NEIL S. ROTHMAN and JOHN A. ECKER

COMPUTER-AIDED ENGINEERING FOR STRUCTURAL ANALYSIS

Computer-aided engineering is the application of computers to the solution of engineering problems. Personal computers and engineering workstations are bringing computer-based tools to the engineer's desk. This article describes the use of computers for mechanical analysis by means of the finite-element method. Graphical preprocessing and postprocessing will be discussed.

INTRODUCTION

The analysis of complex mechanical systems has exceeded the capabilities of traditional strength-of-materials methods. Cost and scheduling limitations often prevent the use of prototypes for testing and design validation, while the risks associated with testing flight hardware often outweigh the benefits. These problems of today's engineering world have led to extensive use of digital computers and sophisticated analysis software to predict mechanical systems behavior, compress design schedules, and improve analysis efficiency. The use of the finite-element method (FEM) for structural analysis is fundamental to this improved capability.

"The finite element method is a numerical procedure for solving continuum mechanics problems with an accuracy acceptable to engineers."[1] The method is based on modeling the component or structure under analysis by dividing it into a finite number of elements, which are analyzed by continuum mechanics methods. The overall structure is thereby characterized if the model is valid.

The greatest difficulty in using FEM, however, has been generation of the model. The introduction of graphical preprocessors and postprocessors for finite-element analysis has not only improved and enhanced the generation process but has also provided significant advances in visualizing the model and the results of the analysis. A preliminary version of the housing for the Cosmic Background Explorer Satellite-Momentum Management Assembly (COBE-MMA) will be used to illustrate finite-element analysis procedures and the preprocessing and postprocessing capabilities now available at APL.

MODEL GENERATION

Generation of the model for finite-element analysis is critical because all results depend on its accuracy and validity. The first step in the generation process is to examine the overall structure to be analyzed and the desired analytical results in order to formulate a modeling strategy. For dynamic problems, modeling of mass and stiffness alone may be sufficient, while stress analyses may require significant geometric detail in critical areas. For the COBE-MMA housing (see Fig. 1a), approximate resonant frequencies and stress and displacement due to loading in three coordinate directions are of interest. We will therefore use a single model incorporating simplified geometry to characterize its dynamics while retaining enough detail to determine regions of maximum stress and displacement.

The modeling strategy provides guidance in dividing the structure into elements. Creation of a model involves

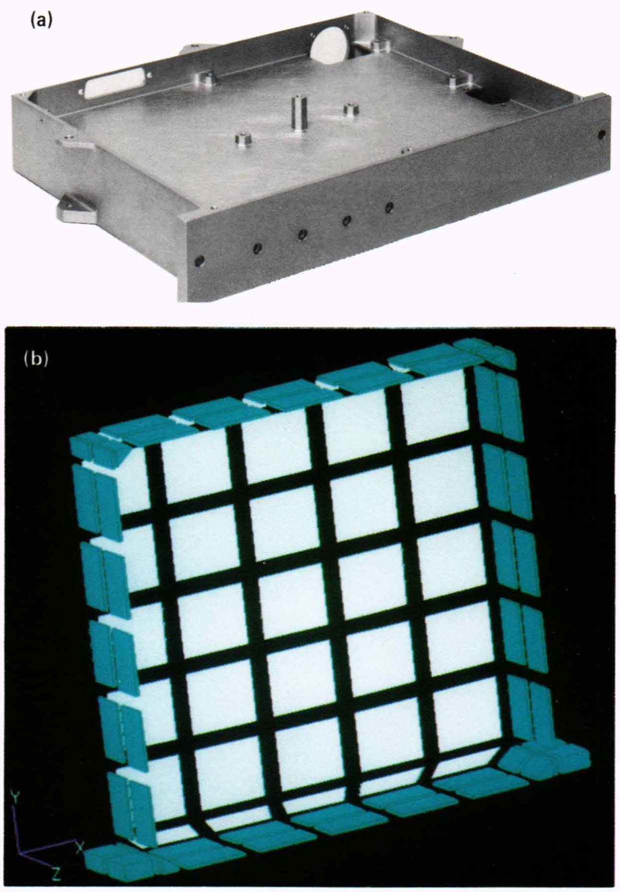


Figure 1—(a) Engineering model housing for COBE-MMA. (b) Finite-element model for preliminary structural analysis of the engineering model housing (elements shrunk 20 percent).

the description of a mesh (the pattern of element interconnection points, or nodes, on the structure) by giving the nodal locations with respect to a coordinate axis reference and the nodal connectivities of each element. Material properties, external loads, and boundary conditions or restraints must also be given. Experience and good engineering sense are required to construct a good mesh. For large complex models, however, the manual determination of nodal coordinates and the tracking of extensive element data are difficult.

A relatively new tool that saves significant time during the modeling stage is the graphical preprocessor. This allows the engineer to create the model geometry and finite-element mesh graphically on a computer terminal through interactive keyboard commands (or menus). Lines, surfaces, and solids are used to define the model geometry; the mesh and element specifications are then added. The model of the COBE-MMA housing (see Fig. 1b) was created in this manner. Comparison of the model with the actual structure illustrates the simplifications used in this preliminary analysis. FEM preprocessors can alternatively obtain the basic model geometry from a computer-aided design database, such as APL's Computervision system, thereby saving an engineer many hours of modeling time when working with complex geometries.

State-of-the-art graphical preprocessing and postprocessing capability is now in use at APL on the Apollo/Mentor network (see the article by West et al. elsewhere in this issue). Some of the available capabilities are solids modeling using primitives and Boolean operations, full three-dimensional representation of geometric models, hidden line plots, light-source shaded color imaging, and section and mass property calculations. Finite-element preprocessing features include automatic grid and element generation with user-definable local mesh refinement, an extensive element library, material property synthesis, geometry-dependent loads, and full model checking and verification. There are also various methods to optimize the model that greatly reduce the time required for solution by an analysis code and, thereby, the cost of the analysis. These powerful preprocessing capabilities simplify a previously laborious and time-consuming process.

The FEM model for preliminary structural analysis of the COBE-MMA housing is relatively straightforward; however, its generation was greatly simplified through the use of a preprocessor. For more sophisticated geometries such as the Advanced Wide Area Missile subsonic combuster shown in Fig. 2, graphical generation and display of the model are necessities. Generating an FEM mesh over such complex surfaces is extremely difficult if attempted manually.

With the introduction of powerful graphical preprocessors, the generation of finite-element models has become deceptively simple. Care must be taken because inexperience with a particular analysis code or with FEM itself may result in reduced accuracy of the analysis. There is also a tendency toward overanalysis when using a powerful preprocessor since it allows a greater amount of geometric detail to be included in a model.

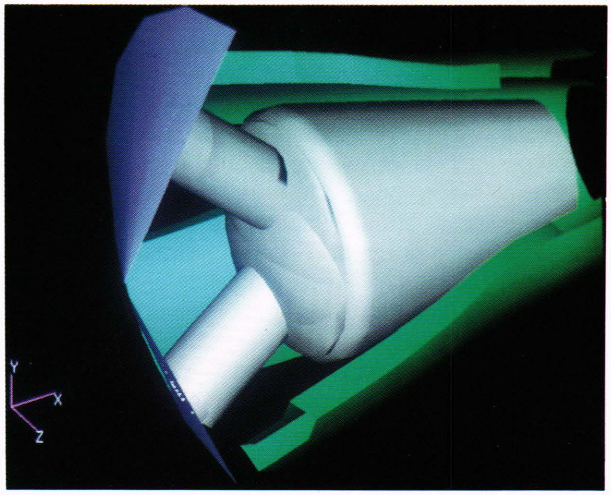


Figure 2—Solid shaded color image of the Advanced Wide Area Missile subsonic combuster model.

Such detail is usually not required for accuracy and serves only to increase the cost of the analysis. In fact, the objective in model creation is to use the simplest model possible while retaining analysis accuracy.

The graphical preprocessor allows us to view three-dimensional geometry and associated data of a FEM model, thereby increasing the accuracy of model building and drastically reducing the time involved and the possibility of errors. The relative ease and speed with which a model can be changed, updated, or tuned to the type of analysis being performed are other advantages of the preprocessor.

ANALYSIS

Traditionally, structural and mechanical analyses have been performed using formulas and methods from engineering textbooks and references. Due to computational limitations, real problems were often idealized, with approximated loadings and conditions. Overly complex systems were simplified, using large safety factors. Generally, worst-case situations were assumed to overcome any deficiencies in the model assumptions. In many cases, results from these applied methods could only be considered reasonable guesses or bounds to the solutions.

Large mainframe computers introduced in the mid-1960s were able to manipulate tremendous amounts of data. Complex real-life problems demanded more detailed analyses and more exact solutions; this was especially true when cost and weight savings were concerns, as with aerospace applications. Sophisticated structural analysis programs were developed to satisfy those demands through the use of growing computing capabilities such as FEM. "In practice, most problems are too complicated for a closed-form mathematical solution. A numerical solution is required, and the most versatile method that provides it is the finite element method."[1] Finite-element analysis programs can solve many types of engineering problems: stress and strain, normal modes, thermal analysis, and fracture analysis. Most can solve linear and nonlinear problems.

Many programs (e.g., satellite programs) have specific requirements for stress, fracture mechanics, and dynamic behavior of the flight hardware. Mechanical testing of flight components or assemblies can be both costly and dangerous because of possible damage, and complete prototypes or engineering models may take too long or be too expensive to build. The use of finite-element analysis to predict structural behavior can be essential to the success of such a program. For the Hopkins Ultraviolet Telescope, preliminary structural sizing and the determination of maximum stresses for fracture mechanics review of the structure were performed using finite-element analysis. Also, a requirement that fundamental vibration modes of the telescope's components be above 35 hertz was verified. The analysis allowed the telescope to be qualified for flight without dynamic testing. Obviously, to be feasible, specific guidelines using adequate safety factors must be followed in this type of analytical approach. Often, a simple prototype is tested to help validate the model and the results of such an analysis.

Following its creation, a model is submitted to an analysis code for solution of a specific type of problem. In the past, model data entry was often done using punched cards; now, interactive computer terminals with full-screen editors are used. If a graphical preprocessor has been used, the transfer of the model data to an analysis code is done electronically through direct file transfer, which eliminates many problems associated with manual data entry. The engineer specifies the solution sequence or method to be used to ensure that he gets the desired analytical results. Common types of analyses, such as static stress or normal modes, are usually contained in a library of solution sequences that is supplied with the analysis code. The user can modify the sequences or run partial solutions to check a model, an extremely important cost-saving measure when working with very large models.

The COBE-MMA housing model described above was analyzed for normal modes of vibration (i.e., resonant frequencies) and stress and displacement due to static loads in each of the three coordinate directions.

RESULTS

The standard output from an analysis code consists of a text printout of various quantities calculated in the problem solution, such as stresses, strains, natural frequencies, or nodal displacements or temperatures. Each solution sequence can provide extensive data in many different output formats. The format variations are useful for specific applications and are important to the engineer for correct interpretation of his results. He is required to review the data and judge its validity and accuracy, but, without a graphical representation of the model, areas of high stress, maximum displacement, or mode shapes can be difficult to determine.

Model creation and data transfer to analysis codes were enhanced and simplified with the introduction of graphical preprocessors. Powerful capabilities for postprocessing results were added as these software packages improved. The postprocessor receives output data from the analysis code for graphical display and inspection. Stress line contour and deformed shape plots were typical of early capabilities. Color was added for improved clarity in examining results. State-of-the-art postprocessors provide a wide range of options to display their data and are currently being used in APL's Engineering and Fabrication Branch.

Powerful postprocessing features, such as animation of mode shapes or color-contour and fringe plots of stresses and displacements superimposed on a model, allow the engineer to interpret results more rapidly and with greater confidence. The display of data from the results can also be manipulated for a complete, detailed inspection of the entire model and analysis solution. Critical areas can be easily determined and examined more closely, and deformed and undeformed geometry may be displayed. If an analysis has been inconclusive or has produced unsatisfactory results, the mesh can be refined for greater geometric detail or improved accuracy and transferred back to the analysis code.

Selected results of the preliminary analysis of the COBE-MMA housing are shown in Fig. 3. The resonant mode shape (Fig. 3a) shows an exaggerated torsional distortion of the housing. The static displacement contours (Fig. 3b) show flexibility of the housing's center web. The stress fringe plot (Fig. 3c) clearly shows a region of maximum stress in the lower corner of the housing. The plots provide important information about the structure under various conditions.

The accuracy of the results is only as good as the initial modeling strategy. The data shown in Fig. 3 summarize this preliminary analysis to provide guidance for design of the housing. Specifics of the flight configuration, such as actual mounting details, support of printed circuit boards by the center web, or geometric modifications for connectors and assembly components, will alter the initial modeling strategy; hence, the model itself and the results of the analysis will change. For the preliminary analysis, however, the results obtained are sufficient and will be particularly useful in formulating a modeling strategy for detailed, quantitative analysis of the flight housing.

The postprocessor provides graphic visualization of the results of finite-element analysis. The output data may reveal deficiencies in the structure and may serve as a guide for design and future analysis. For complex structures, such data clearly identify critical areas and, through integral preprocessing capabilities, provide for model modification and subsequent analysis.

CONCLUSIONS

The use of computers to solve mechanical engineering problems has been a major advance for the engineering world. These tools, together with trained personnel, are available in the Engineering and Fabrication Branch to support APL hardware programs. Quicker, more detailed and complete analyses and more accurate results are direct benefits of today's more powerful computers and software. Graphical preprocessors and postprocessors provide the capabilities for rapid creation and modification of models for finite-element analysis and clearer visualization of analysis results. Prediction of dy-

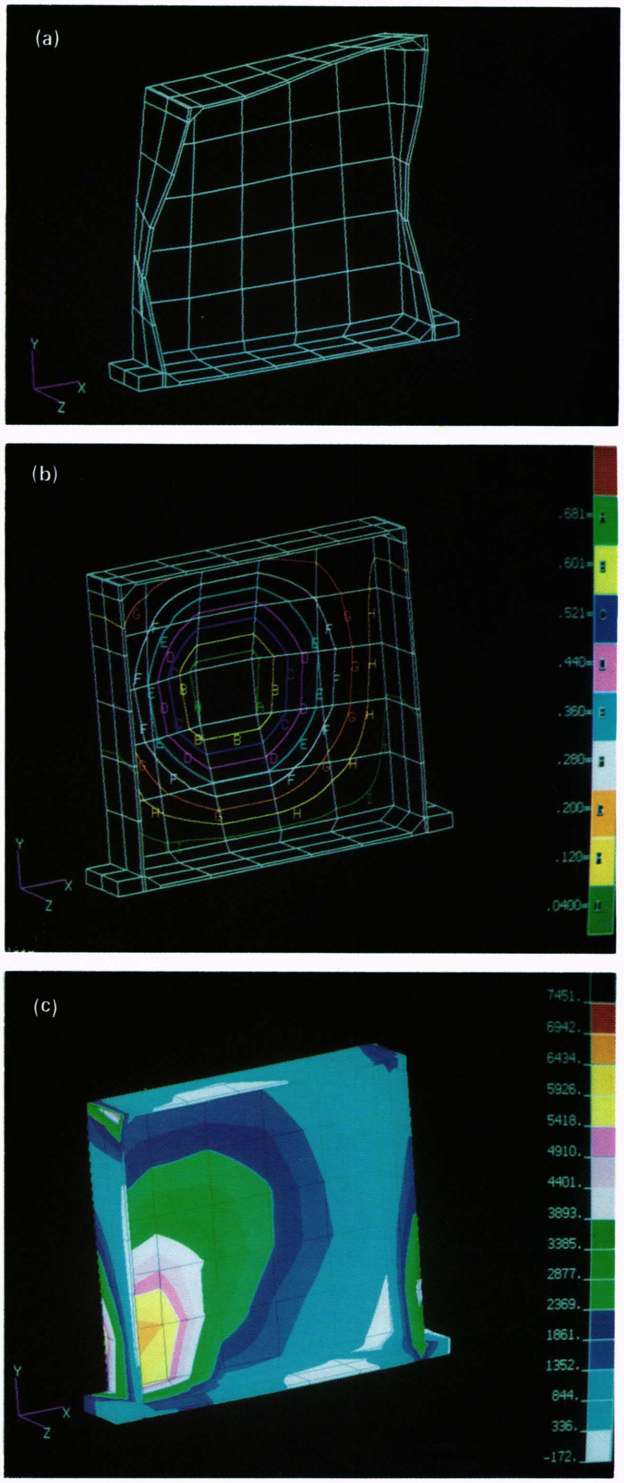


Figure 3—Preliminary analysis results for COBE-MMA housing model: (a) resonant mode shape; (b) displacement contours on the deformed structure from static analysis, z-direction load; and (c) stress fringes from static analysis, x-direction load.

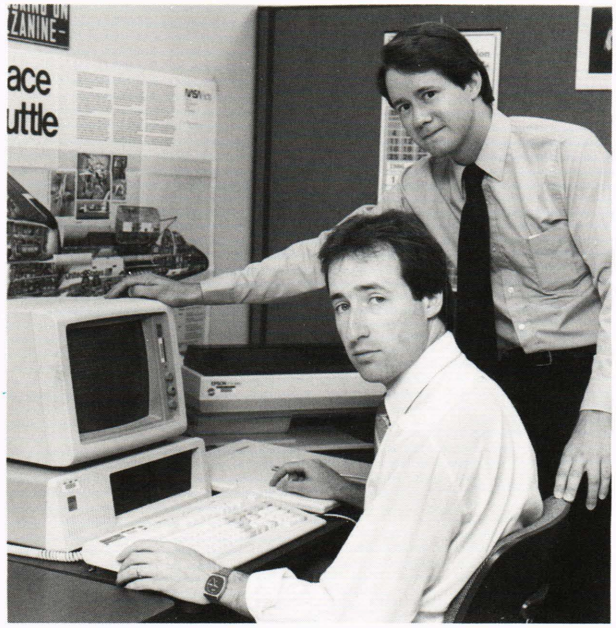
namic behavior or elimination of potential damage to flight hardware from physical testing through computer-aided analysis is also beneficial. Whether used to support design changes, to examine various aspects of a model, or simply to refine a structure for increased strength or weight savings, these computer-aided engineering tools are extremely valuable.

REFERENCE

[1] R. D. Cook, *Concepts and Applications of Finite Element Analysis,* 2nd ed., John Wiley and Sons, New York, p. 1 (1981).

ACKNOWLEDGMENTS—We thank Brian Kemp for the photograph of his model of the Advanced Wide Area Missile subsonic combuster and John Burke for the COBE-MMA housing photograph.

THE AUTHORS



NEIL S. ROTHMAN (right) is an associate engineer in the Design and Engineering Group of the Technical Services Department. Born in New York in 1956, he received a B.S. in biomedical engineering in 1978 and an M.S. in mechanical engineering in 1979, both from Rensselaer Polytechnic Institute. He is pursuing a Ph.D. in materials science at The Johns Hopkins University. Before joining APL, he worked for the Black and Decker Manufacturing Co., where he designed powered instruments for orthopedic surgery. He also received a patent for his design of a cast-cutter system. Since coming to APL in 1983, Mr. Rothman has been a member of the Engineering Analysis Section of the Design and Engineering Group. He is involved with mechanical design and analysis in numerous programs and in independent biomedical research. He is a member of APL's Biomedical Devices Committee.

JOHN A. ECKER (left) was born in Hagerstown, Md., in 1960. After 1980, he worked in mechanical design and computer-aided design operations at the Danzer Metal Works and the Grove Manufacturing Co. After receiving a B.S. degree in mechanical engineering from The Johns Hopkins University in 1983, he joined APL's Design and Engineering Group, where he worked in the areas of structural design and analysis and finite-element analysis in support of various Laboratory programs. In 1986, he joined the Computer-Aided Design Group as coordinator of the PATRAN mechanical computer-aided engineering software and as a mechanical computer-aided design applications engineer. Mr. Ecker is a member of ANSI's Subcommittee on Computer-Aided Preparation of Product Definition Data.