

FEMvis: An interactive visualization tool for mechanical analysis

by G. P. Bala

Increasing competitiveness in the development and manufacturing of mechanically based products requires ever-increasing design and development cycles, and has stimulated the introduction of many computer-based tools to assist with mechanical design and analysis. Currently, strong emphasis is placed upon the effectiveness of such tools, and on their enhancement through improved usability. A major contribution to improved usability is the level of interactivity of a tool. FEMvis is a tool that provides capabilities for interactive visualization of mechanical engineering analysis, including rotation, translation, and magnification of images; views of shape deformations, their time-evolution, and their superposition; visualizations of scalar fields in two and three dimensions using colored isolevels; blending of shape deformation images and isolevel images; visualizations of three-dimensional phenomena by moving a slicing plane through the image, showing cross-sectional deformations and isolevels; and visualizations of multiple shape deformations and multiple scalar fields during a single usage

session. FEMvis has been implemented in a portable language and a portable graphics package, and can run on a spectrum of hardware platforms from workstations to mainframes. It has been applied to the mechanical analysis of direct-access storage devices (DASD), including stress, strain, modal, and deformation analyses. The interactive nature of FEMvis facilitates iterative design refinement and rapid prototyping.

Introduction

Today there are tools available that provide an analysis path for geometric input, preprocessing, mechanical simulation, and output visualization. Many of these focus on the in-depth analysis of *stable* designs, and as a result provide an excess of capabilities not necessary for *iterative* design. The existing packages, therefore, tend to have complex user interfaces and require a significant investment of time per design iteration.

As shown in Figure 1, iterative design is driven by the need to explore a large design space at an early design stage, during which the designer constantly refines the geometry inputs by updating the design parameters, the analytical model, or both. With each refinement, the

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designer repeats the processing, solving, and visualization phases. Clearly, it is desirable to generate and interpret the results of the analyses very rapidly, so that the designer can easily explore the design space and deduce the best design point to visit next.

In efforts to tighten the design/analysis cycle, the steps shown in Figure 1 have become more and more streamlined. The geometry is typically produced interactively, using a solid modeling tool [1]. At the meshing step, the geometry is discretized to a resolution necessary for subsequent analysis. Modern meshing tools are fully automatic [2] and produce discretized geometries tailored to accommodate the properties of the initial solid geometry. The analysis results, produced by a mechanical simulation or *solving* tool [3], include modal and forced deformations (*shape deformations* in general), in addition to *scalar fields* such as stress or temperature. As shown also in Figure 1, visualization of such results with high interactivity plays a very important role in increasing engineering productivity.

FEMvis is a visualization tool that provides the capability to rapidly and interactively browse mechanical analysis results over the mesh of a geometry being analyzed. The name FEMvis was chosen because of its close relationship with the finite-element method [4] of mechanical analysis.

The preprocessing of the inputs accepted by FEMvis is described first, followed by a discussion of its capabilities, with highlights of the algorithms that facilitate the interactive characteristics. The video supplement gives an illustration of these interactive features.

Preprocessing

• Description of inputs

FEMvis accepts the discretized geometry and the analysis results, as shown in Figure 1. Both two- and three-dimensional discretized geometries and multiple sets of shape deformations and scalar fields can be accepted by FEMvis.

Two-dimensional geometries are defined as regions that can be conformally mapped into a plane. Therefore, such geometries need not be planar themselves, but can be assembled from connected planar facets, or *elements*. Such geometries are therefore entered as a set of plate elements built from nodes. A *node* is a point in three-dimensional space, and a *plate element* is a single planar region bounded by edges formed when connecting a subset of the available nodes, acting as *vertices*,

$$\begin{bmatrix} (N_{x1}, N_{y1}, N_{z1}) \\ \vdots \\ (N_{xn}, N_{yn}, N_{zn}) \end{bmatrix}, \quad \begin{bmatrix} (P_{11}, \dots, P_{h_1}) \\ \vdots \\ (P_{1p}, \dots, P_{h_p}) \end{bmatrix},$$

where (N_{xi}, N_{yi}, N_{zi}) represents the coordinates of the i th

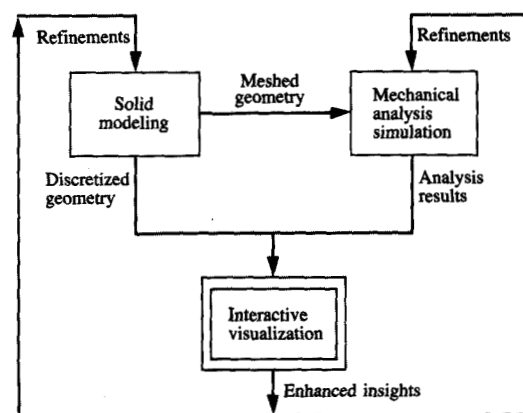


Figure 1

Mechanical design/analysis cycle.

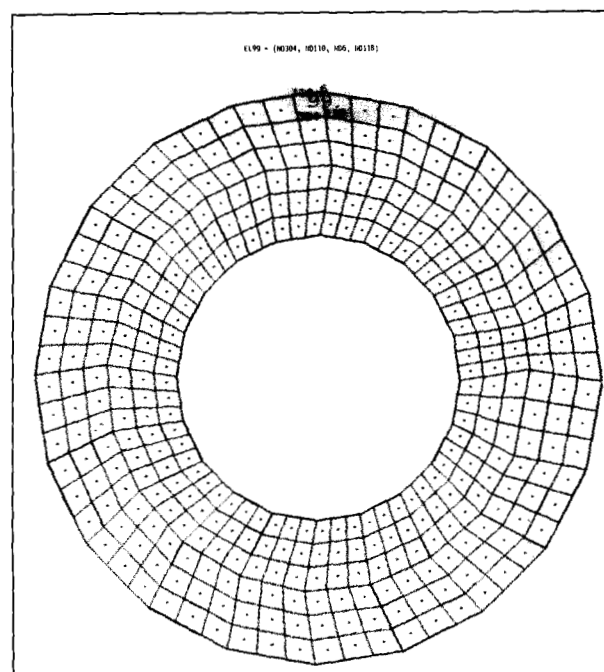


Figure 2

A two-dimensional geometry discretized into quadrilateral elements.

node $(1 \leq i \leq n)$ and P_{jk} represents the node identifier $(1 \leq P_{jk} \leq n)$ of the j th vertex $(1 \leq j \leq h_k)$ on the k th plate $(1 \leq k \leq p)$, given n nodes and p plate elements.

relating an edge to the plate being examined. After examining all plate elements, each edge will reference its adjacent plate elements. The edge-reference mapping is computed for both two- and three-dimensional models.

For two-dimensional models, edge-references are used to expedite computation of the connectivity of a scalar field between adjacent plate elements. The edge-references are also used to detect the object boundary edges, so that the associated graphics data structure can be generated for visualization of the boundary shape deformation.

The three-dimensional analog to edge-references is a plate-reference mapping. For each plate in the discretized geometry, the plate-reference contains the identifier u ($1 \leq u \leq v$) of each volume element on both sides of the plate, and establishes a cross-reference to the sequence number g ($1 \leq g \leq q_u$) of the plate as it appears in the geometric definition of the volume element. Plate-references are established in a manner analogous to the creation of the edge-references, by stepping through the plates around each volume element and recording the above relationships.

For three-dimensional models, plate-references are used to efficiently compute the connectivity of a scalar field between adjacent volume elements. Combined with the edge-references, they are also used to detect the object boundary plates.

Interactive capabilities

FEMvis provides the capability to interactively view, from selectable vantage-points, graphical presentations of multiple shape deformations and scalar fields.

• Changing the point of view

As do the postprocessing modules in several other mechanical analysis tools [5], FEMvis can interactively pan left, right, up, or down; it can also magnify, and rotate about all three coordinate axes. These capabilities allow the user to move around the object to view, in three dimensions, different facets of shape deformations or to focus on an area of rapid scalar change (a corner of a stressed object, for example).

To pan an object, an interactive input device is used to trigger standard translation operations. Similar techniques are employed for magnification and rotation, triggering image-scaling and rotation-matrix operations, respectively.

For panning, the input device sensitivities are context-scaled. That is, for each coordinate direction, the sensitivity is adjusted to just cover the maximum expanse of the object in the given direction (x and y). This eases the burden normally placed upon the user to manually scale the viewing window.

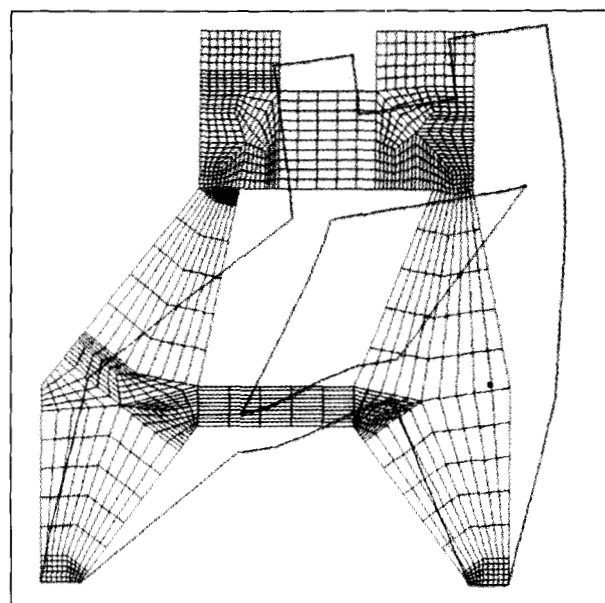


Figure 4

Exaggerated and time-evolved mode shape.

• Viewing shape deformations

Shape deformations can be viewed as separate images and as an image of their superposition.

The separate shape deformations and their superposition,¹

$$(M_{xi\Sigma}, M_{yi\Sigma}, M_{zi\Sigma}) = \sum_{i=1}^m (M_{xil}, M_{yil}, M_{zil}),$$

can be exaggerated interactively using FEMvis. This capability gives the user interactive control of $\alpha_1, \dots, \alpha_l, \alpha_\Sigma$ in the expressions

$$\begin{aligned} &N + \alpha_1 M_1, \\ &\vdots \\ &N + \alpha_m M_m, \\ &N + \alpha_\Sigma M_\Sigma, \end{aligned}$$

representing the exaggerated shape deformations [N is shorthand for all the (N_{xi}, N_{yi}, N_{zi}) and M_i is short for all the $(M_{xil}, M_{yil}, M_{zil})$ over $1 \leq i \leq n$]. The exaggeration factor is displayed on the screen for each coordinate direction (x , y , and z).

In dynamic analysis, the shape deformations are functions of time. In this vibrational-mode analysis, the user also has interactive viewing control of the time

¹ The formula shown computes the superposition based on the assumption that the relative amplitudes are implicit in the individual shape deformations. A later FEMvis implementation will allow the user to interactively produce the weighting factors based upon a forced-response computation.

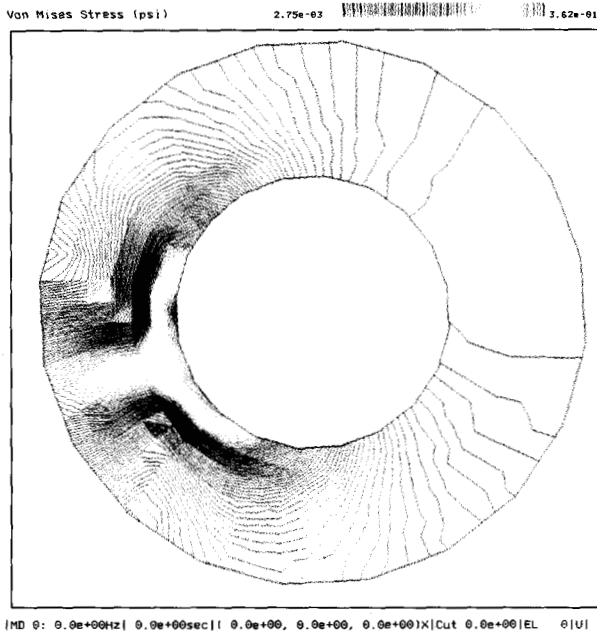


Figure 5

Scalar contours.

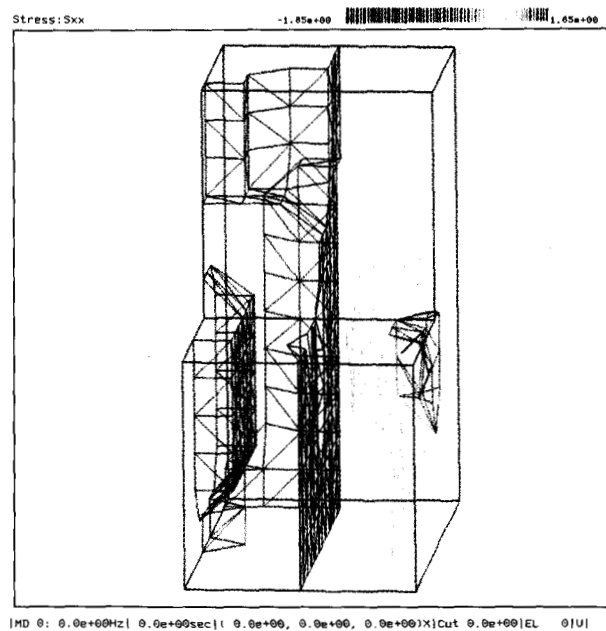


Figure 6

Scalar isosurfaces.

evolution of the modes. For different mode shapes, this means that the user has further control of the time parameter t in

$$\begin{aligned} &N + \alpha_1 \cos(2\pi f_1 t) M_1, \\ &\vdots \\ &N + \alpha_m \cos(2\pi f_m t) M_m, \\ &\vdots \\ &N + \alpha_\Sigma \sum_{l=1}^m \cos(2\pi f_l t) M_l, \end{aligned}$$

which represent the time-evolved modes with exaggerated shape deformations. The time value t is displayed on the screen. Figure 4 shows a time-evolved mode shape.

Again, to ease user setup tasks, the input-device sensitivities are context-scaled. For each shape deformation (and the superposition), the sensitivity is readjusted depending upon the maximum displacement magnitude. These adjustments are done for each coordinate direction (x , y , and z). The time sensitivity is set to span the period of the lowest modal frequency. Further, as the user steps through the shape deformations, FEMvis automatically alters the exaggeration to preserve the size of the maximum image displacement viewed. This feature gives visual continuity in switching from one shape deformation to another.

• Viewing scalar fields

Scalar fields are presented as discrete levels of equal scalar value, or *isolevels*. In two dimensions, isolevels manifest

themselves as contour lines, and in three dimensions, isolevels are represented by isosurfaces.

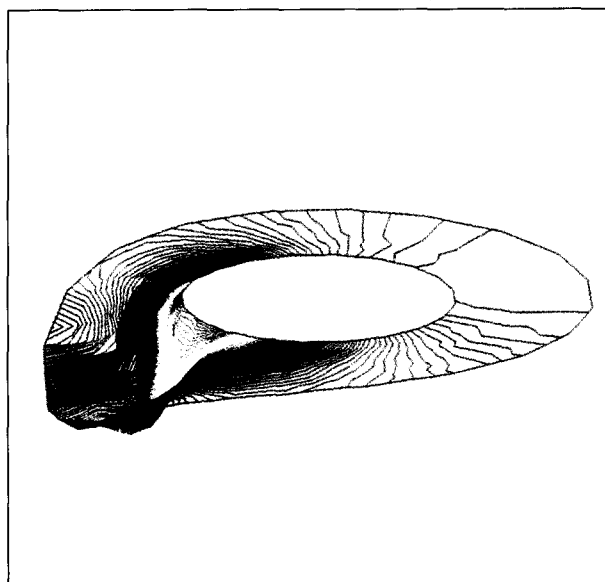
Linear interpolation is applied to determine the *turnpoints* along the plate edges, where isolevels bend. In two dimensions, contours are produced using established heuristics [6]. By using the edge-references to navigate the geometry, all equally valued contour turnpoints are connected by a sequence of line segments. These connections are made only within the confines of the boundary edges, and no connection is made between two turnpoints if the resulting segment would cross a segment of unequal value. Figure 5 illustrates scalar contour lines on the disk geometry.

Here, the necessity for the edge-references is evident. Without such a data structure, a costly search of the geometry for the nearby turnpoints on adjacent plate edges would be required.

In three dimensions, analogous rules [7], combined with the plate-references, are applied to produce isosurfaces built of triangular facets [8], as shown for the L-bracket in Figure 6.

As with the edge-references, the use of plate-references eliminates extensive geometric searches for nearby turnpoints on adjacent volume face edges.

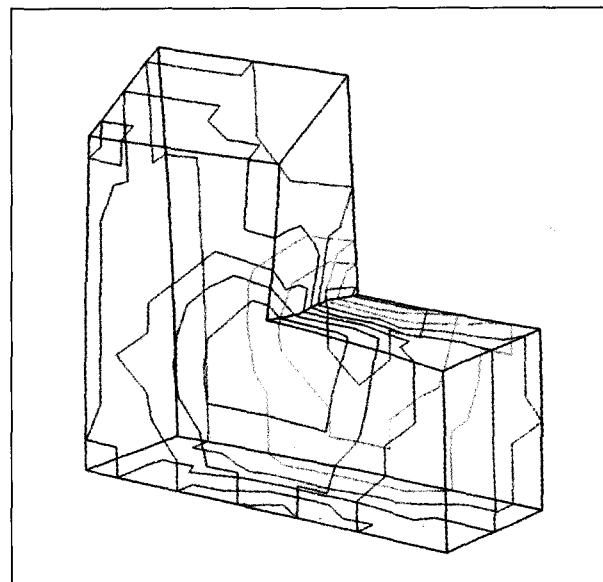
Multiple scalar fields can be viewed, and as the user pages through the corresponding images, a legend is displayed with a band of colors mapped into the dynamic range of the scalar values being graphically presented.



MD 0: 0.0e+00Hz| 0.0e+00sec| 7.8e-01, 7.8e-01, 7.8e+07|X|Cut 0.0e+00|EL 0|U|

Figure 7

Stress contours on an exaggerated shape deformation.



MD 0: 0.0e+00Hz| 0.0e+00sec| 6.6e-03, 6.6e-02, 6.6e-03|X|Cut 0.0e+00|EL 0|U|

Figure 8

Deformed stress contours on a solid object.

When an isolevel of a given color appears on the object (to the accuracy of linear interpolation), any point on that isolevel has the scalar value corresponding to that color. The isolevel density can be set by the user (the default is unity).

To help view large changes in value spanning several orders of magnitude, a feature is available that automatically applies the logarithm (base 10) to each scalar field. The logarithm process creates an additional scalar field for each input scalar field.

The isolevel data are also structured to facilitate interactive shape-deformation and cross-sectioning.

Interactive shape-deformation

To allow greater insight into the phenomena being modeled, isolevel images can be superimposed on a shape deformation and interactively exaggerated in concert with it. **Figure 7** shows the results of a two-dimensional engineering analysis in which a disk is held at its inner rim and a force is imparted upon a plate element on the ring. The deformation exaggeration factors for each coordinate direction (x , y , z) are displayed at the bottom of the screen window.

Interactive cross-sectioning

For three-dimensional models, the user can focus interactively on isosurface cross sections. It is also

possible to make the isosurfaces intersect with the skin of the object to produce surface contours. **Figure 8** shows the surface contours of a deformed object. In addition, the isosurfaces within the model can be sliced with a *cutplane*. The cutplane is allowed to move along the z -axis (toward and away from the viewer along the line of sight) and slice an arbitrarily positioned object (**Figure 9**). Multiple slices can be "snapped" into place on the object as it changes position (**Figure 10**).

Implementation and performance

The current FEMvis prototype runs either on an IBM AIX²-based workstation or on a host system driving an IBM 5080 imaging and display system. The interactive dials attached to the IBM 5080 graphics unit are used primarily to view "continuous" phenomena—to maneuver around the image, dynamically exaggerate shape deformations, step through time slices, browse the elements, and move the cutplane. A "pop-up" menu and PF keys are used to perform "discrete" operations—to browse the combinations of various components of the model (such as isolevels and vibrational modes), to enable and freeze cutplane slices, to set the exaggeration scaling, to reassign the dial functions, and to produce grey-scale figures for imbedding into documents.

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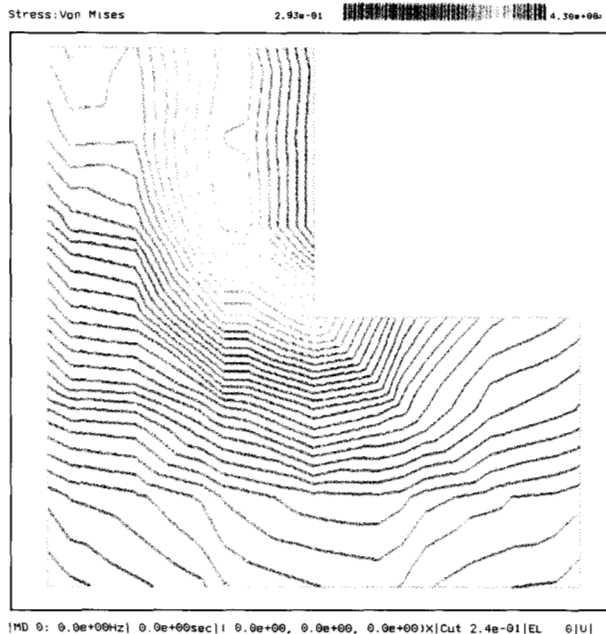


Figure 9

Cutplane slicing scalar isosurfaces.

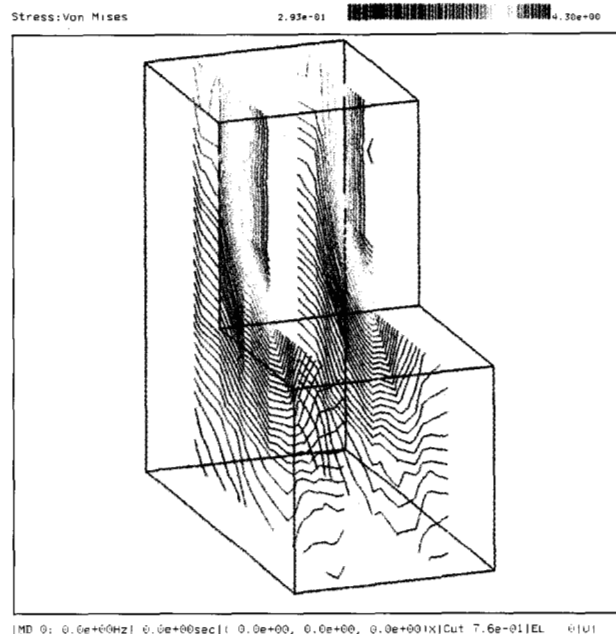


Figure 10

Cross-sectional contours from slicing scalar isosurfaces.

FEMvis is implemented in the C programming language and uses the IBM graPHIGS³ application programming interface. These choices were made to conform to industry standards and allow for portability among systems.

Contributing significantly to the interactiveness of FEMvis, several proprietary algorithms have been employed. These techniques have led to increases in processing speed over conventional methods of approximately an order of magnitude in isosurface generation, deformation, and cutplane slicing. These techniques allow rapid response to the user on specialized graphics hardware, and also preserve interactiveness on simplified hardware platforms.

In the development of FEMvis, linear interpolation methods and linear geometric primitives were chosen to facilitate the speed and flexibility discussed above. Although these choices reduce generality, very little additional insight would be added by using nonlinear interpolation and nonlinear graphics primitives, because the analysis results are known only at discrete locations on a linear geometry.

Conclusions

FEMvis is a tool that facilitates rapid interpretation of mechanical engineering analysis data through the use of

interactive visualization, including viewing the model from different vantage points, examining multiple shape deformations by using interactive exaggeration, and viewing multiple scalar fields that can be superimposed on any exaggerated shape deformation and cross-sectioned arbitrarily.

FEMvis currently addresses results recorded in a discrete manner on linear geometries. Recent developments in engineering analysis would allow the generation of shape deformations and scalar fields in the form of *continuous* functions on a *curvilinear* geometry. Such analyses would include the representation of such functions by polynomial coefficients, as in *p-type* [9] analyses. Efforts are under way to upgrade FEMvis to support that approach.

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³ graPHIGS is a trademark of International Business Machines Corporation.

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Gregory P. Bala *IBM Research Division, Almaden Research Center, 650 Harry Road, San Jose, California 95120.* Mr. Bala received his B.S. degree in applied mathematics from the California Institute of Technology in 1984. He joined IBM that year at the Westlake Village, California, facility of the Federal Systems Division, where he worked as a software engineer in areas of specialized spacecraft applications. He developed algorithms used by ground station computers to track spacecraft orbital parameters for use in communications and telemetry. In 1987 he transferred to the IBM laboratory in San Jose, California, where he joined the Computer Design for Storage (CDS) group and has worked on visualization software as part of an overall effort to accelerate the mechanical design cycle for storage products. Mr. Bala is currently a staff engineer working in areas of graphics, geometric modeling, and visualization.