16 Apr 1992

# Head-Spine Finite Element Computer Model on a Work-Station

Kay F. Schilli

# HEAD-SPINE FINITE ELEMENT COMPUTER MODEL ON A WORK-STATION

Kay F. Schilli
Department of Mechanical and Aerospace Engineering
and Engineering Mechanics
University of Missouri - Rolla
Rolla, MO 65401

## ABSTRACT

In this project, the head-cervical spine finite element computer model has been modified and made portable on the Apollo work-station. The program was developed to aid the researcher in analyzing the simulated behavior of the human spine. The modifications in the computer program have been made in order to utilize the finite element code for continuation of further research.

## INTRODUCTION

The spine is the basic structural element that transmits the forces experienced by the upper body and head in daily living. The interaction of the spine with the upper body involves substantial flexure, which in some situations, may lead to injury. This investigation of the spine has attracted much attention.

In recent years, mathematical modelling has been widely used where biological structures had to be investigated to avoid violation of bioethical codes and practice humane treatment of animal and human subjects. The investigation of the human head-spine complex has evolved in stages which are customarily classified into continuous and discrete models. Toth [1] developed an eight degree of freedom model consisting of rigid masses representing vertebrae and springs and dampers representing inter-vertebral discs. Orne and Liu [2] proposed the first model that included the shear and bending resistance of the intervertebral disc. The first continuum model was proposed by Hess [3], who included only axial response. Subsequently, Moffatt, et al. [4] included both axial and bending response by using a beam type model. However, the analysis was restricted to small displacements. Recently, Liu and Ray [5] developed bar-beam models, including large displacements in the analyses. The stiffness properties of this model were based on that of the isolated, ligamentous spine and the responses they exhibited demonstrated very large deflections.

The model studied and reported here represents the human body by a collection of rigid bodies interconnected by deformable elements. The rigid bodies are used for the modelling of bones, while the deformable elements are used to model ligaments, muscles, and connective tissues. The treatment of bones as rigid bodies is preferable since the stiffness of bones is usually orders of magnitudes greater that of connective tissue.

## MATHEMATICAL MODEL

The computer procedure is basically a matrix structural analysis technique, which serves as a framework for constructing the equations of motion. The program enables these equations of motion to be integrated in time by either explicit or implicit techniques, or analyzed by modal procedures, which give the natural frequencies and modes of the model. The formulation is completely three dimensional and treats arbitrarily large rotations and displacements of the rigid bodies. However, the deformation of some of the elements is restricted to be moderately small. Material properties may be linear or nonlinear and linear viscous forces can be included.

Two types of nodes are used:

a) primary nodes, each of which has six degrees of freedom consisting of three translations and three rotations; the centroid of a rigid body must be a primary node;

b) secondary nodes, each of which is connected through a rigid body to a primary node and which thus has no independent degrees of freedom.

The model consists of the following elements:

1. rigid bodies
2. spring elements
3. beam elements
4. hydrodynamic elements
5. elastic surfaces.

The coordinate system and the element nodes are shown in Figure 1.

The equations are obtained from the principle of virtual work with the inertial forces included in the d'Alembert sense. The principle of virtual work, when applied to the system treated here, states that

$$\dot{\hat{u}}_{iA}{}^{(e)*}\,\hat{f}_{iA}{}^{(e)} + \hat{w}_{iA}{}^{(e)*}\,\hat{m}_{iA}{}^{(e)}$$

$$= \dot{u}_{iI}{}^{*}\,F_{iI}{}^{ext} + \bar{w}_{iI}{}^{*}\,\bar{M}_{iI}{}^{ext}$$

$$- \mu_I\,\dot{u}_{iI}{}^{*}\,\ddot{u}_{iI} - \bar{w}_{iI}{}^{*}\,\dot{\bar{L}}_{iI} \qquad (1)$$

where:

$f$ = element nodal force
$m$ = moment applied to the element
$u$ = displacement of the node
$w$ = angular velocity
$F^{ext}$ = externally applied force
$M^{ext}$ = externally applied moment
$L$ = angular momentum
$\mu$ = density of element material.

The superscript e is summed over all elements, subscript A over all nodes of each element, and I over all primary nodes. Superscript dots denote time derivatives, while asterisks denote virtual quantities.

The left hand side of Eqn. (1) represents the rate of work expended on the deformable elements, that is, the internal rate of work, while the first two terms of the right hand side represent the rate of external work. The rate of work of the inertial forces is represented by the last two terms of the right hand side.

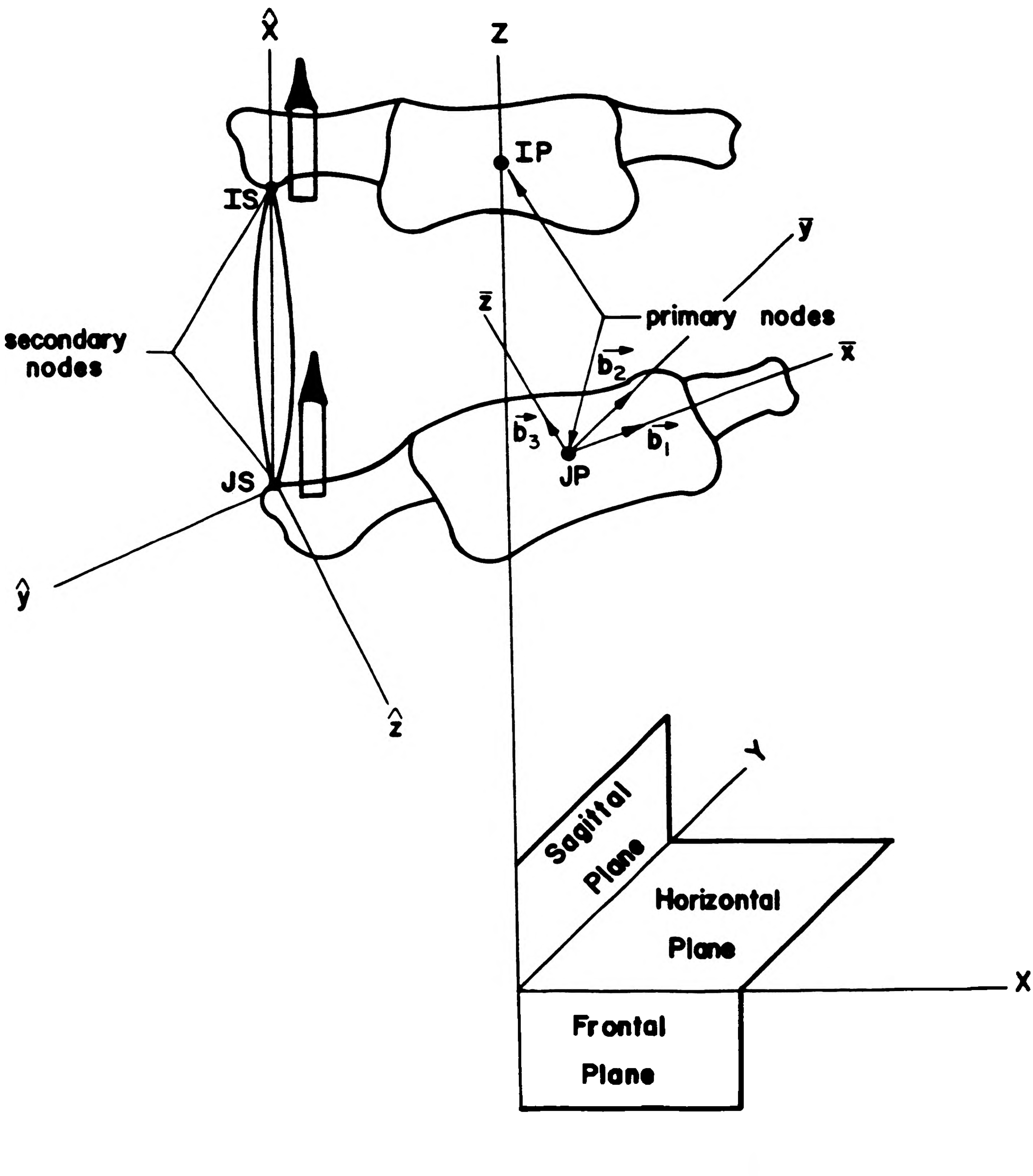


Figure 1 : Rigid body representation and coordinate systems: global coordinates (x, y, z); body coordinates ($\bar{x}$, $\bar{y}$, $\bar{z}$) and element coordinates ($\hat{x}$, $\hat{y}$, $\hat{z}$).

## SOLUTION PROCEDURE

One of the methods for solving the equations of motion of this model is the explicit method. This method is by far the most efficient per time step, but the time step must be quite small if the model has a high frequency content, that is, low masses connected by stiff springs.

The explicit integration employs the Newmark-Beta formulas (Newmark [6]) with $\beta=0$, which are almost identical to the central difference formulas (see Belytschko [7]). These formulas predict the velocities and displacements at a time step in terms of the accelerations at the previous step. For the translational components, these formulas may be used directly, so

$$\dot{u}_{i|}{}^{j+1} = \dot{u}_{i|}{}^{j} + 1/2\ \Delta t(\ddot{u}_{i|}{}^{j} + \ddot{u}_{i|}{}^{j+1}) \quad (2)$$

$$u_{i|}{}^{j+1} = u_{i|}{}^{j} + \Delta t\ \dot{u}_{i|}{}^{j} + 1/2\ \Delta t^2\ \ddot{u}_{i|}{}^{j} \quad (3)$$

where the superscripts denote the time step and $\Delta t$ the time increment during the step. The flow chart for this procedure follows:

1. Set initial conditions, $t=0$.
2. Compute $\{u(t+\Delta t)\}$.
3. Update unit vectors and transform to global components.
4. Find deformation displacements.
5. Find the strain in the convected coordinates.
6. Use the stress-strain law.
7. Find local nodal forces $\{f^d\}$.
8. Add $\{f^d\}$ into $\{f^{int}\}$.
9. Compute $\{\ddot{u}(t+\Delta t)\}$.
10. Compute $\{\dot{u}(t+\Delta t)\}$.
11. $t = t + \Delta t$; go to 2.

## COMPUTER PROGRAM AND MODIFICATIONS

The original program package developed consists of two distinct programs: an analysis program for predicting the dynamic response of the human body under prescribed loads or accelerations and a graphics package for depicting deformed and undeformed anatomical configurations. The programs were developed as a research tool.

The data for the program is input by a separate input file. The file consists of fifteen different lines, including nodal parameters, element properties, and plotting data. The data is read into the program through a series of subroutines.

The program provides the capability of modelling various crash environments. An acceleration time history is given by modifying the equations of motion for those primary nodes of the model that are in contact with the surrounding bodies; primary nodes not in contact are not affected.

In addition to standard printer output, the program has provisions for Calcomp and printer plot graphical output of time histories of responses such as displacements, velocities, accelerations, forces, stresses, and strains.

The input for the graphics package can be automatically generated by the analysis program. In addition, the graphics program can be used independently for other studies.

Both programs were developed on an IBM 370/158 computer system. They are completely written in FORTRAN IV. The program originally written for the IBM 370/158 computer, has been adapted to be run on the Apollo 3000 series computer. By this adaptation, the program becomes more versatile and portable. An effort has been made to maintain the modularity of subroutine functions so that additional features may be added.

## ACKNOWLEDGEMENTS

The author wishes to acknowledge, with thanks, the immense help and guidance of Professor Xavier J.R. Avula, Department of Mechanical and Aerospace Engineering and Engineering Mechanics, without whom this project would have never come about. Thanks are also due to Gerald K. O'Brennan and Chris Townsend of the UMR Computer Center who tolerated the many questions and problems that arose throughout this study.

## REFERENCES


[1] Toth, R., "Multiplying Degree of Freedom, Nonlinear Spinal Model," Proc. of 19th Annual Conference on Engineering in Medicine and Biology 8, 1966.

[2] Orne, D. and Liu, Y., "A Mathematical Model of Spinal Response to Impact," J. of Biomechanics 4, 49-71, 1970.

[3] Hess, J.L. and Lombard, C.F., "Theoretical Investigations of Dynamic Response of Man to High Vertical Accelerations," Aviation Medicine, 66-75, 1958.

[4] Moffatt, C.A., Advani, S.H. and Lin, C., "Analytical and Experimental Investigations of Human Spine Flexure," American Society of Mechanical Engineers, Division of Biomechanical and Human Factors, 71-WA/BHF-7, November 1971.

[5] Liu, Y.K. and Ray, G., "A Finite Element Analysis of Wave Propagation in the Human Spine," Final Report for Contract F33615-72-C-1212, Aerospace Medical Research Laboratory, Wright-Patterson A.F.B., Ohio, 1973.

[6] Newmark, N., "A Method of Computation for Structural Dynamics," J. Eng. Mech. Div., Proc. of ASCE, 67-94, 1959.

[7] Belytschko, T., "Transient Analysis," Structural Mechanics Computer Programs, ed. W. Pilkey, et al., University Press of Virginia, 255-276, 1974.