parameters leads to a set of governing equations whose coefficients are readily evaluated numerically. The equations themselves are easily solved for the unknown Euler parameter derivatives. Moreover, they form uncoupled expressions for the unknown joint moment components.

Finally, the governing differential equations are solved using RKGS [10], a fourth order Runge Kutta integrator. EULER is written, however, so that other numerical integrators may also be used.

IV. DEFINITIONS OF TERMS

This part of the Manual defines terminology, parameters, and procedures used in EULER. These definitions are useful in understanding the input requirements.

1. Multibody System

A "multibody system" is a set of rigid bodies assembled in "tree-like" fashion as shown in Figures 1. and 2. The assemblage is arbitrary except that no closed loops are formed by the bodies.

If adjacent bodies are connected by a spherical joint, they share a common point (the sphere center). If adjacent bodies are connected with a hinge joint, they share a line of common points (the hinge axis).

IV. DEFINITIONS OF TERMS

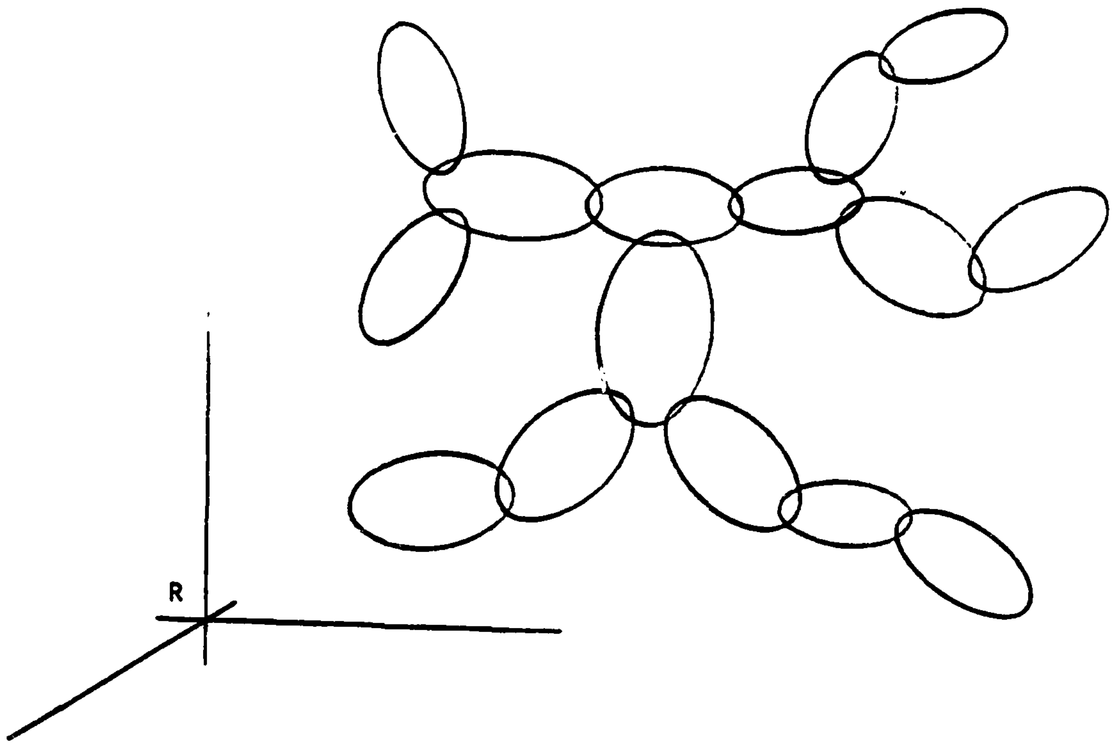


Figure 2. A Multibody System and an Inertial Reference Frame R.

The multibody system is considered to move in an inertial (Newtonian) reference frame R as shown in Figure 2.

2. Body Connection Array

To describe the configuration of the multibody system, let the bodies be numbered as follows: First, select a body (any body of the system) as a reference body. Let this be Body 1. Next, number the bodies in ascending progression away from Body 1 through the branches of the tree structure. Figure 3. shows such a numbering for the multibody system of Figure 2.

If the bodies are numbered this way, each body, except the reference body, is connected to one and only one adjacent lower numbered body. (Note that a body, for example body B_8, may be connected to more than one adjacent

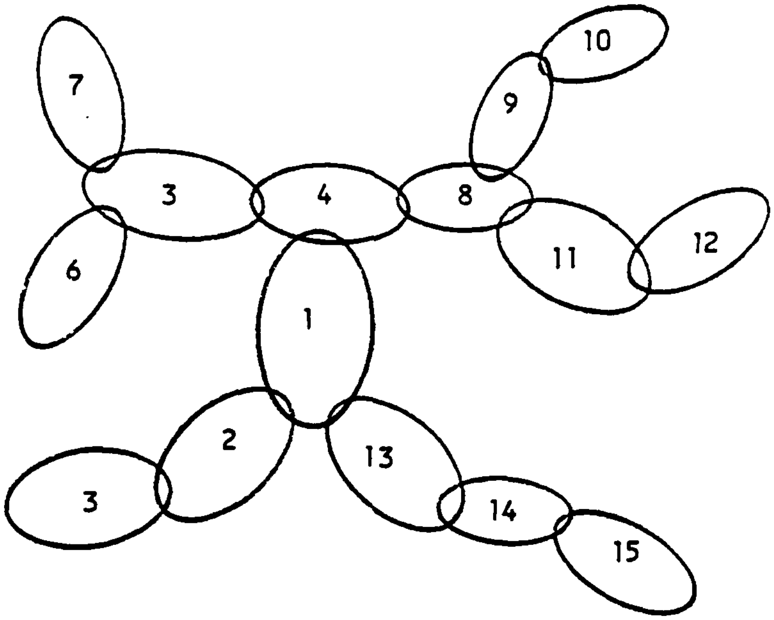


Figure 3. A Numbering of the Multibody System of Figure 2.

higher numbered body.) Hence, let the inertia frame R serve as the lower numbered body of Body 1 and let its number be: 0.

An array listing the lower numbered bodies for each body is called a "body connection array." In EULER this array is called "LOWER."* For the numbering shown in Figure 3., this array is:

BODY:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
LOWER:	0	1	2	1	4	5	6	4	8	9	8	11	1	13	14

Note that the array LOWER could be used to construct the configuration of Figure 3. Or, put another way, the array LOWER and the sketch of Figure 3. are equivalent.

---

* LOWER is a keyword used in the input data. In the sequel such keywords are written in capital letters.

3. Body Reference Points, Axes Systems

Let each body of the system have a reference point or origin. Let this point be at the connection joint with the adjacent lower numbered body. Next, introduce a local rectangular axes system for each body at its origin. The orientations of these axes systems are arbitrary, but it is usually convenient to have these axes parallel to centroidal principal inertia axes. Figure 4. shows axes systems for two typical adjoining bodies, B_j and B_k.

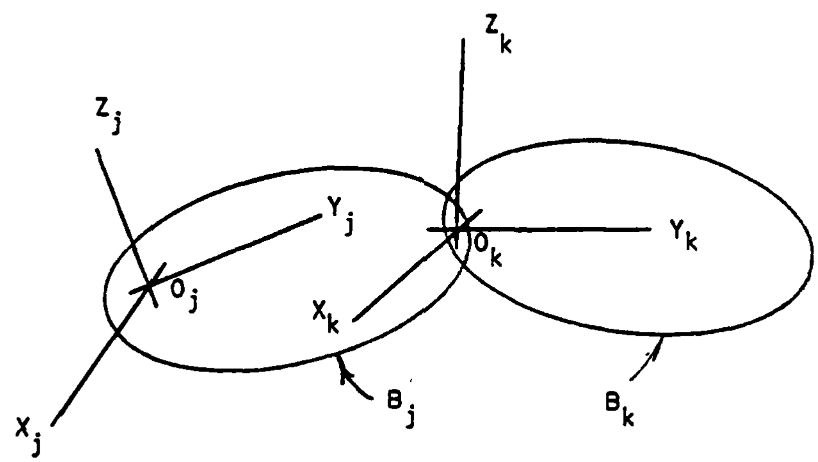


Figure 4. Origins and Axes Systems of Two Typical Adjoining Bodies.

The choice of axes orientation determines the values of the mass center coordinates, the connection joint coordinates, and the components of the inertia dyadic. (Each axes system is fixed in its body.)

The axes systems are not part of the input data for EULER. As noted above, however, their orientation and location determine the physical coordinate and component data. Conversely, this data could be viewed as defining the axes location and orientation.

4. Mass

The MASS of a typical body is simply the body's weight divided by the gravity acceleration in the chosen units.

5. Inertia

The INERTIA of each body refers to the inertia dyadic relative to the mass center and referred to the coordinate axes described in Section 3. above.

6. Mass Center Location: The RS-Vectors

Let the mass centers of each of the bodies be located relative to the body origins (See 3. above.) by a vector $\underset{\sim}{RS}$ whose components are referred to the local axes system of the body. See Figure 5. The components of the

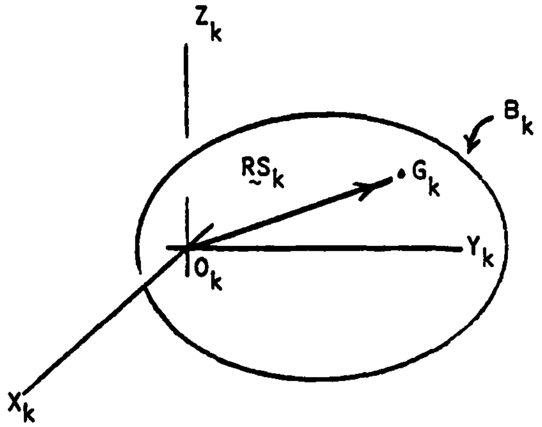


Figure Notati

B_k - Typic Body

O_k - Origi B_k

G_k - Mass k

X_k, Y_k, Z_k - Axes System of B_k

$\underset{\sim}{RS}_k$ - Position Vector of G_k relative to O_k

Figure 5. A Typical Body, Its Origin, Axes System, Mass Center, and $\underset{\sim}{RS}$-Vector.

$\underset{\sim}{RS}$ are thus the coordinates of G_k relative to the axes system X_k, Y_k, Z_k of B_k. (Note that $\underset{\sim}{RS}_k$ is <u>fixed</u> in B_k.)

7. Location of Connecting Joints and Body Origins: The XI-Vectors

As noted earlier, a typical body of the system may be connected to several <u>higher</u> numbered bodies. Let the connecting points with these higher numbered bodies be located relative to the body origin by vectors $\underset{\sim}{XI}$. Let the components of the $\underset{\sim}{XI}$ vectors be referred to the local axis system of

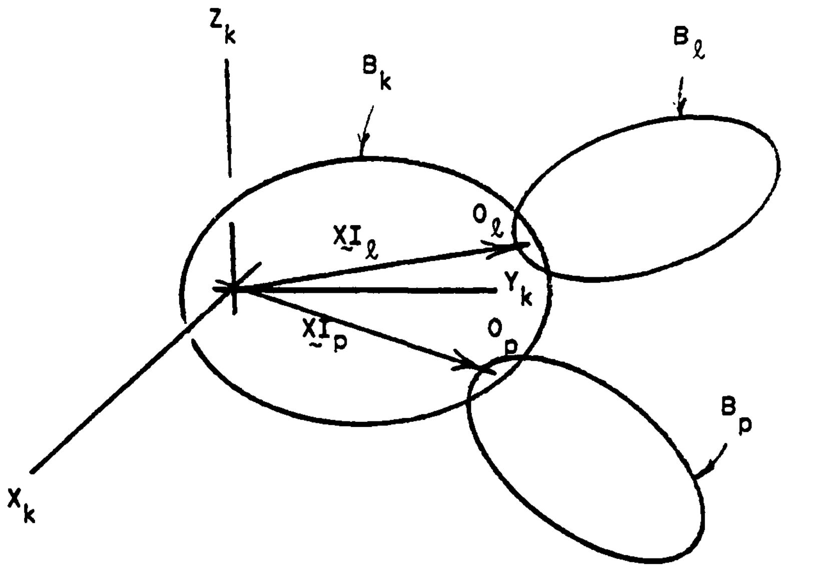


Figure Notation:

B_ℓ, B_p - Typical Bodies of the System

B_k - Adjacent Lower Numbered Body of B_ℓ and B_p

O_ℓ, O_p - Connecting Points of B_ℓ and B_p with B_k. (O_ℓ and O_p are thus origins of B_ℓ and B_p.)

O_k - Origin of B_k

X_k, Y_k, Z_k - Axes System of B_k

$\underset{\sim}{XI}_\ell, \underset{\sim}{XI}_p$ - Position Vectors Locating O_ℓ and O_p Relative to O_k

Figure 6. $\underset{\sim}{XI}$ Vectors for Typical Bodies B and B_p.

the body. See Figure 6. The components of the $\underset{\sim}{XI}$ vectors (in this example, $\underset{\sim}{XI}_\ell$ and $\underset{\sim}{XI}_p$ of B_ℓ and B_p) are thus the coordinates, of the origins (O_ℓ and O_p) of the connected higher numbered bodies relative to the axes system X_k, Y_k, Z_k of the lower body B_k.

8. Orientation Angles

The relative orientation of two adjacent connected bodies can be defined in terms of "dextral" orientation angles. These angles themselves can be defined as follows: Consider the axes systems of the bodies to be mutually aligned as shown in Figure 7. Body B_k can be brought to a general orientation relative to body B_j by three successive rotations through angles α_k, β_k, and γ_k about the axes X_k, Y_k, and Z_k.

These angles are called "dextral" angles since the angle is taken to be positive when the rotation is in the "right-handed" or dextral sense relative to the axis. For example, a positive α_k rotation is shown in Figure 8.

IV. DEFINITIONS OF TERMS

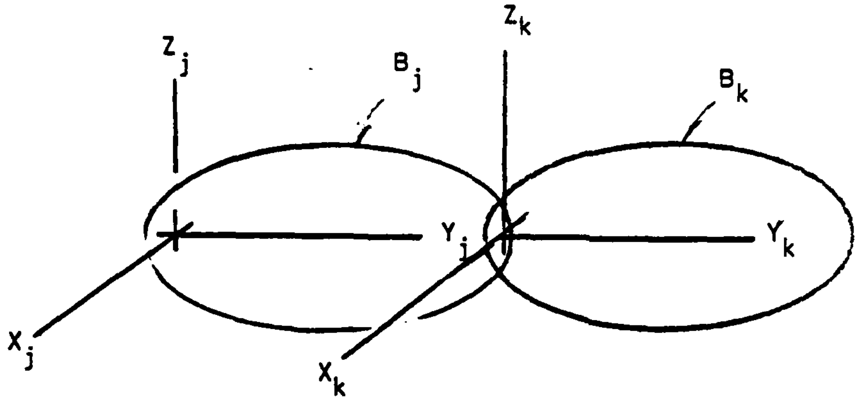


Figure 7. Aligned Axes Systems of Two Adjacent Bodies.

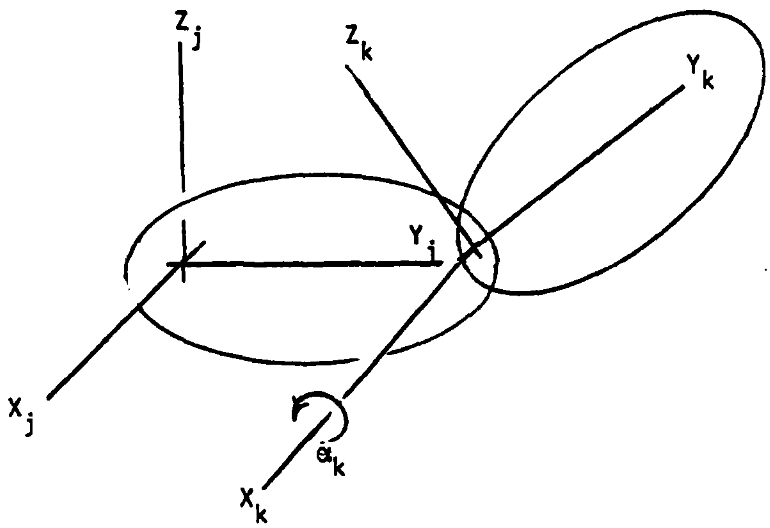


Figure 8. Positive α_k Rotation.

Note that the angles α_k, β_k, and γ_k are defined in terms of rotations of B_k about the X_k, Y_k, and Z_k axes (as opposed to say X_j, Y_j, and Z_j). This means, for example, that if $\alpha_k \neq 0$ then β_k is the rotation of B_k about the "rotated" Y_k axis as shown in Figure 9. γ_k is defined similarly as a rotation about the rotated Z_k axis.

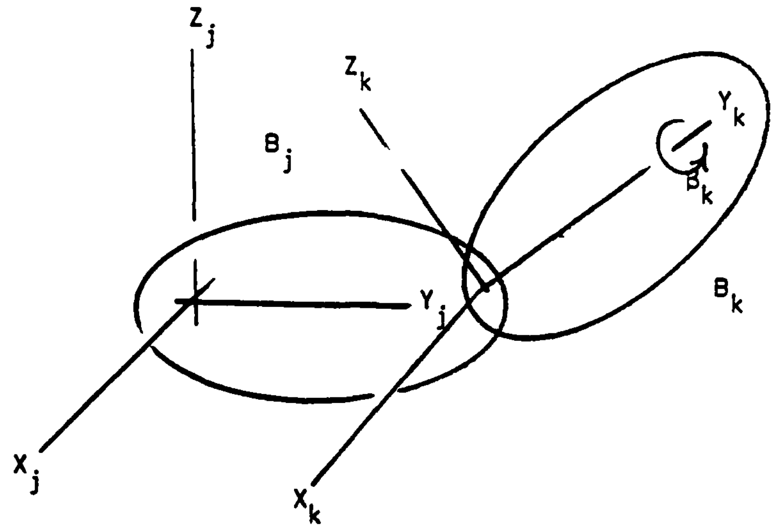


Figure 9. Definition of β_k Rotation.

In many instances the orientation of B_k relative to B_j can be defined in terms of a single rotation about one of the coordinate axes. This occurs with a simple hinge joint (See 10. below). In this case, the relative orientation can be defined in terms of a single angle α_k, β_k, or γ_k depending upon whether the rotation is about X_k, Y_k, or Z_k.

9. Euler Parameters

A different way of defining the relative orientation of adjacent bodies is through the use of Euler Parameters. (The name "EULER" stems from the use of Euler parameters in the computer code.)

When dextral angles, as defined above, are used to describe the relative orientation of the bodies there occur values for α, β, and γ for which singularities arise in the dynamical equations. (For example, $\alpha>0$, $\beta=90°$, $\gamma>0$. See [2].) Such singularities also occur in other sets of orientation angles, such as Euler angles.

These singularities may be avoided through the use of four Euler Parameters to define the relative orientation of the bodies. The Euler parameters themselves are defined as follows: Consider again two typical adjoining bodies B_j and B_k, as in Figure 7. Then B_k may be brought into any general orientation relative to B_j by means of a single rotation about an appropriate axis [9]. If $\underset{\sim}{\lambda}_k$ is a unit vector parallel to this axis and if θ_k is the rotation angle, the four Euler parameters are defined as:

$$\varepsilon_{k1} = \lambda_{k1}\sin\theta_k/2 \qquad \varepsilon_{k2} = \lambda_{k2}\sin\theta_k/2$$
$$\varepsilon_{k3} = \lambda_{k3}\sin\theta_k/2 \qquad \varepsilon_{k4} = \cos\theta_k/2 \tag{1}$$

where the λ_{ki} (i=1,2,3) are the components of $\underset{\sim}{\lambda}_k$ relative to the unit vectors $\underset{\sim}{n}_{ji}$. See Figure 10.

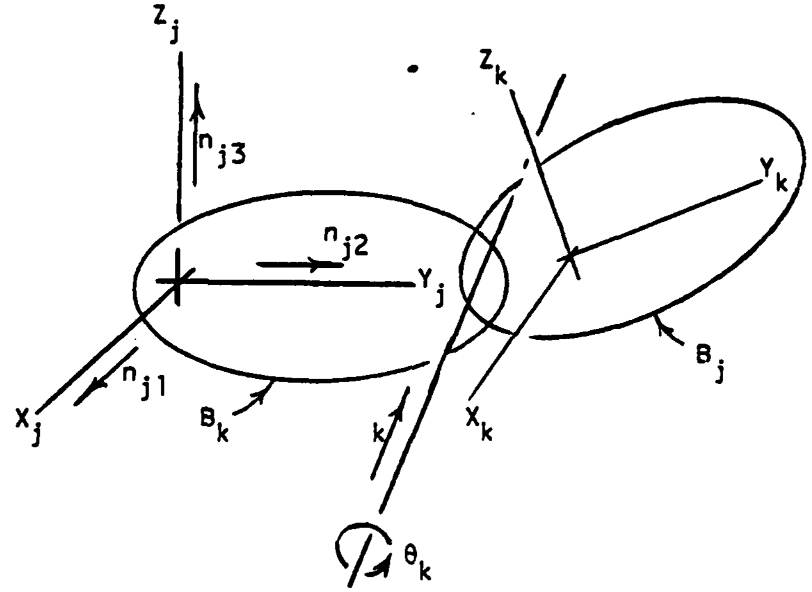


Figure 10. Two Typical Adjoining Bodies, Rotation Axis, and Rotation Angle used in Euler Parameter Definition.

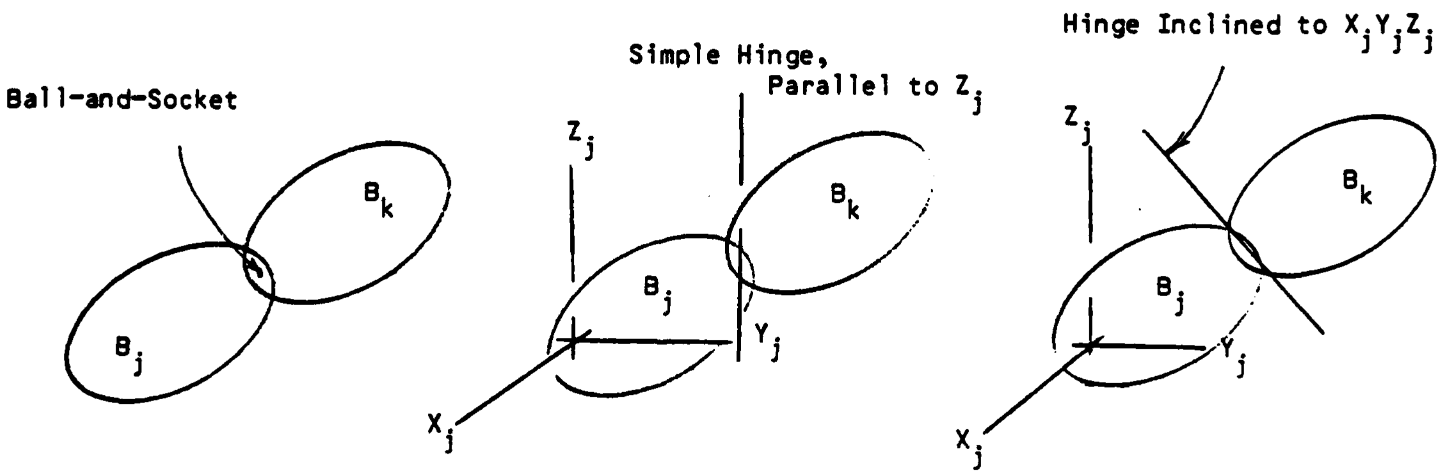
The Euler parameters are not independent, but instead are related by the expression:

$$\varepsilon_{k1}^2 + \varepsilon_{k2}^2 + \varepsilon_{k3}^2 + \varepsilon_{k4}^2 = 1 \qquad (2)$$

Although the Euler parameters are used in the algorithms of the computer program, the input/output is expressed in terms of dextral angles for convenient geometrical interpretation.

10. Connecting Joints

In EULER the bodies of the system may be connected by two kinds of joints: Spherical Joints and Hinge Joints. There are in turn two kinds of hinge joints: Simple Hinges and Inclined Hinges. Simple hinges have axes which are parallel to one of the coordinate axes of the lower numbered body. Inclined hinges have axes parallel to a vector which is inclined relative to the coordinate axes of the lower numbered body. These joints are depicted in Figure 11.



a. Spherical Joint b. Simple Hinge Joint c. Inclined Hinge Joint

Figure 11. Connecting Joints of EULER.

The connecting joints, be they spherical or hinge joints, may be either free joints or they may have specified motion. If they are free joints, the variables describing the relative orientation of the two bodies (that is, the Euler parameters or the orientation angles) are unknowns. These unknowns are then determined by the numerical integrator of EULER. If there is specified motion at the connecting joints, the relative motion of the bodies is known. Probably the most common specified motion is no motion at all: that is, a locked joint. In this case, the relative orientation variables are constants, usually zero. If the orientation variables are not constants, that is, if they are known functions of time, they may be described for input to EULER by using acceleration profiles as defined in Section 14. below.

11. Applied Forces and Moments

Consider the multibody system to be subjected to an externally applied force field. Let this force field as it is applied on a typical body B_k be replaced by a single force $\underset{\sim}{F}_k$ passing through the mass center G_k together with a couple with torque $\underset{\sim}{M}_k$. (In the data input requirements for EULER, $\underset{\sim}{F}_k$ and $\underset{\sim}{M}_k$ are to be provided if they are not zero. This may be accomplished by separate coding in Subroutine EXFRE or by using keywords if the force field is constant. (See Part V, Section 13.)

12. Joint Moments

In addition to the externally applied forces on the system, the bodies of the system themselves may exert forces on each other across the connecting joints. Let these forces be represented by a single force passing through the connecting joint together with a couple. Let the torque of the couple exerted on body B_k by its adjacent lower numbered body B_j be called $\underset{\sim}{T}_k$. If at the connecting joint between B_j and B_k there is specified motion (for example, if the joint is locked), then $\underset{\sim}{T}_k$ is an unknown determined by EULER. Conversely, if the connecting joint is a free joint, $\underset{\sim}{T}_k$ is known and it is required as input data if it is different from zero. (Currently this is done in Subroutine EXFRE.)

13. Gravity Forces

In EULER gravity forces may be applied to the bodies of the system in any coordinate direction of the axes of the inertia frame R.

14. Acceleration Profiles

If the relative motion between two adjoining bodies is known, the motion may be specified for EULER by means of an "acceleration profile." Also, the displacement of the reference body B_1 may be known and specified through acceleration profiles. An acceleration profile is simply a set of data points representing the coordinates of selected points on an acceleration-time curve. Such coordinates may be obtained from the graph of the acceleration function.

EULER has the capability of accepting as many as 25 data points from an acceleration curve. A piecewise linear approximation is then made of the acceleration function. For example, consider the acceleration function and its approximation shown in Figure 12. The acceleration, velocity, and displacement during the i^{th} time interval are then:

$$a = a_i + \left(\frac{a_{i+1} - a_i}{t_{i+1} - t_i} \right) (t - t_i) \tag{3}$$

IV. DEFINITIONS OF TERMS

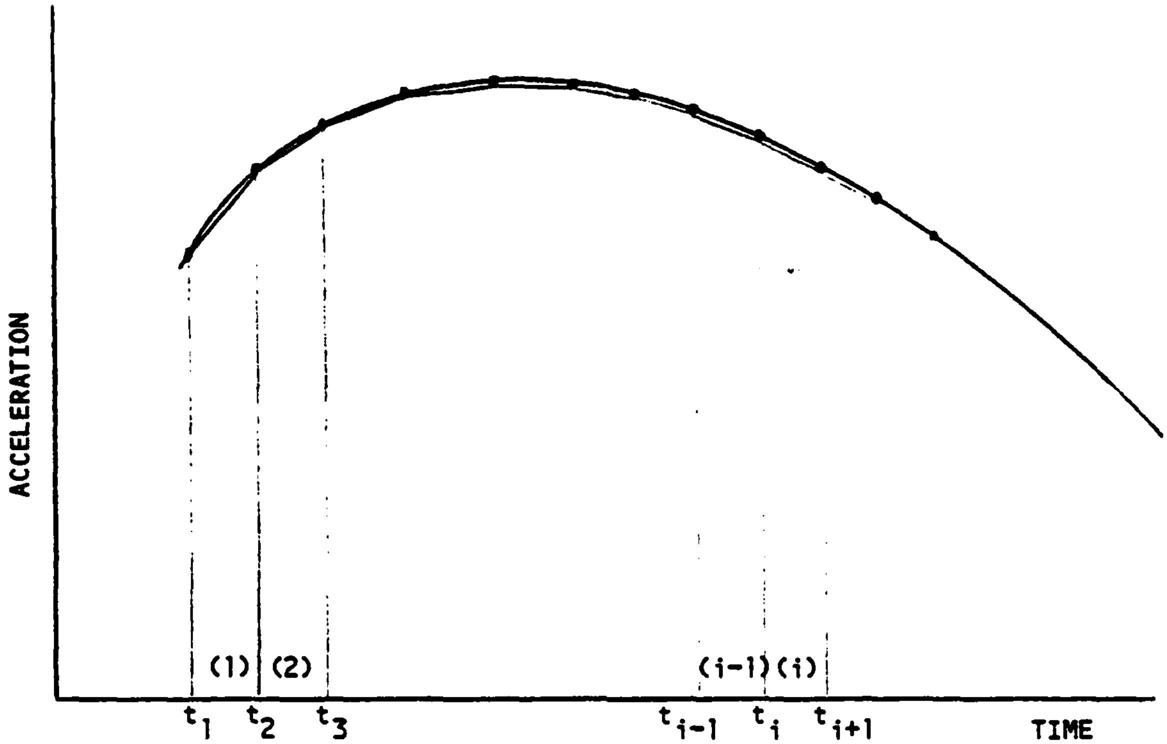


Figure 12. Acceleration Profile Approximation.

$$v = v_i + a_i(t - t_k) + \left(\frac{a_{i+1} - a_i}{t_{i+1} - t_i}\right)(t - t_i)^2/2 \tag{4}$$

$$d = d_i + v_i(t - t_i) + a_i(t - t_i)^2/2 + \left(\frac{a_{i+1} - a_i}{t_{i+1} - t_i}\right)(t - t_i)^3/6 \tag{5}$$

where a_i, v_i, d_i, and t_i are the acceleration, velocity, displacement, and time at the beginning of the i^{th} interval. Thus the entire kinematic profile (displacement, velocity, and acceleration) is known when the a_i are given and when v_1 and d_1, the initial velocity and displacement (at time t_1), are given.

V. INPUT REQUIREMENTS

This part of the manual describes specific input data requirements for EULER. The data itself is described in terms of "card" images, although many users will probably not use cards to transmit the data. Indeed, many users will use an interactive terminal for data input. Thus, for these users the following descriptions are "line images" of the data.

As noted earlier, the algorithms and code of EULER are written in FORTRAN. For the input data however, a set of keywords has been constructed for the convenience of the user. These keywords are identified in the sequel by capitalized words. (They may be abbreviated by using the first four letters of the word.)

1. Number of Bodies

The first card of the input data contains the *number of bodies of the* system. No keyword is needed. For example, for the system shown in the card would read:

12

The number 12 can be placed in any location on the card.

2. Body Connection Array

The second card contains a listing of the adjacent lower numbered bodies of the system. (See Part III, Section 2.) The card contains the keyword LOWER followed, in order, by the numbers of the adjacent lower numbered bodies. For example, for the system shown in Figure 13. this card would read as:

LOWER 0 1 2 3 2 5 1 7 7 1 11 1

Note that blanks are used as delimeters to separate the numbers.

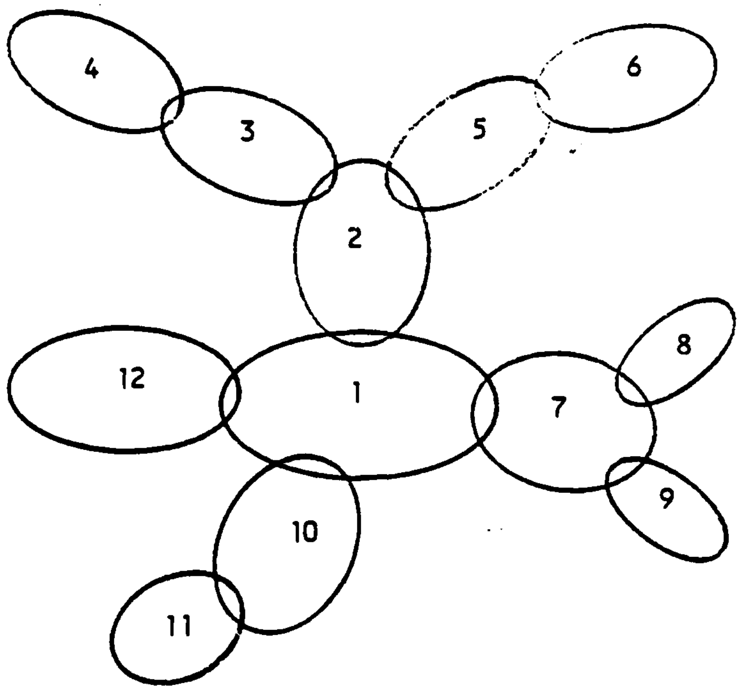


Figure 13. Example Multibody System.

3. Units

The next set of cards is used to select the desired units for the input (and output) data. As a default, EULER uses the English units feet, seconds, pounds, slugs, and degrees for length, time, force, mass, and angle. If different units are desired, the user simply employs the keyword: UNITS followed by the desired units. The following options are available:

Length	Time	Force	Mass	Angle
FEET	SEC	LBS	SLUGS	DEG
METERS	MS	NEWT	LBM	RAD
CM			KG	
INCH			GRAM	

where the abbreviated keywords are:

CM - centimeters
SEC - seconds
MS - milliseconds
LBS - pounds
NEWT - Newtons
LBM - pound mass
KG - kilograms
DEG - degrees
RAD - radians

For example, if the user wanted to use the metric system with milliseconds the card would read as:

UNITS METERS MS NEWT KG

Note that if a unit is not specified (such as DEG) EULER uses the default unit (degrees).

4. *Body Data*

The major portion of the input data for EULER is focused upon data for the individual bodies of the system. The data for the bodies is entered separately for each body of the system.

The first part of this data describes the geometrical and physical characteristics of the body. This is contained on 8 cards as follows:

1) The first card contains the keyword BODY followed by the body number. As an option, the body number can be followed by a label of up to 16 characters. For example, such a card might read:

BODY 8 HEAD

2) Next, there is a card containing the keyword MASS followed by a number representing the mass of the body. For example, this card might read:

MASS 5.7

3) Next, there is a card with the keyword RS followed by three numbers representing the local components (in the body) of the mass center position vector (See Part IV, Sections 3. and 6.). For example, this card might read:

RS 0.0 1.0 -2.3

4) Next, there is a card with the keyword XI followed by three numbers representing the components, in the adjacent lower numbered body, of the position vector of the body origin (See Part IV, Sections 3. and 7.). For example, this card might read:

XI 1.0 2.0 -0.5

Note that for Body 1 the XI vector is a variable describing the translation of Body 1. Hence, Body 1 is an exception and its XI card should always read:

XI 0.0 0.0 0.0

5) Finally, there is a set of cards describing the inertia dyadic of the body (See Part IV, Section 5.). The first of these cards contains the keyword INERTIA. This is followed by three cards, each containing three numbers representing the moments and products of inertia of the body relative to its mass center for the local X, Y, and Z directions respectively (See Part III, Section 3.). For example, this set of cards might read:

```
INERTIA
12.232     0.0      0.0
 0.0      12.338    0.0
 0.0       0.0      0.17110
```

Note that the numerical data on these cards must be consistent with the units selected above. Also, if desired, the order of the MASS, RS, XI, and INERTIA cards may be altered.

5. Joint Data

Each body is connected to its adjacent lower numbered body by a connecting joint. Thus, each joint is associated with one of the bodies of the system. The following paragraphs describe the input data needed to characterize these joints. This data must be included immediately following the geometrical and physical body data for each body respectively.

As discussed earlier, a joint may be selected from the following types of joints:

1) Spherical (ball-and-socket)
2) Simple hinge (axis along a coordinate axis)
3) Inclined hinge (axis parallel to an inclined line in the lower numbered body)
4) Locked (no motion at the joint)

The type of joint desired is designated by the keywords: FREE, INCLINED, or LOCKED. For a spherical or simple hinge joint, the keyword FREE is used followed by combinations keywords ALPHA, BETA, and/or GAMMA designating the axes (X, Y, and/or Z) of rotation.

1) Spherical Joint

At a spherical joint the connected bodies are free to rotate relative to each other about all three axes. Therefore, to select a spherical joint the following keywords are used:

FREE ALPHA BETA GAMMA

2) Simple Hinge Joint

At a simple hinge joint the connected bodies are free to rotate relative to each other about either the X, Y, or Z axis. To select a simple hinge joint with rotation about the X axis, the following keywords are used:

FREE ALPHA

Similarly, to select a simple hinge joint with rotation about the Y axis, the keywords are:

FREE BETA

Finally, to select a simple hinge joint with rotation about the Z axis, the keywords are:

FREE GAMMA

3) Inclined Hinge Joint

To select a hinge joint with an inclined axis connecting the bodies, the keyword INCLINE is used followed by three numbers which are the components in the lower numbered body of a vector parallel to the inclined axis. For example, consider an inclined hinge joint whose axis is parallel to the vector [1.0, 2.0, 3.0] (components relative to the axes system of the lower numbered body). For such a joint the following data is used:

INCLINE 1.0 2.0 3.0

(Note that a simple hinge joint is a special case of an inclined hinge joint. For example, a hinge joint with rotation about the Y axis can be selected by either the data: FREE BETA or INCLINE 0 1 0 .)

4) Locked Joint

A joint can be selected so that there is no relative motion between the connected bodies. To select a locked joint use the keyword

LOCKED

Any quantity which does not appear following the FREE statement is constrained; that is, locked. However, as a default, if the FREE statement is omitted, everything is free.

6. Joint Data for Reference Body 1

Since the reference Body 1 can undergo both rotation and translation relative to the inertia frame R (its lower numbered body), it can have as many as 6 degrees of freedom. Therefore, in the joint data for Body 1 the translation description needs to be included with the rotation description. Specifically, Body 1 can be either free or constrained in translation in any or all of the directions X, Y or Z. To select one of these options, the user need simply adjoin the letters X, and/or Y, and/or Z to the joint data statement as described above. For example, for a spherical joint (free rotation) and for freedom in translation in the X and Z directions, the following data is used:

FREE ALPHA BETA GAMMA X Z

As a second example, for freedom to rotate about the Y axis with complete freedom in translation, the following data is used:

FREE BETA X Y Z

See the default statement at the end of the previous section.

7. Initial Orientation

EULER provides an option of selecting an arbitrary initial orientation of the bodies. To specify an initial orientation at a joint, the keyword ANGLE is used followed by one or three numbers representing the hinge joint or spherical joint angles. For example, if at a hinge joint the initial angle is 30°, the following data is used:

ANGLE 30

For a spherical joint with initial angles of say $\alpha = 10^{\circ}$, $\beta = 0^{\circ}$, and $\gamma = 65^{\circ}$, the data would be:

ANGLE 10.0 0.0 65.0

If no initial angles are specified at a joint, they are assumed to be zero. (That is, the default values are zero.)

8. Initial Angular Velocity

Similarly, EULER provides the option of selecting arbitrary initial relative angular velocities of the system. To specify the initial relative angular velocity of a body the keyword AVELOCITY is used. The keyword is then followed by three numbers which are the components of the relative angular velocity vector of the body with respect to an axis system fixed in the adjacent lower numbered body. The specification of the relative angular velocity needs to be consistent with the type of joint connecting the body to its adjacent lower numbered body.

For example, if a body is connected to its adjacent lower numbered body by a simple hinge joint along the Y-axis, and if the initial angular speed about this axis is say 55.0 (in the selected units), then this initial angular velocity is specified as:

```
AVELOCITY 0.0 55.0 0.0
```

If no initial relative angular velocity is specified, it is assumed to be zero. (That is, the default is zero.)

9. Initial Velocity of Body 1

Finally, EULER provides the option of having the mass center of Body 1 have an arbitrary initial velocity. To specify this initial velocity, the keyword LVELOCITY is used followed by three numbers representing the initial velocity components of the mass center relative to the inertial frame.

For example, if the initial velocity of the mass center is $3.0\, \underset{\sim}{n}_{ox} - 5.0\, \underset{\sim}{n}_{oy} + 6.3\, \underset{\sim}{n}_{oz}$ the input data would be:

```
LVELOCITY 3.0 -5.0 6.3
```

10. Specified Angular Motion

EULER has the option of allowing the user to specify the relative angular motion of the bodies which are connected with hinge joints. This is done using the inclined hinge joints and the acceleration profiles described in Part IV, Section 14.

The data is entered as follows: First, the inclined hinge axis is selected as in Section 5. above. (If the rotation is to occur about one of the coordinate axes, the inclined axis vector is simply taken along the desired axis. For example, for rotation about the Z axis, the joint data is: INCLINE 0.0 0.0 1.0 . Next a card with the keyword ACCELERATION is inserted. This is followed by a card containing four numbers representing in order: 1) the initial time, 2) the initial relative angular acceleration, 3) the relative angular velocity, and 4) the initial angle (all in consistent units). Finally, this is followed by a series of cards each containing two numbers representing the time and the relative angular acceleration at that time.

For example, consider a hinge joint parallel to the Y axis. Let the relative angular acceleration profile be as depicted in Figure 14. with an

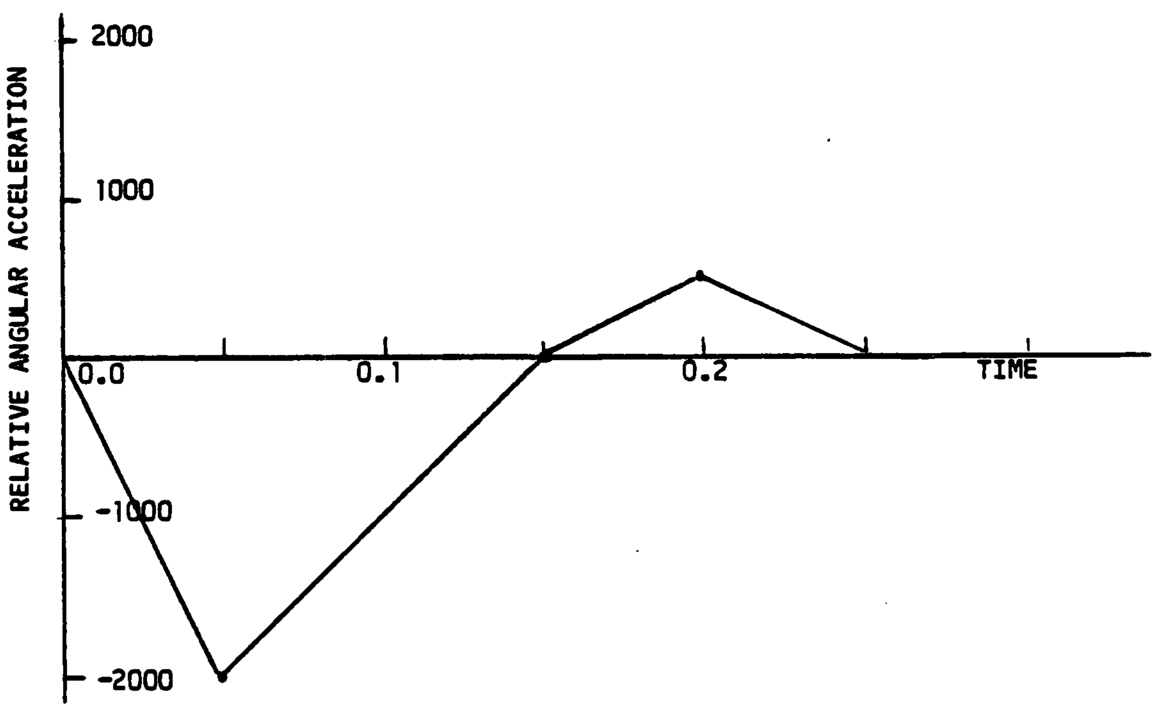


Figure 14. Example Relative Angular Acceleration.

initial relative angular velocity of 400.0. Then the data is entered as follows:

```
ACCELERATION
0.0    0.0    400.0    0.0
0.05   -2000.
0.10   -1000.
0.15   0.0
0.20   500.0
0.25   0.0
```

11. Joint Labels

EULER has the option of allowing the user to name the joints. This is accomplished by using the keyword ALABEL followed by the desired name (up to 16 characters).

For example, to name a joint "elbow" use the data:

```
ALABEL ELBOW
```

If a body is the last body in a branch of the chain (that is, an "ending" body), the "end" of the body itself may be named. This is accomplished by the keyword DLABEL followed by the desired name (up to 16 characters).

For example, to name the end of the body "hand," use the data:

```
DLABEL HAND
```

12. Specified Translation of Body 1

The translation of Body 1 relative to the inertial frame R can also be specified using the acceleration profiles. This is accomplished by using the keyword ACCELERATION followed by the letter X, Y, or Z, signifying the direction. This keyword card is then followed by the acceleration profile data as in Section 10. above.

For example, for specified motion in the X direction, the keyword card is:

```
ACCELERATION X
```

Specified translational motion of Body 1 may be included for more than one direction -- indeed, in all three directions. This is done by sequentially entering the data for the two or three directions.

13. Applied Forces and Moments

Forces and moments may be applied to the bodies of the system. This may be accomplished through user supplied coding in the Subrouting EXFRE.

If the applied forces and moments are constant, they may be included as part of the input data by keywords. Specifically, let the force system as it is applied to a typical body B_k be replaced by a single force $\underset{\sim}{F}_k$ passing through the mass center G_k together with a couple with torque $\underset{\sim}{M}_k$. Then $\underset{\sim}{F}_k$ may be included in the input data by the keyword FORCE followed by three numbers representing the components of $\underset{\sim}{F}_k$ in the inertia space R. Similarly, $\underset{\sim}{M}_k$ may be included in the input data by the keyword TORQUE followed by three numbers representing the components of $\underset{\sim}{M}_k$ in the inertia space R.

For example, suppose $\underset{\sim}{F}_k$ and $\underset{\sim}{M}_k$ are:

$$\underset{\sim}{F}_k = 6.1\, \underset{\sim}{n}_x + 8.2\, \underset{\sim}{n}_y - 3.7\, \underset{\sim}{n}_z \tag{6}$$

and

$$\underset{\sim}{M}_k = -4.3\, \underset{\sim}{n}_x - 2.0\, \underset{\sim}{n}_y + 5.6\, \underset{\sim}{n}_z \tag{7}$$

where $\underset{\sim}{n}_x$, $\underset{\sim}{n}_y$, and $\underset{\sim}{n}_z$ are mutually perpendicular unit vectors fixed in R. Then, $\underset{\sim}{F}_k$ and $\underset{\sim}{M}_k$ may be included in the input data of Body B_k by the statements:

```
FORCE 6.1 8.2 -3.7
```

and

```
TORQUE -4.3 -2.0 5.6
```

14. Gravity Forces

Gravity forces may be applied to the system by using the keyword VERTICAL followed by the vertical axis in the inertia frame R. The vertical axis may be either X, Y, Z, -X, -Y, or -Z. The gravity forces will then be directed opposite to this vertical direction.

For example, to apply gravity forces in the -Z direction, use the keyword and data:

```
VERTICAL  Z
```

15. Integration Parameters

EULER uses the numerical integrator RKGS. (See Reference [10].) This integrator requires: 1) a starting time, 2) an ending time, 3) an increment size, and 4) an error. These parameters may be entered into the program by using the keyword TIME followed by four numbers representing these data.

For example, if the time units are seconds, and if the integration is to occur over 3 seconds with an increment of 0.2 seconds and an error of 0.001, the following data would be used:

```
TIME  0.   3.   0.2   0.001
```

As a default EULER assumes a starting time of 0. and ending time of 10.0 with increments of 0.1 and an error of 0.001.

16. Comment Statements

Comment statements can be placed at any point in the input data. This is done by placing a & in column 1. The characters and data in the subsequent columns are then printed with the output record of the input data. For example:

```
&    THIS IS A COMMENT.
```

VI. OUTPUT OPTIONS

This part of the manual describes the output options. These are, for the most part, optional features for the convenience of the user.

1. Routing

EULER has the option of allowing the user to send the computed data to a temporary disk file for further processing. This is accomplished by using the keyword OUTPUT followed by the file number. These numbers must be consistent with the numbers specified by the Job Control Language. (This feature is dependent upon the local computer system.)

2. Heading

A heading or title of an EULER run may be placed at the top of each page of printout by using the keyword HEAD followed by the desired title or heading (up to 65 characters). For example:

```
HEAD   EXAMPLE RUN
```

3. Printing Times

The times the output data is printed is determined by the user through the keyword PRINT followed by a number indicating the printing time interval.

For example, if the units of milliseconds are used, the following will cause the data to be printed every 10 milliseconds:

```
PRINT  10
```

4. Printing Priority

EULER computes the following data for each body of the system at each time step:

1) The relative orientation angles and their time derivatives.
2) The Euler parameters.
3) The connecting joint mass center position, velocity, and acceleration.
4) The angular velocity and angular acceleration.
5) The joint moment.

In addition, for Body 1 EULER computes the position, velocity, and acceleration of reference point O_1 in the inertial reference frame R. If the motion of O_1 in R is specified or constrained, the constraining force components are computed.

Not all of this data need be printed. Indeed, the data which is printed is dependent upon a user supplied printing priority. The printing priority is set by the keyword PRIORITY followed by an integer I between -100 and 100. The data printed is then determined by this integer as follows:

Integer Value	Printing
$-100 < I < 0$	Prints all data at every printing time and at every integration step.
$0 \leq I \leq 10$	Prints all data at every printing time.
$10 < I \leq 20$	Prints all data except the joint moment constraints and the force constraints on Body 1.
$20 < I \leq 25$	Prints as immediately above, but deletes the acceleration of O_1.
$25 < I \leq 28$	Prints as immediately above, but deletes the angular velocities and angular accelerations.

Integer Value	Printing
$28 < I \leq 30$	Prints as immediately above, but deletes the Euler parameter derivatives.
$30 < I \leq 40$	Prints as immediately above, but deletes the velocity of O_1 and the orientation angle derivatives.
$40 < I \leq 50$	Prints as immediately above, but deletes the mass center velocities and accelerations.
$50 < I \leq 70$	Prints as immediately above, but deletes the joint and mass center position vectors.
$70 < I \leq 90$	Prints as immediately above, but deletes the Euler parameters.
$90 < I \leq 95$	Prints as immediately above, but deletes the position vector of O_1 and the orientation angles.
$95 < I \leq 100$	Prints as immediately above, but deletes the heading.

In addition to the computed data, EULER prints a record or "echo" of the input data.

5. Reference Axes

The joint and mass center positions are computed relative to both the inertial space R and relative to the axes of one of the bodies of the system. Normally this body is Body 1. It is possible, however, to compute these position vectors relative to an axis system of a body other than by using the keyword REFERENCE followed by the desired body number.

For example, to compute the joint and mass center positions relative to the axes of Body 3, use the data:

REFERENCE 3

If this option is not used, the axes of Body 1 will be used by default.

VII. EXAMPLE DATA

1. Introduction

This part of the Manual contains specific input data for an example multibody system. The system itself does not refer to any specific physical system. Instead, it is designed to illustrate the majority of the input and output options discussed in the previous parts.

2. The Example System

Figure 15. depicts the example system. It consists of spheres and

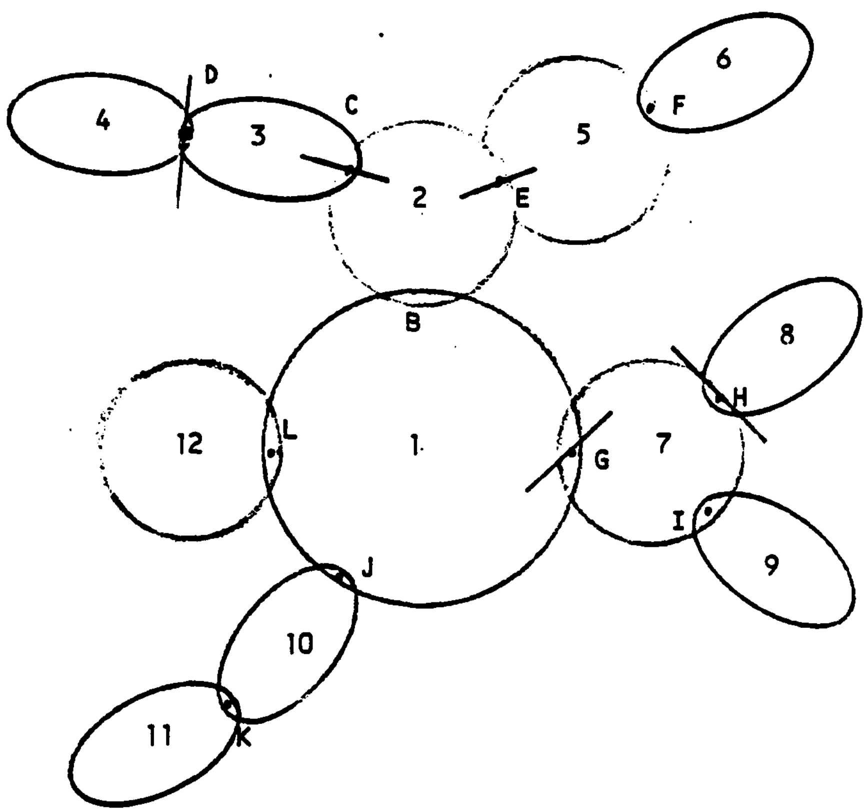


Figure 15. Example System.

ellipsoids connected by a variety of connecting joints. The bodies are labelled numerically and the joints are labelled alphabetically as shown in Figure 15.

There are 12 bodies. They may be described as:

Body 1: Large Sphere	Body 5: Sphere	Body 9: Ellipsoid
Body 2: Sphere	Body 6: Ellipsoid	Body 10: Ellipsoid
Body 3: Ellipsoid	Body 7: Sphere	Body 11: Ellipsoid
Body 4: Ellipsoid	Body 8: Ellipsoid	Body 12: Sphere

Similarly, there are 12 connecting joints. They may be described as:

Joint A: Spherical	Joint E: Hinge Z	Joint I: Spherical
Joint B: Spherical	Joint F: Locked	Joint J: Spherical
Joint C: Hinge X	Joint G: INCLINED(1,1,-2)	Joint K: Spherical
Joint D: Hinge Y	Joint H: INCLINED (1,0,0)	Joint L: Spherical

3. Physical and Geometrical Data

Let the masses, mass center vectors (RS), body connection vectors (XI), and inertia dyadics of the bodies be as listed in Table I. (The components are in the local coordinate system.)

Let the units be inches, pounds, slugs, seconds and degrees.

4. Applied Forces, Specified Motion, and Initial Conditions

To illustrate the input of externally applied constant forces*, let force systems be exerted on Bodies 3 and 7 which are equivalent to:

Body 3:

Force: $7\underset{\sim}{n}_{31} - 5\underset{\sim}{n}_{32} + 4\underset{\sim}{n}_{33}$ lb

Couple Torque: $-6\underset{\sim}{n}_{31} + 4\underset{\sim}{n}_{32} + 2\underset{\sim}{n}_{33}$ in lb

* If the applied forces are not constant, they can be separately coded in Subroutine EXFRE.

VII. EXAMPLE DATA

TABLE I. Physical and Geometrical Data for the Bodies.

Body Number	Mass	RS Components			XI Components			Inertia Components		
1	10.0	0.0	0.0	0.0	0.0	0.0	0.0	144.	0.0	0.0
								0.0	144.	0.0
								0.0	0.0	144.
2	2.5	0.0	3.0	0.0	0.0	6.0	0.0	9.0	0.0	0.0
								0.0	9.0	0.0
								0.0	0.0	9.0
3	5.0	0.0	0.0	6.0	-3.0	6.0	0.0	12.0	0.0	0.0
								0.0	9.0	0.0
								0.0	0.0	3.0
4	5.0	0.0	0.0	6.0	0.0	0.0	12.0	12.0	0.0	0.0
								0.0	9.0	0.0
								0.0	0.0	3.0
5	2.5	3.0	0.0	0.0	3.0	4.0	0.0	9.0	0.0	0.0
								0.0	9.0	0.0
								0.0	0.0	9.0
6	5.0	6.0	0.0	0.0	4.0	3.0	0.0	3.0	0.0	0.0
								0.0	9.0	0.0
								0.0	0.0	12.0
7	2.5	3.0	0.0	0.0	6.0	0.0	0.0	9.0	0.0	0.0
								0.0	9.0	0.0
								0.0	0.0	9.0
8	5.0	6.0	0.0	0.0	6.0	0.0	0.0	3.0	0.0	0.0
								0.0	9.0	0.0
								0.0	0.0	12.0
9	5.0	0.0	-6.0	0.0	4.0	-3.0	0.0	9.0	0.0	0.0
								0.0	3.0	0.0
								0.0	0.0	12.0
10	5.0	0.0	-6.0	0.0	0.0	-6.0	0.0	9.0	0.0	0.0
								0.0	3.0	0.0
								0.0	0.0	12.0
11	5.0	-6.0	0.0	0.0	0.0	-12.0	0.0	3.0	0.0	0.0
								0.0	9.0	0.0
								0.0	0.0	12.0
12	2.5	-3.0	0.0	0.0	-6.0	0.0	0.0	9.0	0.0	0.0
								0.0	9.0	0.0
								0.0	0.0	9.0

Body 7:

Force: $-8\underset{\sim}{n}_{71} + 9\underset{\sim}{n}_{72} - \underset{\sim}{n}_{73}$ lb

Couple Torque: $-3\underset{\sim}{n}_{71} + 6\underset{\sim}{n}_{73}$ in lb

Let there be gravity forces in the -Z direction.

b. Specified Motion

To illustrate the specified motion option, let the linear acceleration of Body 1 be specified in the Y direction and let the angular acceleration of Body 7 relative to Body 1 be given. Let the "profiles" of these accelerations be as shown in Figures 16. and 17.

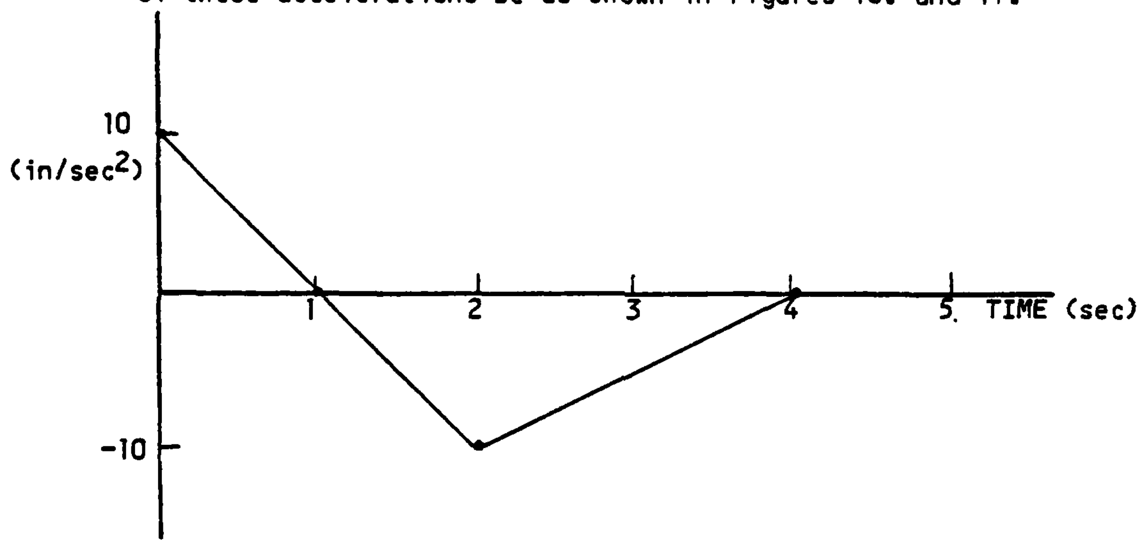


Figure 16. Acceleration of Body 1 in Y Direction.

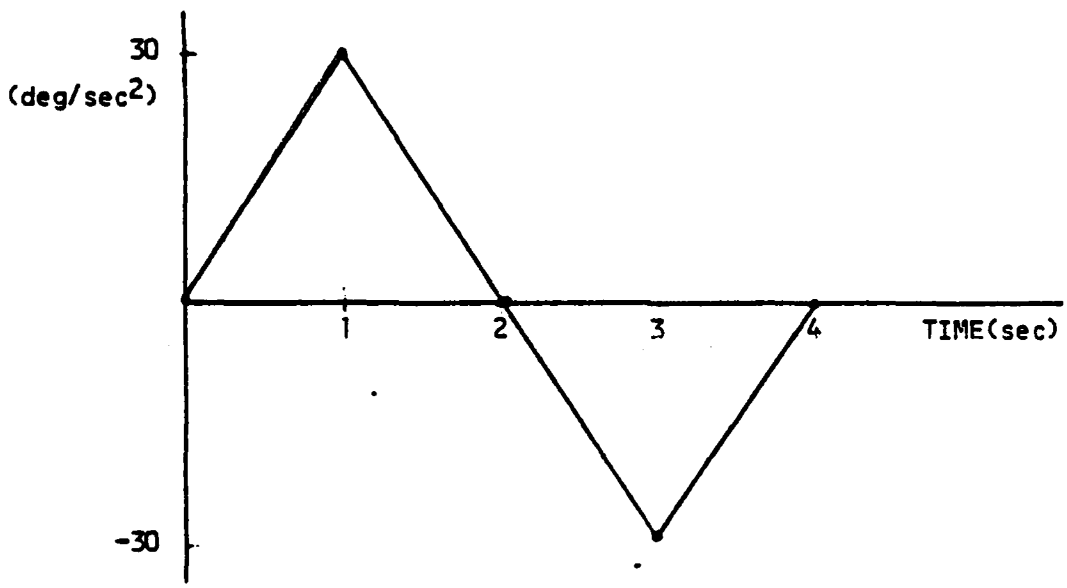


Figure 17. Angular Acceleration of Body 7.

VII. EXAMPLE DATA

c. Initial Conditions

Let the initial velocity of the mass center of Body 1 relative to the inertial frame R be: $3.0\underset{\sim}{n}_{ox} - 5.0\underset{\sim}{n}_{oy} + 6.3\underset{\sim}{n}_{oz}$ in/sec.

Let the initial orientation and initial relative angular velocities of the bodies be as shown in Table II.

TABLE II. Initial Orientation and Initial Relative Angular Velocities.

BODY	ANGLES			ANGULAR VELOCITY COMPONENTS		
1	0°	0°	0°	10.0	5.0	0.0
2	0°	5°	-5°	0.0	0.0	0.0
3		0°			0°	
4		0°			0°	
5		-15°			10.0	
6	0°	0°	0°	0.0	0.0	0.0
7		0°			0.0	
8		0°			0.0	
9	10°	-15°	25°	-5.0	5.0	10.0
10	0°	0°	0°	0.0	8.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0

5. Integration and Printing

Let the starting time for the example motion be: 0.0. Let the ending time be: 4.0 sec. Let the integration increment be every 0.25 sec and let the error be 0.01. Also, let all the data be printed every 0.25 sec. Let the exercise be called "Example Run."

6. Specific Input Data

Listed below is the specific input data for the above example.

```
&
& CARD IMAGES OF INPUT DATA FOR EXAMPLE RUN
&
& NUMBER OF BODIES
      12
& BODY CONNECTION ARRAY
 LOWER  0  1  2  3  2  5  1  7  7  1  11  1
&
 UNITS INCHES
&
& INPUT DATA FOR BODY 1
&
 BODY 1  LARGE SPHERE
&
& PHYSICAL AND GEOMETRICAL DATA FOR BODY 1
&
 MASS  10.0
 RS  0.0  0.0  0.0
 XI  0.0  0.0  0.0
 INERTIA
 144.   0.0   0.0
 0.0    144.  0.0
 0.0    0.0   144.
&
& JOINT DATA FOR BODY 1
```

VII. EXAMPLE DATA

```
&
  FREE ALPHA BETA GAMMA X Y Z
&
& INITIAL CONDITIONS
&
  LVELOCITY   3.0   -5.0   6.3
  AVELOCITY  10.0    5.0   0.0
&
& SPECIFIED MOTION
&
  ACCELERATION Y
  0.0     10.0    -5.0    0.0
  2.0    -10.0
  4.0      0.0
&
& JOINT LABEL:
  ALABEL JOINT A (SPHERICAL)
&
&
  BODY 2 SPHERE
&
& PHYSICAL AND GEOMETRICAL DATA FOR BODY 2
&
  MASS   2.5
  RS   0.0   3.0   0.0
  XI   0.0   0.0   0.0
  INERTIA
  9.0    0.0    0.0
  0.0    9.0    0.0
  0.0    0.0    9.0
&
& JOINT DATA FOR BODY 2
&
  FREE ALPHA BETA GAMMA
&
```

VII. EXAMPLE DATA

```
& INITIAL CONDITIONS
&
  ANGLE   0    5    -5
&
& JOINT LABEL:
  ALABEL JOINT B (SPHERICAL)
&
&
  BODY 3 ELLIPSOID
&
& PHYSICAL AND GEOMETRICAL DATA FOR BODY 3
&
  MASS   5.0
  RS     0.0    0.0    6.0
  XI    -3.0    6.0    0.0
  INERTIA
  12.0    0.0    0.0
   0.0    9.0    0.0
   0.0    0.0    3.0
&
& JOINT DATA FOR BODY 3
&
  FREE ALPHA
&
& JOINT LABEL:
  ALABEL JOINT C (HINGE: X AXIS)
&
& APPLIED FORCE SYSTEM ON BODY 3
&
  FORCE    7.0    -5.0    4.0
  TORQUE  -6.0     4.0    2.0
&
&
  BODY 4 ELLIPSOID
&
```

VII. EXAMPLE DATA

```
& PHYSICAL AND GEOMETRICAL DATA FOR BODY 4
&
  MASS    5.0
  RS      0.0    0.0    6.0
  XI      0.0    0.0   12.0
  INERTIA
  12.0    0.0    0.0
   0.0    9.0    0.0
   0.0    0.0    3.0
&
& JOINT DATA FOR BODY 4
&
  FREE BETA
&
& JOINT LABEL:
  ALABEL JOINT D (HINGE: Y AXIS)
&
&
  BODY 5 SPHERE
&
& PHYSICAL AND GEOMETRICAL DATA FOR BODY 5
&
  MASS     2.5
  RS       3.0    0.0    0.0
  XI       3.0    4.0    0.0
  INERTIA
  9.0    0.0    0.0
  0.0    9.0    0.0
  0.0    0.0    9.0
&
& JOINT DATA FOR BODY 5
&
  FREE GAMMA
&
& INITIAL CONDITIONS
  ANGLE   0    0    -15
  AVELOCITY    0.0    0.0    10.0
&
```

```
& JOINT LABEL
  ALABEL JOINT E (HINGE: Z AXIS)
&
&
  BODY 6 ELLIPSOID
&
& PHYSICAL AND GEOMETRICAL DATA FOR BODY 6
&
  MASS    5.0
  RS      6.0    0.0    0.0
  XI      4.0    3.0    0.0
  INERTIA
  3.0    0.0    0.0
  0.0    9.0    0.0
  0.0    0.0    12.0
&
& JOINT DATA FOR BODY 6
&
  LOCKED
&
& JOINT LABEL
  ALABEL JOINT F (LOCKED JOINT)
&
&
  BODY 7 SPHERE
&
& PHYSICAL AND GEOMETRICAL DATA FOR BODY 7
&
  MASS    2.5
  RS      3.0    0.0    0.0
  XI      6.0    0.0    0.0
  INERTIA
  9.0    0.0    0.0
  0.0    9.0    0.0
  0.0    0.0    9.0
&
```

VII. EXAMPLE DATA

```
& JOINT DATA FOR BODY 7
&
  INCLINE    1    1    -2
&
& JOINT LABEL
  ALABEL JOINT G (INCLINED HINGE (1,1,-2))
&
& SPECIFIED MOTION
&
  ACCELERATION
  0.0     0.0     0.0     0.0
  1.0    10.0
  2.0     0.0
  3.0   -10.0
  4.0     0.0
&
& APPLIED FORCE SYSTEM ON BODY 7
&
  FORCE    -8.0    9.0    -1.0
  TORQUE   -3.0    0.0     6.0
&
&
  BODY 8 ELLIPSOID
&
& PHYSICAL AND GEOMETRICAL DATA FOR BODY 8
&
  MASS   5.0
  RS     6.0    0.0    0.0
  XI     6.0    0.0    0.0
  INERTIA
  3.0    0.0    0.0
  0.0    9.0    0.0
  0.0    0.0   12.0
&
& JOINT DATA FOR BODY 8
&
```

VII. EXAMPLE DATA

```
  INCLINE (1,0,0)
&
& JOINT LABEL
  ALABEL JOINT H (HINGE X AXIS)
&
&
  BODY 9 ELLIPSOID
&
& PHYSICAL AND GEOMETRICAL DATA FOR BODY 9
&
  MASS   5.0
  RS     0.0   -6.0   0.0
  XI     4.0   -3.0   0.0
  INERTIA
  9.0    0.0    0.0
  0.0    3.0    0.0
  0.0    0.0   12.0
&
& JOINT DATA FOR BODY 9
&
  FREE ALPHA BETA GAMMA
&
& INITIAL CONDITIONS
&
  ANGLE    10    -15    25
  AVELOCITY   -5.0    5.0    10.0
&
& JOINT LABEL
  ALABEL JOINT I (SPHERICAL)
&
&
  BODY 10 ELLIPSOID
&
& PHYSICAL AND GEOMETRICAL DATA FOR BODY 10
&
```

```
  MASS    5.0
  RS      0.0    -6.0    0.0
  XI      0.0    -6.0    0.0
  INERTIA
  9.0     0.0     0.0
  0.0     3.0     0.0
  0.0     0.0    12.0
&
& JOINT DATA FOR BODY 10
&
  FREE ALPHA BETA GAMMA
&
& JOINT LABEL
  ALABEL JOINT J (SPHERICAL)
&
&
  BODY 11 ELLIPSOID
&
& PHYSICAL AND GEOMETRICAL DATA FOR BODY 11
&
  MASS    5.0
  RS     -6.0     0.0    0.0
  XI      0.0    12.0    0.0
  INERTIA
  3.0     0.0     0.0
  0.0     9.0     0.0
  0.0     0.0    12.0
&
& JOINT DATA FOR BODY 11
&
  FREE ALPHA BETA GAMMA
&
& JOINT LABEL
  ALABEL JOINT K (SPHERICAL)
&
&
```

VII. EXAMPLE DATA

```
 BODY 12 SPHERE
&
& PHYSICAL AND GEOMETRICAL DATA FOR BODY 12
&
 MASS   2.5
 RS    -3.0   0.0   0.0
 XI    -6.0   0.0   0.0
 INERTIA
 9.0   0.0   0.0
 0.0   9.0   0.0
 0.0   0.0   9.0
&
& JOINT DATA FOR BODY 12
&
 FREE ALPHA BETA GAMMA
&
& JOINT LABEL
 ALABEL JOINT H (SPHERICAL)
&
&
& GRAVITY FORCES IN THE -Z DIRECTION
&
 VERTICAL Z
&
&
& INTEGRATION PARAMETERS
&
 TIME   0.0   4.0   0.25   0.01
&
& PRINTING TIMES:
 PRINT  0.25
&
& HEADING:
 HEAD EXAMPLE RUN
&
& PRINTING PRIORITY:
 PRINT 0
```

A C K N O W L E D G E M E N T

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This is a User's Manual for the computer program UCIN-EULER. The program is designed and developed to study the dynamics of multibody systems. The multibody systems encompassed by EULER are systems of linked rigid bodies with no closed loops, such as robot arms, chains, antennas, manipulators, and human body models. The manual provides instruction for using EULER to study multibody system dynamics. It also provides sample input and output data. Input procedures and commands are expressed in terms of keywords in order to make the program useful and readily accessible to even the casual user.

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