Cover Illustration

Experimental setup for determining how aging affects the material properties of a polymer. The apparatus is used to inflate a polymeric membrane (balloon at the bottom of the setup). We determine material properties by measuring the inflating-pressure history while the membrane's deformation is fixed. The report on p. 31 reviews this research.

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Foreword

Our intent in this progress report is to provide a summary of the activities pursued by members of the Mechanical Engineering (ME) Department's Engineering Research Program. The Program's mission is to do research for specific applications in mechanical-engineering fields that are of immediate or potential interest to the Laboratory.

The FY84 Program comprises nine projects in four thrust areas in the ME Department. The thrust areas are:

- Surface Measurements and Characterization
- Fabrication Technology
- Materials Characterization and Behavior
- Computer-Aided Engineering

In the past, our research was supported almost exclusively by weapons programs; recently, however, we significantly increased our involvement in other Laboratory programs as well. In response to this change, we have established new procedures and guidelines for the submission, review, and selection of research proposals.

We hope that this report will inform personnel in the ME Department of the kinds of activities conducted in engineering research, and that it will also interest Laboratory programs in our capabilities and in the types of research we offer.

We attach great importance to the exchange of information with members of the outside technical community. Readers desiring more information on the activities reported here are encouraged to contact the authors.

Howard H. Woo, Program Manager
Engineering Research Program
ME Department

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Surface Measurements and Characterization

Topometric Interferometry

Topometric Interferometry

J. A. Monjes, C. H. Gillespie, and D. F. Edwards

Fabrication Technology Section
Materials Fabrication Division

The goal of this project is to characterize convex spherical surfaces with great resolution and accuracy. To achieve that goal, we are using the principle of topometric interferometry. Earlier in the project we designed a topometric interferometer; now we report the successful operation of a test model.

The model produced good results even though it lacked environmental controls; therefore proper controls, and a tunable source, should bring greater accuracy. As a result of the model's success, we are building a prototype instrument for inspection and characterization of demonstration parts.

Background

For some time, increased accuracy has been needed to characterize optical components and other parts for nuclear weapons programs, for the Laser Program, and in thin-film measurement. Our project has sought to meet this need through the following:

- First year (1982-1983): research and analytical work to determine the best technique to achieve a resolution of $0.2 \mu\text{m}$ and an accuracy of $0.001 \mu\text{m}$. We considered several techniques. In topometric interferometry, an extended area is plotted simultaneously with successive contour lines of equal level. In contrast, a profilometer plots a single line of varying levels along a pre-established path. We concluded that topometric interferometry offered the best chance of achieving maximum accuracy, resolution, and speed, with simple data interpretation. During this period we completed the layout of a topometric interferometer and purchased the main components.

- Second year (1983-1984): experimental verification of first-year results. We built an experimental setup, for which this report gives the initial results. We also established a development program.

- Third year (1984-1985): production of a reliable design and prototype for direct application.

This project follows the footsteps of many investigators, especially S. Tolansky¹ regarding the characterization of metallic surfaces; Herriott,² Heintze,³ Gates,⁴ and Biddles⁵ regarding the characterization of spherical

surfaces; and Pilston and Steinberg⁶ and others regarding the use of discrete wavelength intervals to reduce fringe spacing. The concept being explored here uses a very narrow bandwidth ($\delta\lambda = 10^{-14} \text{ m}$) for the illuminating light. We measure height differences on the object's surface by determining the differential wavelength at which the interference fringes are produced. Since it is not required to have two or three fringes in the field of view (to gauge fringe distortion), the theoretical fringe spacing can in principle be made arbitrarily large. If there is only one fringe for each wavelength in the field of view, the fringe center can be located with respect to the next fringe boundary with greater accuracy.

The theoretical limit of the method is a function of the $\delta\lambda$ of the source; a practical limit exists which is related to the quality of the surface tested. The higher the object's quality and reflectivity, the sharper the fringe boundaries and the more accurate the measurement.

It is important to notice here that the broadening of a fringe, when related to the $\delta\lambda$ of the source, is a measure of the surface roughness of the object.¹ In such cases, an instrument based on these principles can be adapted to yield information on any of three surface parameters, namely, surface figure, surface roughness, and sphericity or curvature.

Our main objective is to improve the interferometric characterization of spherical surfaces. To this end, our goals are (1) to overcome the method's theoretical and practical limitations by more accurately tuning the source, and (2) to implement a design which is not a research tool but an inspection and characterization instrument suited to regular use.

Methodology

Topometric Approach. Figure 1 is a conceptual design of a topometric interferometer, which is defined as an instrument that by interferometric principles can provide numerical and graphical information on surface height variations over an extended but finite area.

The topometric instrument basically measures surface profile. From the measurements, statistical data over the entire area can be calculated. The instrument also provides automatic statistical information by direct measurement, and it can be adapted to measure surface curvature and surface roughness. The accuracy of such an instrument has been calculated to be 10^{-10} m. The following are the instrument's operational principles.

1. The test object is illuminated with light of a narrow-frequency line.
2. The illuminating-light frequency is scanned over a given bandwidth.
3. The narrow line is made to resonate in the reflecting cavity formed by the surfaces of the test object and illumination lens (concentric Fabry Perot interferometer).
4. The multiple interference fringes produced by the resonant cavity are detected by an array detector for digital display or by a

monolithic detector for analog display or statistical interpretation.

5. The display is a magnified representation of lines of constant phase or constant spacing d between the reference and test surfaces (Fig. 1).

6. An entire sphere with a diameter in the range of about 1 cm to less than 1 mm can be explored in less than 20 min by rotating it to a maximum of 6 to 8 concentric angular positions.

7. The maximum diameter of the test object is limited by the curvature of the reference aplanat (illumination lens).

8. The minimum diameter of the test object for a given aplanat is limited by the desired accuracy and resolution.

Theoretical Considerations

Accuracy of Measurement. If the source Fabry Perot interferometer is tuned to a wavelength λ_1 , the constructive interference in the resonant cavity between surfaces 1 and 2 (Fig. 1) will take place at a set of elevations which fulfills the condition

$$d_1 = (M/2)\lambda_1 \quad (1)$$

where

d is the spacing between mirrors.

M is the number of half-waves in the distance d .

Figure 1. Conceptual design of a topometric interferometer, used for the setup shown in Fig. 2.

If next the source is tuned to a different value λ_2 , we will have a new fringe. The result is that the elevation differential $\delta\lambda$ between the two interference fringes is given by:

$$\delta\lambda = d_1 - d_2 = (M/2)(\lambda_1 - \lambda_2) \quad (2)$$

$$= (M/2)\delta\lambda \quad (3)$$

So the accuracy limit is proportional to the $\delta\lambda$ at which the source can be tuned. Such $\delta\lambda$ is the line width or bandpass of the Fabry Perot interferometers. There are on the market standard Fabry Perots of $\delta\lambda$ better than 10^{-14} m.

For each revolution of the scanning detector array, the bandpass is stepped by $\delta\lambda = 10^{-14}$ m. Therefore the detected δh will be

$$\delta h = (M/2) \times 10^{-14} \text{ m},$$

where $M = 2d_1/\lambda_1$. If the distance between surfaces 1 and 2 is 5×10^{-3} m and the wavelength of the light is 500×10^{-9} m, we have:

$$M = (10 \times 10^{-3})/(500 \times 10^{-9}) = 2 \times 10^4$$

Therefore

$$\delta h = 10^4 \times 10^{-14} = 10^{-10} \text{ m} \\ = 1 \text{ \AA}$$

Hence the display of the instrument will represent level lines at a 1-Å-high differential over the entire illuminated area, without the test object being moved. This result must be qualified as follows:

- It is representative only of the tunability of the Fabry Perot interferometer and represents the upper limit of accuracy that can be achieved for a given $\delta\lambda$. It does not guarantee that such a limit can be reached, but only indicates that such a limit exists.

- Whether or not a δh of 1 Å can be measured depends on the lateral resolution of the recorded interferogram, which is a function of the sharpness of the line.

To properly evaluate the significance of this result, we have to consider two resolving characteristics of the instrument:

- Lateral resolution of the recorded interferogram.

- Lateral resolution on the surface of the test object.

The lateral resolution δs of the interferogram was initially estimated to be 5 Å.⁷ The

maximum advantage of having the capability of measuring $\delta h = \pm 1 \text{ \AA}$ is fully realized only if the lateral resolution of the fringe can be improved to a value equal to or better than 1 Å.

The achievement of such an improved value is the goal of the tests under way. The rationale supporting such a possibility is that the fringe spacing can be made very much larger than the one normally used. Therefore, for good-quality surfaces and small spacing, with a small angle between the test and reference surfaces, a single wide (but sharp) fringe will represent a very narrow $\delta\lambda$, thereby allowing a more accurate location of the fringe center for each value λ_1 and λ_2 with $\delta\lambda = 10^{-14}$ m.

On the other hand, even if the centerline of the two fringes cannot be measured to better than 5 Å, by recording the intensity of each fringe at different values of λ the instrument will yield a ratio between amounts of surface area at each elevation for intervals $\delta h = 1 \text{ \AA}$.

At this point, we consider the resolution limit D on the surface of the test object. A given fringe is the interference of rays coming from a finite area on the object surface. The width D of such an area is given by:

$$D = 2n^2t\theta \quad (4)$$

where

n is the number of reflections,

t is the spacing between the surfaces,

θ is the wedge angle between the surfaces.

The sharpness of the fringe is a function of n , so we want n as large as possible. Therefore we have to find the minimum practical values of t and θ . If the reference and test surfaces are concentric, $\theta = 0$ (parallel surfaces). If a sphere of radius $R = 5 \text{ mm}$ is displaced 1 nm off-center, the wedge between the surfaces as seen by a ray at 45° with respect to the optical axis is

$$\theta = \frac{\delta \sin \alpha}{R} \\ = \frac{10^{-9} \text{ m} \times 0.7}{5 \times 10^{-3} \text{ m}} \\ = 0.14 \times 10^{-6} \text{ rad}$$

α is the angle between the incident ray and the optical axis. If we made $t = 10^{-4}$ m and we want a resolution of $D = 0.2 \times 10^{-6}$ m, the number of reflections becomes

$$n = D/2t\theta = 85$$

Surface Measurements and Characterization

The value $n = 85$ will give a finesse F of about 50, a reasonable value for good optical mirrors.

This calculation shows that a resolution of $D = 0.2 \mu\text{m}$ on the surface of the object is an achievable objective.

Conclusions. The calculations indicate that the following objectives are achievable.

1. For objects of good optical quality, the resolution on the test surface can be as good as $0.2 \mu\text{m}$.
2. The interferometer fringe resolution can be as good as $5 \text{ \AA}$ and may be improved to $1 \text{ \AA}$ with proper instrumentation.
3. The accuracy limit as given by the width of the light source is $1 \text{ \AA}$.
4. To keep the accuracy for large distances (5 mm) between test object and reference surface, the bandwidth of the light source should be as narrow as possible ($\delta\lambda = 10^{-14} \text{ m}$).
5. To keep the surface resolution, it is required to work with small wedge angles ($\theta = 10^{-7} \text{ rad}$) and small t , so the number of

reflections collected by the optical system is as large as possible to increase finesse.

Experimental Results

Figure 2 shows the experimental setup, and Fig. 3 shows the interferograms recorded from the TV screen. Figure 3a corresponds to a steel ball longitudinally displaced along the optical axis. The lens reflectivity was 30%. Figure 3b corresponds to the same ball displaced laterally. These are the first interferograms, and they have not been calibrated. The source is a helium-neon laser which cannot be tuned.

The value of these pictures is that they show that the system produced the desired interference localized in the object lens space. The fringes can be detected either on the reflecting surface of the lens or on the surface of the object. This last condition can be reached only when the object reflectivity is larger than the lens reflectivity.⁴

The fringes obtained with the simple setup of Fig. 2, which lacks environmental controls,

Figure 2. Setup used to test our concept of a topometric interferometer. The system produced the desired interference fringes, shown in Fig. 3.

indicate that with proper control the instrument will yield more accurate readings. Figure 4 shows a proposed design, which contains an environmental enclosure and an Invar table that supports the entire instrument (except the laser). The instrument is vibration- and environmentally

isolated from the exterior. Figure 5a shows the spectrum analyzer free spectral range (FSR, the range of wavelength within an order) at a value of 2000 MHz, and the laser multiple axial modes spaced by $\Delta\nu = 385$ MHz. Figure 5b shows the elimination of the laser multiple axial modes

Figure 3. First interferograms produced by our interferometer (Fig. 2). The test object is a lapped steel ball 10 mm in diameter; lens reflectivity is 30%. The ball is shown (a) longitudinally displaced along the optical axis, and (b) laterally displaced. The fact that we were able to record these fringes on an instrument which lacks environmental controls indicates that proper controls, and a tunable source, will bring greater accuracy.

Figure 4. Proposed interferometer design which includes an environmental enclosure and an Invar table to improve accuracy.

Surface Measurements and Characterization

when the three Fabry Perot interferometers are properly detuned. This display was stable for more than 30 s without environmental control or closed loop. Figure 5 demonstrates the following:

1. It is possible to properly align the three Fabry Perot interferometers to achieve maximum transmission without resorting to sophisticated controls.

2. The Fabry Perot interferometers can be tuned and detuned to different frequencies to allow the desired frequency to pass while eliminating the unwanted ones.

3. The three Fabry Perot interferometers offer no major stability problems in the short term after they have reached equilibrium (steady state) with the environment.

The capabilities of the three Fabry Perot interferometers to eliminate the laser lateral mode frequencies with a spacing $\Delta\nu = 385$ MHz translates into a minimum spectral resolution limit given by:

$$\begin{aligned}\Delta\lambda &= \frac{\lambda^2}{c} \Delta\nu \\ &= \frac{0.633^2}{300 \times 10^{12}} \times 385 \times 10^6 \\ &= 0.5 \times 10^{-6} \mu\text{m}\end{aligned}$$

where c is the velocity of light.

From here we can determine how accurately we have tuned the confocal Fabry Perot. The resonant condition is

$$d = \lambda M/4$$

where M is the number of quarter waves in the cavity.

$$4\Delta d = \Delta\lambda M$$

where $M = 4d/\lambda = 4 \times 10^4$. Therefore, $\Delta d = 0.5 \times 10^{-2} \mu\text{m} = 5$ nm. This is how accurately the position of the Fabry Perot mirrors was controlled during the experiment. Since the piezoelectric responsiveness of the stack controlling the mirror is 2 nm/V, the value $\Delta d = 6.33$ nm can be improved.

If for the final instrument the etalon has a spacing $d_1 = 20$ cm $= 20 \times 10^4 \mu\text{m}$, and the object distance $d_2 = 10^3 \mu\text{m}$, the relationship between the tuning Fabry Perot and the object-lens concentric etalon is

$$\begin{aligned}M_1 &= \frac{4d_1}{\lambda} = 80 \\ M_2 &= \frac{4d_2}{\lambda} = 0.2 = 400\end{aligned}$$

This is the leverage provided by tuning with a confocal etalon to select the illuminating wavelength. To explore a differential high of $\delta h = 1$ Å, the etalon mirror has to be displaced. The displacement is given by

$$\Delta d_1 = 400\delta h = 400 \text{ Å} = 40 \text{ nm}$$

Since we have already been able to control the mirror spacing with an accuracy of 5 nm, the instrument should be easily tunable to the desired wavelength.

Figure 5. Displays showing the tuning accuracy of the Fabry Perot interferometers. (a) Spectrum analyzer FSR equals 2000 MHz, and the laser multiple axial modes are spaced by 385 MHz. (b) Elimination of the laser side-band modes when the three Fabry Perot interferometers are properly tuned. This display was stable for more than 30 s without environmental control or closed-loop feedback.

Future Work

During the rest of FY84, we expect to fabricate and purchase the components required to assemble the test prototype shown in Fig. 4. During FY85 we will perform the final test, and if possible, integrate the computer into the system to scan the Fabry Perot and provide both data display on the TV screen and hard copy. This will provide a reliable, ready-to-use prototype instrument for our present and future requirements.

Once the prototype is built, we will determine the following:

1. Accuracy and resolution limits as functions of (a) the signal-to-noise ratio, and (b) the test-object surface finish and aplanat reflectivity.
3. Accuracy and resolution as functions of system instabilities.
4. Thermal and mechanical instabilities; methods of compensation; possible benefits of passive-active and open-loop-closed-loop feedback.
5. Optimum wavelength to minimize external perturbation and maximize accuracy.
6. Choice of proper light source: tunable dye laser or broadband light.
7. Methods of detection: homodyne vs heterodyne.
8. Best means of data handling and interpretation.
9. Selection of graphics display and control computer.

Financial Status

The Topometric Interferometry project has been funded by Engineering Research since FY83 at the following rate.

FY	Requested	Expended	Returned
1983	\$115 K	\$90 K	\$25 K
1984	\$145 K	\$55 K	\$90 K

The basic reason for the considerable differences between requested and expended funds is the Principal Investigator's (J. A. McNjes's) previous programmatic commitments, which reached more than 75% during FY84. This commitment is scheduled to decrease to about 30% during FY85.

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Fabrication Technology

Precision Contour Grinding Development

9

Precision Contour Grinding Development

J. B. Bryan and D. L. Carter

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Materials Fabrication Division

To meet our goals for the precision contouring of glass, we changed from precision grinding to single-point diamond crushing. This new approach enables us to go from the very rough blank to polishing in much less time. The shorter time is due to the slow tool wear produced by crushing, which results in greater form accuracy.

We obtained a surface finish of 50 μin . peak-to-valley, with occasional deeper pits, on

Zerodur glass and BK-7 glass. A depth of cut of 0.008 in. or more can be taken at a surface speed of 900 ft/min. Wear was on the order of only 10 μin . after removal of 1 in.³ of Zerodur glass. The accuracy and slow tool wear of diamond turning promise to produce great savings of time and money in the precision contouring of glass.

Introduction

The need for large, complicated aspherical optical elements of glass makes a method of inexpensive fabrication very desirable. Fabricating these elements out is expensive primarily because of the imprecise metrology available to guide the removal of glass from the rough blank to the point where precise interferometric metrology can be used. An enormous amount of time and labor are usually required to reach this point.

The goal of this project is to develop and demonstrate an improved fabrication process for the precision contouring of glass. The process must produce as little subsurface damage as possible in order to minimize subsequent polishing. The original proposal for this project, issued in June 1983, stated that we were to use contour grinding, with the aim of regaining the competence in grinding glass that we had achieved in earlier work in 1978. The we were to adapt our knowledge and equipment to Diamond Turning Machine No. 3 (DTM-3), a better machine than the one used in 1978.

After the project began, we changed our approach from grinding to single-point diamond crushing. This new approach enables us to go from the very rough blank to the point of polishing in much less time. The shorter time is due to the small degree of tool wear, and hence the greater form accuracy, of crushing.

Figure 1 compares diamond crushing with turning. Single-point diamond crushing was originally developed by Dr. R. E. Reason of Rank Taylor Hobson in the U.K. 34 years ago for shaping glass aspheres before polishing. Because

of the change in our approach, an appropriate title for the project might now be "Precision Contouring of Brittle Materials."

We changed our approach because of initial success in using inexpensive diamond scribes (Fig. 2) for removing Zerodur glass (Schott Glaswerke, Mainz, FRG). Scribes cost only \$5 each; by comparison, the sharpened diamond tools used for turning cost several hundred dollars each and wear very quickly. The normal use for scribes is marking surfaces; the suggestion to use them for fabricating glass was made by R. W. Clouser. In addition to being low-cost, scribes are attractive as an alternative to grinding because less equipment and time are required to prepare a machine for removing glass.

Figure 1. (a) Single-point diamond turning of a ductile material compared with (b) single-point diamond crushing of a brittle material. The diamond scribes used in crushing are low-cost. Another advantage of scribes is that less equipment and time are required to prepare a machine for removing glass.

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Background

Grinding has several disadvantages: the grinding spindle must have a true axis of rotation, drive-motor vibration must be at an absolute minimum, the wheel and spindle must be balanced to perfection, and wheel runout must be held to a few microinches. When a grinding spindle is retrofitted to a diamond turning machine, the spindle's size and weight can cause problems, and access to small recesses in workpiece geometry may be difficult. Some system is also needed to keep the grinding wheel clean, for workpiece chips or abrasive particles may cling to the wheel and be carried into the gap between the wheel and the work, causing pits. In numerically controlled contour grinding, the wheel nose must be dressed perfectly round and be of known size.

In contrast to grinding, diamond crushing allows us to merely insert the scribe into the tool post of a lathe and use it as a normal tool. Thus anyone with a lathe can contour glass at minimum expense.

Contact with the Outside Engineering Community

We benefitted from the expertise of many people outside the Laboratory. J. Osantowski, C. Fleetwood, and G. Wright of the NASA Goddard Space Flight Center, Greenbelt, MD, provided information on their work with Zerodur, including acid-etching and mechanical-polishing techniques. Professor I. Finnie of the Mechanical Engineering Department, University of California, Berkeley, has worked in the field of brittle fracture for many years and is a leading authority on the subject. He helped us to describe the fracture mechanisms and patterns associated with our crushing techniques, and is interested in conducting further research in this area.

The following people also provided assistance: C. Wyman, NASA, Huntsville, AL; G. Sanger and W. Sigman, United Technology Research Center, West Palm Beach, FL; Dr. R. E. Reason (Retired), Rank Taylor Hobson, Leicester, U.K.; Drs. R. Hocken and T. Charlton, National Bureau of Standards, Washington, D.C.; Professor S. Bowe, University of California

Space Science Laboratory, Berkeley, CA; "Bud" Rigby, Perkin Elmer Co., Norwalk, CT; and P. Hannah, Moore Special Tool Co., Bridgeport, CT.

Technical Status

So far, we have been able to crush both Zerodur and BK-7 glass to a finish of 50 μ in. peak-to-valley or better, with occasional deeper pits (Fig. 3). The plateaus or high points tend to be coplanar, however, so it is possible to speak of form accuracy to much smaller values. On BK-7, we achieved a roundness of 5 μ in. on a 6-in.-diam, 0.5-in.-long cylindrical surface (Fig. 4). Preliminary measurement of tool wear is 10 μ in. after stock removal of 1 in.³ of Zerodur, with depths of cut of 0.008 in. tapering down to 1 μ in.

The term *crushing* implies a rather brutal process which is likely to leave a cracked or damaged surface. This is basically true. Our present theory is that the tool creates a stress in the glass which causes a series of conchoidal fractures ahead of the tool. (Conchoidal is defined in Webster's New Collegiate Dictionary as "having depressions shaped like the inside surface of a bivalve shell," e.g., a clam or oyster shell.)

Figure 2. Diamond scribe used in crushing. Scribes cost only \$5 each; by comparison, the sharpened diamond tools used in turning cost several hundred dollars each.

Some of the conchoidal fractures are not complete, and some particles of glass remain attached to their parent. When viewed in a microscope, these particles tend to "glint" since light is reflected from the crack below the particle. The totality of the glint creates a frosty appearance and reduces the transparency of the glass. The cracks tend to be horizontal and seem to coexist with the topographical roughness rather than lie beneath it.

The cracks can be eliminated through the use of acid etching or mechanical polishing to remove the entire layer in which they reside. Acid etching of Zerodur with a mixture of sulphuric acid and hydrofluoric acids was suggested to us by J. Osantowski, C. Fleetwood, and G. Wright of the NASA Goddard Space Flight Center. We have confirmed their results, which indicate a rate of removal of about 0.0005 in./min per side. The acid removes Zerodur at a fairly uniform rate on a macroscopic scale. On a microscopic scale there is some kind of preferential attack. After etching, the glint seen in the microscope disappears and the part becomes transparent.

In considering the issue of damage caused by single-point crushing, one should bear in mind that a similar level of damage is caused by loose abrasive grinding, ordinary diamond-wheel grinding, and ultrasonic machining. These processes all depend on crushing. The extent of the damage depends on grit size and the depth of the cut. Polishing, on the other hand, is a different process, one which removes, or in some cases heals the damage.

Tool Wear. Initial results indicate that there is very little wear of the diamond scribing tool. Assuming that the data are correct and that wear is negligible, the question is, why? In previous attempts to diamond-turn glass, we experienced massive tool wear. There are two possible explanations.

The first possibility is that the crystallographic orientation of the diamond with respect to the work is different, and the diamond is more resistant to wear in the crushing mode. The second possibility is that the conchoidal fractures occur ahead of the tool intermittently, and that for some short period of time the tool is crushing oil and has a chance to cool. In any case, it seems that there is less

Figure 3. (a) Sample of BK-7 glass after single-point diamond crushing. (b) Trace of the glass surface. The finish is 50 μ in. peak-to-valley or better, with occasional deeper pits.

Fabrication Technology

rubbing because the chips fly away from the work and do not flow across the rake face of the tool.

Tool wear is a crucial issue. If wear is small enough, the accuracy of diamond-turning machines can be brought directly to bear on optical figure accuracy. If the roughness is uniform, we can search for *in situ* polishing techniques that remove a uniform amount of stock.

Another major area of concern is tool wear in numerically controlled contouring with a fixed-attitude tool. Our experiments so far have been straight-line crushing with the tool normal; or

three-axis, tool-normal contouring on Diamond Lathe 2. In the latter technique, a rotary axis to keep the tool normal is an expensive nuisance. The tool tip must be adjusted exactly on the center of the rotary axis; there is a loss of accuracy due to the error motion of the rotary axis; and in some cases requiring internal corners, there may not be room to accommodate the tool.

Other Accomplishments

In addition, we accomplished the following in the first 6 months of FY84.

- Prepared the paper *Single Point Diamond Crushing of Glass* (ICRL-90833) for the Precision Machining Workshop, held in Berkeley, CA on June 5, 1984.
 - Rearranged and tested a precision grinding head for use with an oil shower on DTM-2, and obtained silicon carbide grinding wheels for use with the head. (See Future Work, below.)
 - Purchased two Zerodur glass cylinders (12-in. o.d., 1-in. wall; and 10-in. o.d., 3/4-in. wall), both with lapped faces, for internal material removal by diamond crushing.
 - Fabricated aluminum vacuum chucks for holding the Zerodur cylinders.
 - Fabricated fixturing for acid etching the Zerodur cylinders.
 - Purchased an air-driven dentist's handpiece to be used for the development of polishing, and designed fixturing for mounting it in place of a tool on both DTM-2 and DTM-3.
 - Received \$80,000 funding from NASA Huntsville to study the application of these techniques to the fabrication of the Advanced X-Ray Astrophysics Facility (AXAF) Telescope.
- We are also working with the University of California Space Science Laboratory on the design of an x-ray telescope that could be made from our Zerodur glass cylinder blanks.

Figure 4. (a) Setup used to measure the roundness of a 6-in.-diam glass disk contoured by crushing. The disk is the same sample shown in Fig. 3. The recording chart (b) shows that the disk is round within 5 μm.

Future Work

We shall continue to pursue single-point diamond crushing. The highest priority is to understand and optimize the crushing process in order to obtain a better finish at lower cost and

greater speed. We shall also look at tool wear as a function of material-removal rate and tool orientation.

If further work shows that diamond crushing doesn't produce a satisfactory finish for polishing, it may still be necessary to do some grinding after crushing. In that case, constant-force grinding with silicon carbide wheels offers interesting possibilities. The constant-force approach eliminates the consequence of wheel wear on form accuracy. Form accuracy is excellent with single-point diamond crushing since tool wear is slight. Therefore, we believe that single-point diamond crushing followed by constant-force grinding may bridge the gap that presently exists between grinding and polishing. Use of these techniques could save a great deal of time and money.

Financial Status

We spent \$28,900 as of the end of April 1984. This is significantly less than the linear spending projection of \$87,500. There are two reasons for this. First, our plan was to put the Metrology Group's primary effort for the first 6 months of the fiscal year into making DTM-3 operational, and concentrate our efforts on Engineering Research in the second 6 months. Second, programmatic demand on DTM-2 during the first 6 months was greater than anticipated.

For the balance of the fiscal year we plan to spend as much time as we can using DTM-2 on this project. Some work can now also be done on DTM-3. At this point we plan to spend \$95,000 during FY84.

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Characterization of Martensitic Transformations Using Acoustic Emission

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Materials Test and Evaluation Section
Engineering Sciences Division

Acoustic emission (AE) is a highly sensitive technique which can reveal changes in materials not detectable by other means. Our goal in this project is to obtain basic information on the AE response to martensitic transformation in steel. This information will enable us to use AE for improved quality assurance testing of rough-cut component blanks and semifinished parts.

We measured the AE response, as a function of temperature, in four steels undergoing martensitic transformation, and compared the AE response with martensitic start temperature M_s and finish temperature

M_f obtained by other methods. As measured by AE activity, M_s occurred as much as 26°C higher than previously reported using less sensitive measurement techniques. We also found that 10 to 30% of an alloy of Fe-0.2% C-27% Ni transformed to martensite during one AE burst. These results show that AE can be used to study transformations both inside and outside the classical M_s - M_f ranges. The findings will help us to achieve our goal of using AE for quality assurance testing, and will add to our knowledge of the basic materials science of martensitic transformations.

Introduction

The objective of this project is to study the acoustic emission (AE) response of materials that undergo martensitic phase transformations. The martensitic transformation is common to many materials, such as uranium- and plutonium-based alloys, gold-cadmium alloys, and indium-tellurium alloys.

We have two goals. The first is to compare the AE response, as a function of changing temperature, to the martensitic start temperature M_s and finish temperature M_f revealed by other methods such as dilatometry. The second is to define the AE response outside the range of classical M_s and M_f temperatures. The high sensitivity of AE to material changes may reveal phenomena not otherwise detectable. This precursor and "postcursor" behavior could well relate to residual stress, nonuniform composition, or impurities. Thus, our research has practical consequences in quality assurance testing. For example, semifinished parts or rough-cut component parts could be analyzed based on AE response under changing temperatures.

We studied the martensitic transformations of four steels under athermal, stress-assisted, and strain-induced conditions, and defined the range of AE characteristics for different materials, material compositions, heat treatments, and thermal and mechanical conditions.

Background

This project is a modification of an FY83 project of the same title, with A. Goldberg as co-principal investigator. The FY83 objective was to use the results of our AE research to conduct quality assurance tests of rough-cut component blanks or semifinished parts. Although planned for one year, as the FY83 effort unfolded, many unanticipated questions arose concerning the AE response from martensitic transformations. It became clear that results reported in the literature were highly selective and led to a very distorted and simplified picture of AE characteristics from martensitic transformations. Further study of AE characteristics was thus warranted.

The results of the FY83 effort are reported in the project's FY83 progress report.¹ Among the tasks completed was A. Goldberg's metallurgical characterization of the four iron-high nickel steels retained for study in the current effort. Based on the FY83 results and on our experience, we proposed a two-year study of fundamental AE characteristics from martensitic transformations. Results from this study will contribute significantly to the basic materials science of martensitic transformations and will provide a base for our practical applications.

The Research Team

A. Goldberg was reassigned and could not continue in the FY84-85 effort. He acts as a consultant on metallurgical matters, however. We maintained contact with P. Adler of Plutonium Metallurgy in the Chemistry and Materials Science Department, although we have not begun joint activities. Professor S. C. Carpenter of the University of Denver has made substantial contributions to this work as a consultant. Professor A. K. Mukherjee of the University of California, Davis, and his graduate student J. Mohr are completing an intramural contract study of stress-assisted and strain-induced martensitic transformations. The experimental portion of their work has been completed, they will deliver a full and final report in September 1984.

Technical Status

Equipment. We had conducted our FY83 athermal transformation experiments in the Thermophysical Laboratory (Engineering Sciences Division/Engineering Measurements Section) in Bldg. 231. It was convenient to move the necessary AE equipment across the Bldg. 231, 1600-area high bay to the Laboratory (Room 1638), which had the environmental equipment—furnace, cryostats, inert gas, etc.—readily available. Unfortunately, the Thermophysical Laboratory was moved to Bldg. 131 and smaller quarters in the fall of 1983, and was unavailable for almost two months. In addition, moving AE equipment and personnel back and forth between the two buildings would have been a major task. The AE equipment could not be installed there because it had to be used for several programmatic tasks as well. For these two reasons, we decided to build the necessary environmental equipment for this experiment into the AE laboratory.

The two principal pieces of environmental equipment needed were a cryostat capable of being cooled to -100°C in a controlled and repeatable manner, and a furnace capable of programmed heating to 1000°C . In addition, we needed a supply of argon gas to provide an inert atmosphere. These hot and cold environments were both designed to be

acoustically quiet so that AE data would be free of interfering noise.

We retained for this project the wave guide/specimen holder used in the FY83 effort. The specimen is a 6.35-mm-diam by 25.4-mm rod. It is furnace-brazed at 1020°C to a 6.35-mm-diam by 300-mm stainless steel rod using gold-nickel foil as a braze material. The stainless steel rod is an acoustic wave guide that permits sound generated by the martensitic transformation to be conducted from the specimen to the AE sensor.

Methodology. The wave guide, with a specimen attached, is immersed in a temperature bath that can be brought to the martensitic transformation temperature in a controlled and repeatable manner. About half of the wave guide is inserted into the temperature bath; the other half remains at room temperature. This arrangement is necessary because the AE sensor, mounted on the end opposite to the specimen, must be kept near room temperature to operate properly.

We constructed a temperature bath for those specimens that transform below room temperature. We started with a commercial 70-mm-diam by 30-mm vacuum-walled Dewar flask, and constructed a stainless steel cylinder with top and bottom centering flanges to fit inside the vacuum Dewar. This inner container had a baffled bottom inlet for cold nitrogen vapor. The vapor exited through a path devised to cool an annular space between the vacuum Dewar and the inner container. The inner container was closed into the vacuum Dewar with a polystyrene bead foam plug, with a center hole permitting introduction of the wave guide/specimen into the inner container. We then closed the remaining space with a special cotton-type material (Fiberfrax).

We used a 100-W heater powered from a Variac to boil controlled amounts of liquid nitrogen in a 25-L Dewar flask. We then used a simple insulated 8-mm tube to conduct cold vapor from the Dewar to the temperature bath. The performance of this device in cooling the specimen is shown in Fig. 1. The heater device described in the FY83 report was broken in the move of the Thermophysical Laboratory to Bldg. 131. The present device has been ruggedized and tailored to fit the performance of the first heater as closely as possible.

A furnace is needed to study specimens

whose martensitic transformations are above room temperature and to heat-treat the specimens after they have been tested. The heat treatment returns the specimens to the austenitic state. An acoustically quiet furnace with good temperature control is needed to cover the temperature range from ambient to 1000°C. The quad-elliptical furnace designed for tension specimen testing and already available in the Materials Testing Laboratory should fill all requirements. The necessary modifications and fixturing to assure this method of heating are in progress.

The AE data are acquired by routing the preamplified data from the single AE sensor to a commercial data-processing unit (Physical Acoustics, Model 4300). The processed AE data are then recorded on a strip-chart recorder. We simultaneously generate records of energy accumulation, count accumulation, and event accumulation as a function of time and temperature. The data acquisition and processing unit permits us to select an AE activity level above which data can be taken. We measured the energy accumulation by squaring the amplitude of all AE signals over the preselected activity level and summing the result. Similarly, the count accumulation is the

sum of all the individual excursions of the AE signal as it crosses the preselected threshold. The event accumulation is the count of events based on the level of an rms representation of the AE activity. Each time this rms level exceeds a preselected threshold, an event is signaled. When the rms level drops below this threshold, the event is ended.

We reprocessed these data by digitizing the strip-chart records with a Hewlett-Packard Model 8916 Work Station. We then used the digitized records to produce energy rate, count rate, and event rate charts as a function of temperature.

Programming the Work Station proved to be a major task. Several improvements and modifications made to the program permitted its use over a wider range of AE data processing applications. The improved program was used to reprocess field data from a weapons program test, and the improved display curves could easily be read and interpreted by nonexperts in AE. We found that the program to postprocess data from AE instruments that perform on-line real-time processing operates well. Some additions and modifications may be made as needed.

We encountered delays in obtaining a new strip-chart recorder. The six-channel recorder used previously was old and unreliable. A key part, the inking manifold, could not be replaced. A new recorder was purchased in October 1983, with delivery promised in November. Manufacturer shipping delays and misplacement of the unit on-site during checkout resulted in it becoming unavailable until April 1984.

Results. Preliminary results from the tests described above are included here. First tests in the current year were performed the week of June 4. We tested two pairs of specimens. The composition of the first specimen pair (alloy B) was Fe-0.6% C-21% Ni. The composition of the second specimen pair (alloy W) was Fe-0.2% C-27.1% Ni. Both transform to a twinned, lenticular martensite. Alloy B has higher strength and is more brittle than alloy W.

Alloy W, tested for the first time, showed a very remarkable AE response. The rms records taken at two sensitivity levels and plotted against temperature (thermocouple voltage) are shown in Fig. 2 for the pair of specimens tested. Note the almost exact duplication of the AE response for these specimens, which were nominally identical. The triangular feature of the

Figure 1. Performance of the device used to cool the specimens in our AE studies. The system provides nearly linear cooling in the martensitic transformation range.

Materials Characterization and Behavior

records in Fig. 2, appearing on the right side of each of the plots, is an indication of a very large AE burst, which signaled the beginning of the martensitic transformation activity. The temperature change which accompanied this huge AE burst was much too fast for the recorder to follow, so the hypotenuse of the triangular feature represents the "slewing rate" of the recorder. The off-scale indication on the vertical axis shows that this burst fully saturated all of the AE instrumentation except the sensor.

One can also observe the magnitude of this event based on the energy it represents. The temperature change was 55°C. Considering the volume of the specimen and its specific heat,

the energy released in the event was 160 J. The instrumentation could have detected an event containing only 10^{-11} J, and in fact the rest of the subject record shows no signal saturation, so the remainder of the signals were of this order of magnitude. Based on our estimates of the strain energy and the chemical free-energy change, we calculated that at least 10% of the specimen transformed to martensite during this one event. Another estimate, based on some details of the temperature-time record, is that about 30% of the specimen transformed. Others have observed burst transformations involving this fraction of volume for ferrous alloys similar to the one we used.^{1,2}

Figure 2. Remarkable AE response to martensitic transformation of two specimens of alloy W. The triangular feature at the right in each plot indicates that 10 to 30% of the specimen transformed during one very large AE burst. This result shows that AE is a highly sensitive technique which may reveal phenomena not detected by any other means. There are two sensitivity levels, with full-scale readings at 49 dB gain as follows: upper curve, 0.1 V; lower curve, 0.3 V.

Figure 3 shows the normalized energy rate as a function of temperature for specimens W1, W2, B41, and B44. Figure 4 shows the normalized event rate as a function of temperature. The rate for these plots is referred to temperature for the same specimens.

Martensitic start temperatures M_s for these materials, measured by the dilatometer method, are -42°C for the W alloy and -36°C for the B alloy.³ The AE records show beginning activity at -47°C for W1 and -43°C for W2, with the large burst discussed above at -55°C . Specimen B41 indicated AE activity at about -15°C .

The system gain at the start of this test was 66 dB. The instrumentation started saturating at about -36°C , and gain was lowered by a factor of 10, to 45 dB. Thus -36°C was the temperature at which AE "began in earnest." Early activity, detectable at higher gains, was reported in the FY83 Annual Report.¹ Specimen B44 data were all taken at an even lower gain, 32 dB. Activity started as early as -10°C , 26°C higher than the measured M_s temperature reported in the literature. If the AE data are correct, the meaning of M_s temperature is uncertain at this time.

Figure 3. Normalized energy rates during martensitic transformation in four specimens: W1, W2, B41, and B44. The counts shown are for full scale.

Materials Characterization and Behavior

Summary. The results we obtained by monitoring AE on two specimen types confirmed the operational capability of our method of producing low temperature for the martensitic transformation in these materials. The new W specimens gave an especially interesting AE response. Our results continue to demonstrate that AE is a valuable tool for studying the martensitic transformation of materials, both inside and outside the classical M_s - M_f range.

Future Work

Our first priority is to complete the high-temperature furnace used to produce the martensitic-to-austenitic phase reversion. Next, each of the 11 currently available specimens should be AE-monitored through its martensitic transformation range. Analysis of the data from these tests will help guide decisions concerning perturbation of the heat treatment so that a range of AE responses can be defined.

Figure 4. Normalized event rates during martensitic transformation in four specimens: W1, W2, B41, and B44. The counts shown are for full scale.

Materials Characterization and Behavior

As soon as it is available, the information to be provided by Mukherjee and Mohr on stress-assisted and strain-induced martensitic transformations will be analyzed. A decision on whether to expand this portion of the work will be made when the report is received.

Financial Status

Expenditures through March 1984 totaled \$65,500. Projected project cost, including expenditures through May 1984, is \$134,000 for the full year. Some increased activity is

projected, so this project should end the fiscal year near to its initial budget estimate of \$147,000.

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Flaw Characterization by Combining System Identification and Elastic Wave Scattering Theory

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The major goal of current Nondestructive Evaluation researchers is to determine, with an acceptable degree of accuracy and confidence, the size, shape, and orientation of flaws. If we are able to successfully combine system identification and elastic wave scattering theory, we might have the ability to accurately size cracks and evaluate surface characteristics. This would make possible a quantitative description of internal cracks, surface-breaking cracks due to machining, and the lack of fusion in a weld root. Accurate evaluation of surface characteristics would, in

turn, enable us to assess surface roughness, surface grain size, and surface residual stress. These factors can be important in fatigue and stress-corrosion crack growth.

Our ultrasonic procedures show promise for extracting more information than was previously available about the size, shape, and orientation of flaws located in engineering materials. In addition, we extended throughout the Nondestructive Evaluation Section the useful technology of waveform digitization. We accomplished this by doing our experiments on all the available ultrasonic equipment.

Background

For some time ultrasonics have been used for the detection and location of flaws. Now ultrasonics are being used for the quantitative evaluation of cracks, inclusions, and many surface features. This new application is made possible by recently developed techniques for predicting the failure probability of components.^{1,2}

Rapid progress has been made in estimating the remaining lifetime of a structural component when knowledge of the following factors is available: material property, stress level, flaw geometry, and flaw location. Catastrophic failure is predicted when the flaw has reached a critical size, which varies considerably for different materials and conditions.

Most ultrasonic equipment works as follows. An electrical potential is applied to an ultrasonic transducer. This causes the transducer to exhibit damped oscillatory motion. The transducer is then coupled to the test specimen and the resulting stress wave is propagated throughout the specimen.

* W. Cook is at LLNL during his sabbatical leave.

If the wave encounters a flaw, a portion of the initial energy contained in the wave will scatter and eventually encounter the original transducer or another transducer. If we assume that the generation, propagation, and receiving of ultrasonic stress waves are linear, the modification of the initial electrical signal can be described as:

$$\begin{aligned} y(t) &= e(t) * T_1(t) * P_1(t) * P_2(t) * T_2(t) * S(t) \\ &= h(t) * S(t) \end{aligned} \quad (1)$$

where

$e(t)$ is the electrical time profile initially applied, $T_1(t)$ and $T_2(t)$ are the transduction impulse responses of the transducers, transmitting and receiving, respectively, $P_1(t)$ and $P_2(t)$ represent the changing of an impulse while propagating to and from the flaw, $S(t)$ is the impulse response of the material defect, and

$$h(t) = e(t) * T_1(t) * P_1(t) * P_2(t) * T_2(t)$$

The symbol $*$ means convolution; $h(t)$ is the impulse response of the experimental system. By examining $y(t)$ in Eq. (1), it is relatively simple to determine the approximate location of

a flaw by a number of alternative techniques. We must be able to separate and quantify the terms of Eq. (1) with an acceptable degree of accuracy and confidence in order to determine the size, shape, and orientation of flaws.

Separating $h(t)$ and $S(t)$ in Eq. (1) is termed "system identification." Interpreting $S(t)$ is termed "elastic wave scattering theory." System identification and elastic wave scattering theory are complementary. System identification entails separating the terms of Eq. (1) by experimental measurement and signal processing. Once the individual terms have been separated, they can be related to the individual phenomenon. Elastic wave scattering theory involves calculating the terms of Eq. (1), combining the results, and then using the results to predict variations caused by the experimental system.

System identification and elastic wave scattering theory have received a great deal of attention in the literature. A small fraction of this attention is indicated in Refs. 1-15.

If our attempt to combine system identification and elastic wave scattering theory is successful, we might have the ability to accurately size cracks and evaluate surface characteristics. This will allow a quantitative description of lack of fusion at the weld root, internal cracks, and surface-breaking cracks due to machining. If we can evaluate surface characteristics, we can then assess surface roughness, surface grain size, and surface residual stress. These can be important factors in fatigue and stress-corrosion crack growth.

The Research Team

The team consists of R. L. McKinney, Dr. G. A. Clark, Professor W. Cook, and Professor A. Mal. G. A. Clark is a signal-processing expert in LLNL's Electronics Engineering Department. Professor Cook of the University of Houston is working at LLNL during his sabbatical leave, and Professor Mal of the University of California, Los Angeles (UCLA) is our consultant.

G. A. Clark devised the system-identification techniques used to reduce the data. He worked on the VAX 11/780, using signal-processing techniques developed in the Engineering Research Program as a starting point for his solution. Professor Cook was involved in all aspects of the work, which ranged from performing the experiments to consulting and working with G. A. Clark.

Our work involved comparing the theoretical calculations performed by A. Mal at UCLA with the experimental measurements collected at LLNL. We assembled a computer system consisting of an LSI 11/2 minicomputer, a hard disk, and a VT-100 terminal. We delivered this system and the data to A. Mal, who analyzed the data on the computer system and on a VAX 11/780 owned by UCLA. He wrote a report outlining the analysis and delivered it to us on May 15, 1984.¹⁶

Figure 1. Experiment configuration for crack sizing using ultrasonic inspection methods.

Methodology

Combining elastic wave scattering theory and system identification is particularly difficult under these conditions: the precise location of the transducer is not known, the measurements are noisy, and there are zeros and poles in the Fourier spectra of the measurements. Our approach is shown in Fig. 1. We constructed flawed specimens in which the location and geometry of the flaws are known. Then we took measurements in places where the specimen was flawed and where it was unflawed. Finally, we compared these sets of measurements in a way which allowed separation of $h(t)$ and $S(t)$, and also allowed the comparison of $S(t)$ with theoretical scattering calculations.

We divided the work into three tasks.

1. Specimens with known defects were fabricated at LLNL and appropriate experiments were performed.

2. We developed system identification techniques to reduce the data.

3. We delivered the data and a computer system to A. Mal at UCLA so that he could make a comparison between his theoretical calculations and the data.

Task 1. Specimen Fabrication and Experiments.

Twenty rectangular aluminum blocks (6 in. x 4 in. x 3/4 in.) were fabricated at the LLNL machine shop. Each block had a simulated crack modeled by a saw cut or channel. The depth of the crack varied from block to block, with a range of 5 to 500 mils. A representative specimen is shown in Fig. 1. The following three experiments were performed on each block.

1. We placed each block in an ultrasonic scanning tank filled with water. We mounted the focused transducer above the block with θ at 20° , and positioned it in z at a distance such that the recorded signal was a maximum at the intersection of the crack and the specimen water surface (crack corner). Having θ set at 20° causes a 45° shear wave to be launched into the specimen. While maintaining the position of the transducer in θ and z , we varied the y position of the transducer. We moved the transducer in the y position in increments of 1/66 in. At each position, we pulsed the transducer and recorded the reflected echo from the crack.

We set the initial position of y so that a reflection from the crack corner was noticeable. The final position of y was the position from which we recorded several reflections from the specimen corner. We used reflections from the specimen corner to estimate the experimental system impulse response.

2. In Experiment 2, we duplicated Experiment 1 with θ set at 0° and z set so that we saw a maximum reflection from the back surface of the part. We used reflections from the back surface of the part in Experiment 2 to estimate the experimental system impulse response.

3. We repeated Experiment 1 in order to establish what effect the estimate of the alignment and the positioning of the transducer had on the results. We recorded numerous signals from the specimen corner at different positions of y and z , and used each of these signals in the data reduction.

We performed all the experiments on three different instruments: a research scanner, an acoustic microscope, and an ultrasonic test bed. These instruments consist of mechanical systems for transducer manipulation, together with associated electronics and computers used for generating and measuring ultrasonic responses. We felt it was necessary to perform the experiments on all three instruments because the digitization of entire waveforms is a new concept to the Nondestructive Evaluation Section. Our effort promoted the use of this technology throughout the Section.

Task 2. System Identification. In Eq. (1), we used $h(t)$ to designate the reflection from the specimen corner, and $y(t)$ to designate the reflection from the crack. Before we identified $h(t)$ and $y(t)$, we preprocessed them to condition the data for good identification results and to minimize artifacts of processing.^{4,5,10} We carried out several basic operations, including the following ones:

- Alignment to ensure causality (the system output does not precede the input).
- Mean removal.
- Low pass filtering.
- Decimation (to lower the sampling frequency to only that which is required by the Nyquist sampling theorem²).
- Windowing of the data to remove correlated background noise that is known to

occur before and after the pulse event.

We used two basic system-identification algorithms with this data. The algorithms are of the least-mean-square error type and use linear system models. The first is a Wiener filter algorithm which uses a finite impulse response (or moving average) model and a Toeplitz matrix inversion scheme for solving the Wiener-Hopf equation.^{3-8, 11-15} The second is a nonlinear least-mean-square algorithm designed especially for use with transient identification. The algorithm uses a linear pole-zero model with output error and a choice of several nonlinear

optimization schemes for computing the model parameters.^{3,4,10} This second algorithm has proved useful in several other applications at LLNL and elsewhere.

Figures 2 and 3 show $h(t)$ and $y(t)$ for a crack size of 150 mils. Figure 4 shows the $H(f)$ spectra (discrete Fourier transform), and Fig. 5 shows the $Y(f)$ spectra (discrete Fourier transform). Note that the signals are well behaved in the sense that zeros are not contained in the spectra. Small spectral values, particularly in $H(f)$, cause ill-conditioning in the identification procedure.^{3,4,5,10} As mentioned

Figure 2. Preprocessed interrogating signal $h(t)$.

Figure 3. Preprocessed crack-response signal $y(t)$.

Figure 4. $H(f)$ of the discrete Fourier transform of the interrogating signal $h(t)$.

Figure 5. $y(f)$ of the discrete Fourier transform of the response signal $y(t)$.

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earlier, we preprocessed the data in order to remove high-frequency zeros caused by oversampling the data.

Figure 6 shows the impulse-response estimate for the crack $S(t)$, and Figure 7 shows its spectrum $S(f)$.

Task 3. Theoretical Calculations. The comparison between theoretical calculations and experimental measurements is at this time questionable. The analysis of the experimental data by A. Mal proceeded as follows. He calculated the diffraction of a 45° shear wave

Figure 6. Estimated crack impulse response $S(t)$.

Figure 7. $S(f)$ of the discrete Fourier transform of the estimated impulse response $S(t)$.

from the crack tip of a crack that has an infinitely thin width and an infinitely long depth. The experimental crack is finite in width and finite in depth. Once the impulse response of the diffracted wave field was calculated, it had to be modified by the experimental system-response impulse. This was achieved by convolving the reference signal with the calculated diffracted field. A comparison between the calculated and measured fields is shown in Fig. 8.

Future Work

Short-term future work includes evaluating the existing data to study the effects of:

- Alignment of the transducer.
- Using different reference signals $[h(t)]$.
- Varying the parameters and algorithms associated with different reference schemes.

For example, we found that when we used two reference signals recorded at slightly different locations of the transducer, one echo from the crack we were processing produced different processing artifacts from each location. Another example is that we found the alignment of the signals before processing to be extremely important. Theoretically, one signal processed with itself should give a perfect impulse, but this is not true unless the signals are aligned to within one sample interval.

Figure 8. Responses of the crack tip obtained by (a) calculation, and (b) measurement.

Once these effects are known, the signal processing techniques will be extended to welded samples in an effort to deduce lack of penetration. Welded samples have been prepared with different penetrations. Each sample was cut and etched at the weld site. If the system-identification techniques work for these samples, we feel a viable new tool will be available for nuclear design engineering.

Other goals include evaluating the terms contained within $h(t)$. We hope to eventually answer the following questions:

1. Given an electrical signal applied to a transducer, what is the pressure field in front of the transducer?
2. Once pressure fields are calculated or measured, how do different specimen surface curvatures affect the field transmitted into the part?
3. Given that the pressure field in the specimen can be deduced, what effect do different grain sizes have on the propagating stress field?

The signal processing we described has been successful in providing information about the flaw, but problems still exist. We have identified some processing artifacts that were causing ambiguities, and we have avoided them by the preprocessing operations discussed above under Task 2, System Identification. There is still some question as to the best system-identification procedure to use. We are working on ways to resolve that issue. A. Mal's comparison of his theoretical calculations with our data was not conclusive, and we are presently studying this issue.

Financial Status

The cost for this work as of the end of April 1984 was \$38,000. The average monthly cost was \$5500. We originally estimated that the project would take 12 months to complete, which would mean a total cost of \$66,000. However, additional needed work brings the total projected cost to about \$85,000. The amount spent is less than expected because the cost of the work was spread among other accounts. It was possible to share costs because:

- The experimental work involved is applicable to other projects.
- The signal processing is applicable to the ultrasonic-test-bed project and the scanning-bridge project.
- Professor W. Cook was receiving half of his salary from the University of Houston.

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A Study of Conditions that Control Damage Progression in Fiber Composites During Repeated Loading

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The goal of this research is to develop an experimentally sound proof test for composites. To achieve that goal, we must first study how damage occurs and progresses in composite materials. We used acoustic emission (AE) data to monitor damage in Kevlar-49/epoxy strands, and to locate AE sources within individual strands and within dry and lubricated bundles. By using

progressively complex test samples, we verified the source mechanism of the observed AE signals. These results are essential to the development of a spatial damage accumulation distribution. Such data will show how and where damage starts and progresses within composites, and may lead to the development of a rational proof test for composites used in critical structures.

Introduction

The purpose of this project is to study conditions that control damage progression in fiber/epoxy composites during repeated stressing. Composites are materials composed of two or more components. The matrix, or bulk, material is reinforced by imbedded materials.

Composites may contain defects not detectable by conventional means. For example, most pressure vessels must be proof-loaded, i.e., stressed at higher-than-rated levels, before, and at regular intervals, throughout service life. An experimentally sound proof-testing method to verify the strength of composites used in pressure vessels and other critical structures has not yet been established. (One unresolved issue is that one does not know whether proof tests themselves contribute to the growth of damage in composites.) The information generated from our research will fundamentally contribute to an understanding of the variables that control the growth of damage in composites. The largest payoff of the research would be the development of a rational proof test for composites, since the usage of composite materials is increasing at a rapid rate.

Our approach uses acoustic emission (AE) to monitor damage as a function of variables that potentially control the physics of the Felicity effect¹ in fiber composites. The Felicity effect refers to the presence of AE indications in

a successive load cycle at a load below the previous maximum. The indications signal damage progression. This AE information allows the significant control variables to be determined, and will thus guide the selection of proper critical experiments most likely to delineate the physics of damage progression with repeated loading.

Contact with the Outside Engineering Community

We presented our research at the meeting of the Committee on Acoustic Emission from Reinforced Plastics (CARP) in Salt Lake City, UT (March 6-8, 1984). As a result of that presentation, Boeing Commercial Airplane Company sent B. Dykes and M. Mayhle to Livermore for discussions with M. A. Hamstad. Boeing plans to do research on materials. We gave a second presentation at the Acoustic Emission Working Group meeting in Reno, NV. M. A. Hamstad is preparing a journal article detailing work to mid-March.

Technical Status

This is the first written report on this new three-year project. In October and November 1983, we:

- Obtained technician support. R. Moore joined us from Chemistry and Materials Science's Composites and Polymers Group.
- Designed and fabricated fixtures to hold special NBS-type, point-contact, conical AE

* Now at the University of Denver. R. B. Engle is the current Project Leader.

sensors against the grips of the strand specimens.

- Fabricated and attached grips to the specimens.
- Checked and calibrated the Physical Acoustics Model 3000/3400 AE equipment.

Although we completed each task successfully, we found that the AE equipment did not meet frequency specifications. We planned to begin testing at low-bandpass frequencies (5–25 kHz), where AE stress waves would be least attenuated. Because of equipment limitations, however, we started testing with a 100- to 300-kHz bandpass rather than with the more desirable lower bandpass.

Equipment testing began early in December 1983. We first loaded Kevlar-49/epoxy strands to 80% of expected failure. If the 80% loading did no damage, subsequent loadings would be quiet. Flaws were then deliberately introduced into the strands by local bending. Differences in arrival time Δt for subsequent events showed that AE sources could be located in the 7-in. strands. This result is of key importance for subsequent work because the experimenter can develop a spatial damage accumulation distribution. Unfortunately, these tests turned up an error in the commercially supplied AE equipment software used to determine the location of AE events. The manufacturer corrected this software error late in February 1984, and the tests need to be re-run. Fortunately, this error did not cause a problem, since the experimental plan from late December until early March emphasized fiber-bundle testing.

We first tested single Kevlar filaments. We used the same end clamps and AE sensors that were used for bundle or strand tests. A number of filaments were individually loaded until they failed. The key result was that amplitudes of AE from filament failure did not depend upon load at failure, an unexpected outcome for failures originating at about the same location in the filaments. An examination of transient recorder records from the filament failures indicated (as a result of distinct differences in time domains) that the time rate of energy release during filament failure varied. This result may be due to different mechanisms of filament failure. Work by R. J. Morgan and coworkers in Chemistry and Materials Science indicates a potential for different failure mechanisms for Kevlar filaments

due to the "strong" and "weak" core of the filament. Possible future work may use a scanning electron microscope to correlate AE signals with failure mechanisms of the filaments.

We then used a two-step approach to move from single filaments to composite bundles. First, we tested lubricated bundles to failure. These tests were unique because we could verify in two ways that certain AE events were due to individual filament failures within the bundle of 267 filaments. The first verification came from observed load drops. We used a special electronic device, developed by R. Moore, to expand the usual load scale by a factor of 10. We could then see load drops for individual filaments. A switch on this device allowed us to suppress zero on the plotter so that we could plot with high resolution the load drop from each filament failure. The second verification came from the 267 known filaments in the bundle. Breaks in the filaments should produce 267 AE events. We were able to break one filament at a time by slowly loading the bundle until the first filament broke. Subsequent slow loading and periods of load hold at fixed displacement produced a sequential failure of individual filaments in the strand. The error in filament counts from AE events was less than 1%. The tests produced a statistically large set of data to characterize the AE from a single, verifiable AE source: the individual filaments as they broke. These data are unique in the field of AE and composites.

The second step in our approach was to test dry bundles. For this test, friction between filaments begins to simulate the role of the matrix in transferring load from one filament to another. We can still observe single filament breaks both by AE and by load drops, and can thus determine total damage and the load at which damage occurs. The effect of friction is such that the whole bundle fails shortly after peak load is reached. Our data tell us how many filaments failed just before the total failure.

The data from the above two steps also revealed an important effect of propagation conditions on the amplitude and energy of AE signals. We observed that both the amplitude and energy of AE signals from filament breaks were less for the lubricated than for the dry bundle. Discussions with E. M. Wu of the Materials Test and Evaluation Section resulted in

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a preliminary model which attributes these differences to the acoustic coupling provided by the silicon oil lubricant used. This observation is important because the matrix material in the strands will have a similar role for the propagation of AE energy.

Early in March 1984 we conducted the final tests: low-cycle fatigue tests for dry and lubricated bundles of Kevlar. These tests stopped when M. A. Hamstad left LLNL; they continue at the University of Denver.

Summary

We produced significant and unique results during this reporting period. By using progressively more complex test samples, we verified the source mechanism of the observed AE signals. We also observed progressive filament failure in two ways under loading. Therefore, damage progression under load cycling and deviations in the Felicity ratio can be measured quantitatively. Finally, we verified the source location for a composite strand sample. This means that in future tests, AE data can be used to determine damage accumulation as a function of location.

Financial Status

The rate of expenditures was low in October and November 1983. The December-March expenditures were considerably higher; if spending continues at the same rate, expenditures will be about \$175,000 at the end of FY84, the amount originally projected.

Future Work

Efforts at LLNL will emphasize techniques for testing uniaxial single-layer or multilayer bars about 8 in. long. These bars represent the next level of complexity. M. A. Hamstad's departure and the consequent change in Project Leader will mean a temporary change in schedule.

Future work at the University of Denver depends upon the availability of funding. M. A. Hamstad submitted a funding proposal to LLNL in March 1984.

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Methodology for Predicting Aging of Polymers

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The goal of this project is to predict how aging affects the material properties of polymers. To achieve that goal, we are modeling the effects of short-term aging on the elastic and viscoelastic properties of polymers. Our emphasis is on the prediction of long-term effects from short-term aging experiments.

During this reporting period, we developed the experimental apparatus for inflating a membrane—an effective method for obtaining large deformations in aging tests. We began to develop a theoretical solution for the deformations of an axisymmetric polymeric membrane. We also developed an approximate analysis which produces a simple closed-form

solution, greatly simplifying the reduction of data from the inflation tests. Our theoretical work yields a relation between the deformation of the membrane and the inflating pressure, with material properties given. When deformation is fixed and the time history of the inflating pressure is measured, the material properties of the polymer can be determined. Since these properties are functions of the aging history of the membrane, we can determine the specific effects of aging.

In the rest of FY84, we will begin acquiring and analyzing data to determine the effects that different aging times have on material properties.

Introduction

This project is concerned with the prediction of the aging behavior of polymeric materials. Our specific objective is to model the short-term elastic and viscoelastic properties of these materials, and the long-term effects of aging. We emphasize the ability to predict long-term aging effects from relatively short-duration aging experiments.

In earlier work, we studied the uniaxial deformation of a cylindrical polymeric specimen with stress-free lateral surfaces, in order to determine the material properties of a homogeneous elastomer.¹ We used those properties in a model which predicted the one-dimensional compressive behavior of elastomeric cushions. Recently, we extended the results to the viscoelastic case.² In this project we extend the formulation further to study the effects of aging of polymers.

Other aspects of the project have concerned the response of polymeric materials under biaxial tensile loads. An effective method

for obtaining large deformations under biaxial tensile loads is the inflation of a membrane. Yang and Feng solved several mechanics problems of large deformation of nonlinear elastic membranes.³ In this project, we extended the formulation to the viscoelastic time-dependent region. The polymeric material considered here is taken to be incompressible; the nonlinear constitutive relation developed by Christensen⁴ is used to study the short-term deformation of viscoelastic membranes.

The large deformation of membranes provides one of the simplest experimental methods for biaxial testing under nonlinear conditions. With these theoretical and experimental results, the material properties of the membrane can be determined. In future work, some uniaxial and biaxial tensile creep curves will be obtained for various values of aging time. Based on the experimental and theoretical results, the specific effects of aging can be determined.

The results obtained from this project have direct application to the design of rubber latex balloons used in a weapons program. They also

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have direct application to the cushion project, in which the aging effect is one of the major factors to be considered.

Technical Status

In this reporting period, we obtained an approximate analysis for the inflation of an initially flat, circular elastic disk. In addition, we almost completed the experimental setup. This section describes these accomplishments in detail.

We give the approximate analysis for the inflation of a thin, flat circular disk of elastomeric material. The analysis results in a closed-form analytical solution for the maximum displacement as a function of pressure. The method is illustrated through the use of a viscoelastic material model. When the results for neo-Hookean material are compared with the exact solution obtained by numerical means, they are satisfactory, up into the range of several hundred percent strain. The method greatly simplifies the procedure for reducing test data, from this type of test, to nonlinear-range mechanical properties.

Analytical Method. In developing the approximate method, we assumed plane stress type, and two-dimensional and isotropic conditions. The approximation resides in the assumption that the deformed shape of the pressurized material constitutes a segment of a

Figure 1. Inflation of a flat polymeric disk, used in our analysis of deformation.

spherical surface. The analysis was performed using this assumption.

The initially flat disk is shown as the flat dotted surface in Fig. 1. The deformed shape is taken to be spherical, with radius r . To relate maximum displacement Δ to the applied pressure p , a hypothetical initial position must be found for the spherical shell. In Fig. 2, R is the radius of the initial position of the spherical shell. The first problem is to evaluate the hypothetical initial position by some criterion. For example, the undeformed spherical shell at position R could be taken to have the same thickness as the given flat disk and the same surface area. Alternatively, the initial spherical shell could be taken to have the same linear surface dimension S in Fig. 2 as the diameter of the flat disk, along with the same thicknesses. There is no unique method for deducing position R . We analyzed both of the above methods, and the latter procedure is more in accordance with the exact solution, so we follow it here.

First, some basic geometry can be defined. From Fig. 1 and spherical geometry, it follows that

$$\Delta = r - \sqrt{r^2 - B^2} \quad (1)$$

from which

$$\frac{B}{r} = \frac{2}{\Delta + B} \quad (2)$$

Figure 2. Hypothetical initial position of the spherical shell after inflation.

In Fig. 1, it follows that

$$\sin \frac{\theta}{2} = \frac{B}{r} \quad (3)$$

Next, from Fig. 2, the arc length S is given by

$$S = R\theta \quad (4)$$

The criterion of equivalence between the hypothetical initial shell at R in Fig. 2, and the initial flat disk in Fig. 1, is given by

$$\frac{S}{2} = B \quad (5)$$

along with the same thickness H in both configurations. Combining Eqs. (4) and (5),

$$\theta = \frac{2B}{R} \quad (6)$$

When we obtain θ from Eq. (3) and insert it into Eq. (6), we get

$$R = \frac{B}{\sin^{-1} \frac{B}{r}} \quad (7)$$

Finally, by substituting from Eq. (2) into Eq. (7), we obtain

$$R = \frac{1}{\sin^{-1} \left(\frac{2}{\Delta + B} \right)} \quad (8)$$

This gives the position R of the undeformed shape of the hypothetical spherical shell in terms of the displacement Δ and the size of the initial disk, radius B . The stretch ratio, defined by $\lambda = r/R$, is then given by

$$\lambda = \left(\frac{\Delta + B}{2} \right) \sin^{-1} \left(\frac{2}{\Delta + B} \right) \quad (9)$$

In Eqs. (8) and (9), from basic geometry, we have

$$\sin^{-1}(\cdot) \rightarrow \text{first quadrant for } \frac{\Delta}{B} \leq 1$$

$$\sin^{-1}(\cdot) \rightarrow \text{second quadrant for } \frac{\Delta}{B} \geq 1$$

These results comprise the basic nonlinear kinematics for the problem.

At this point, the material model of interest must be specified. We take the constitutive equation developed by Christensen⁴ for nonlinear viscoelastic materials. For homogeneous deformation of a spherical membrane, the stress resultant s (force per unit length of the deformed surface) is

$$s = H \left[g_0 \left(1 - \frac{1}{\lambda^6} \right) + \frac{1}{2} g_1 * \lambda^2 - \frac{1}{2\lambda^6} g_1 * \left(\frac{1}{\lambda^6} \right) \right] \quad (10)$$

where H is the thickness of the spherical membrane before deformation. The long-term elastic material constant is g_0 and the relaxation function is $g_1(t)$. In Eq. (10) the convolution integrals are denoted by the symbol $*$, i.e.,

$$g_1 * \lambda^2 = \int_0^t g_1(t - T) \frac{d\lambda^2}{dT} dT \quad (11)$$

The only equation of equilibrium to be satisfied is

$$2ks = p(t) \quad (12)$$

where k is the curvature of the spherical membrane and p is the inflating pressure. The curvature is a function of the stretch ratio:

$$k = \frac{1}{\lambda R} \quad (13)$$

Hence

$$p(t) = \frac{2H}{\lambda R} \left[g_0 \left(1 - \frac{1}{\lambda^6} \right) + \frac{1}{2} g_1 * \lambda^2 - \frac{1}{2\lambda^6} g_1 * \left(\frac{1}{\lambda^6} \right) \right] \quad (14)$$

Equation (14) can be rewritten in the following form:

$$\frac{p(t)B}{g_0 H} = \left(\frac{\Delta + B}{2} \right) \left[1 - \frac{1}{\lambda^6} + \frac{g_1}{2g_0} * \lambda^2 - \frac{g_1}{2g_0 \lambda^6} * \left(\frac{1}{\lambda^6} \right) \right] \quad (15)$$

Equation (15), with λ given by Eq. (9), yields a relationship for the maximum displacement

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Δ and the applied pressure p . With proper experimental data, Eq. (15) can also be used to determine the material properties of the membrane. Determining the viscoelastic material properties is the main objective of this project.

Methodology. As Fig. 3 shows, the membrane is clamped at the edge and inflated by pressure.* The pressure is measured by a pressure transducer. The digital values of the pressure are obtained by a Keithly voltmeter which is controlled by an Apple computer, as shown in Fig. 4. The photo sensors and the solenoidal valve control the deformation of a membrane so that a constant height is maintained at all times. Figure 5 shows a typical pressure-time history curve. The radius of the membrane before deformation is 1 in. The maximum deformation of the membrane at the pole is 1.2 in. The thickness of the membrane before deformation is 0.031 in.

* The biaxial stress state test apparatus was designed and built by K. Blaedel, T. Gorman, M. Prusse, C. Radewan, and W. Schopp of Engineering Sciences Division.

Figure 3. Experimental setup used to measure deformation of an inflated polymeric membrane.

In the data reduction, the value for Δ is considered as a step function, i.e.,

$$\Delta = 0 \quad , \quad t < 0 \quad , \quad (16)$$

$$\Delta = \Delta \quad , \quad t \geq 0 \quad .$$

Then λ is also a unit step function, or

$$g_1 * \lambda^2 = g_1 \lambda^2 \quad , \quad g_1 * \left(\frac{1}{\lambda^6} \right) = \frac{g_1}{\lambda^6} \quad . \quad (17)$$

Equation (15) reduces to

$$g_1(t) = \frac{1}{\left(\lambda^2 - \frac{1}{\lambda^2} \right)} \left[\frac{p(t)B \left(\frac{\Delta}{B} + \frac{B}{\Delta} \right)}{2g_0 H} - 2 \left(1 - \frac{1}{\lambda^6} \right) \right] \quad . \quad (18)$$

There are two unknown functions to be determined: g_0 and $g_1(t)$. When t approaches infinity, $g_1(t)$ approaches 0. Hence

$$g_0 = \frac{\infty B \left(\frac{\Delta}{B} + \frac{B}{\Delta} \right)}{4H \left(1 - \frac{1}{\lambda^6} \right)} \quad . \quad (19)$$

Therefore, g_0 is determined. With g_0 determined and $p(t)$ obtained from the experiment, $g_1(t)$ can

Figure 4. Data acquisition system. Digital values of pressure are obtained by a Keithly voltmeter which is controlled by a microcomputer.

be obtained from Eq. (18). For the experimental data shown in Fig. 5, g_0 is 64 psi and $g_1(t)$ is shown in Fig. 6.

The accuracy of this approximate analysis is illustrated here. A special case is used in which the viscoelastic solution reduces to the elastic solution.

The first term in Eq. (15) represents neo-Hookean behavior, corresponding to the kinetic theory of rubber elasticity. It is useful to examine the neo-Hookean behavior in some detail. Under small deformation conditions, with the neglect of higher-order terms, Eq. (15) reduces to

$$p = 16 \frac{g_0 H \Delta^3}{B^4} \left(\frac{\Delta}{B} \ll 1 \right) \quad (20)$$

where $g_0 = \mu$, the infinitesimal theory shear modulus. Alternatively, for very large deformation conditions, Eqs. (15) and (9) become respectively

$$p = \frac{4H g_0}{\Delta} \quad (21)$$

$$\lambda = \frac{\pi \Delta}{2B} \left(\frac{\Delta}{b} \gg 1 \right)$$

From Eq. (20) we see that there is no linear range behavior, as is well known, while Eq. (21) shows that the neo-Hookean material exhibits a behavior such that the pressure approaches zero

Figure 5. Experimental pressure relaxation history, obtained with the setup shown in Fig. 3.

at very large deformations, also in accordance with expectation.

To evaluate the accuracy of this approximate analysis, we compare the pressure-displacement relation directly with the exact solution of the problem, first obtained by Adkins and Rivlin⁵ through numerical integration. We obtained the present exact-solution results by numerical integration using CRAY computers. The governing equations were developed by Yang and Feng.³ First, it should be noted that the exact solution does show the deformed shape to be nearly spherical in the deformation range $\Delta B \leq 3$, which is the range of interest here. However, the exact solution also shows that the meridional and circumferential stretch ratios are functions of position on the deformed shell. The present approximate method, assuming equivalent spherical inflation, has a uniform deformation over the entire surface. Obviously, this could not be corrected, since the edge support provides constraint against circumferential stretch along the perimeter. Thus the present approach should be viewed as providing an "average" deformation for the deformed shell, with λ given by Eq. (9) being the average. Figure 7 shows the stretch as a function of maximum displacement. If interest were in deformation as a function of position on the shell, then the present work provides little information. The interest here, however, centers upon the most accessible experimental observation, namely, the maximum displacement as a function of applied pressure. Since maximum displacement is an integrated effect of the deformation state, it is reasonable to expect useful results from the spherical deformation assumption.

Figure 6. Viscoelastic material properties g_0 and $g_1(t)$ for the data shown in Fig. 5.

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First, a point comparison will be made to show explicit numerical results. For the neo-Hookean material at a deformation level of $\Delta/B = 0.91$, the comparison is as follows:

$$\begin{aligned} \frac{pB}{H_0} &= 1.80 \text{ (present solution)} \\ &= 1.75 \text{ (exact solution)} \end{aligned} \quad (22)$$

Figure 8 shows a more complete comparison for the neo-Hookean material. Our solution, from Eq. (15), is seen to model the neo-Hookean

Figure 7. Stretch as a function of maximum displacement.

Figure 8. Displacement response to pressurization, obtained by two methods: the exact solution and our approximate solution. The latter models the behavior very well over the entire deformation range shown.

behavior very well over the entire deformation range shown. The difference between the approximate analytical solution and the exact solution is well within the range of typical experimental accuracy.

The present approach, based upon assumed spherical deformation, thus provides results which would be within the experimental accuracy of most test methods. The utility of the inflation of a flat disk relates to its simplicity for obtaining a biaxial stress state. The advantage of the present approach over that of the exact solution is that this approach leads to a closed-form analytical solution for the problem. In fact, the solution form is surprisingly simple considering the inherent nonlinear kinematics in the problem.

Financial Status

The actual cost for this project as of March 31 was \$105,000. The total budget is \$175,000. Building the biaxial test apparatus cost \$2,000 and required 0.4 FTE. We have requested a budget increase from \$175,000 to \$200,000.

Future Work

We plan to prepare specimens and begin testing to determine the effects of different aging times on material properties. Our emphasis will therefore be centered on data acquisition and analysis. We also plan to publish the theoretical work done in this project.

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Early Characterization of Graphite Composites by Fiber Testing

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Graphite composites are being increasingly used in load-bearing structures. Assessing the reliability of composites requires a large data base of information, and certifying their reliability requires a methodology to screen materials. The goal of our project is to meet these needs by developing a fundamental

understanding of the strength and life of a composite's constituent graphite fibers. In addition, we seek to predict long-term composite life from short-term fiber strength tests. We have completed the characterization of fiber strength by improved methods; life characterization work continues.

Introduction

The objective of this research is to develop a methodology which characterizes short-term strength and long-term life of graphite fibers for the purpose of quantifying and enhancing the reliability of fiber-reinforced composite weapon structures. We have found that such characterizations are vital for weapons work, but existing models of composites developed by the aerospace industry are inadequate. Because these composites will be used in the near future, we must use short-term data to predict long-term composite behavior.

The use of fiber-reinforced composites in load-bearing structures in weapons systems requires both the assessment and the certification of their structural reliability. The assessment of reliability requires a large data base of information for the statistical analysis of short-term *intrinsic strength* and long-term life of the composite. The certification of reliability requires a procedure to screen production materials for comparison with information contained in a previously accumulated data base, to assure similar statistical reliability properties.

The first requirement, an adequate data base, has been met for Kevlar-49/epoxy composite: a data base encompassing 10 years of life is available from NASA. The second requirement, an on-line production materials screening methodology, has not been developed. The importance of this second requirement can be seen in a recent alarming association made between short-life Kevlar vessels and certain substandard spools of constituent fibers.

For graphite/epoxy composites, neither a data base nor a screening methodology has been developed. No long-term life data base for reliability assurance exists, even though graphite

fibers have been selected both as a potential replacement in current weapons systems and for near-term future applications. The aerospace industry is not expected to provide a long-term life data base and a screening methodology for such high-performance graphite fibers. Furthermore, aerospace data are not directly applicable to weapons because fabrication methods and load histories in weapons applications differ significantly. This difference presents a research and development challenge for us: we must establish a characterization theory which will provide confident long-term life and reliability predictions based on short-term data. We are meeting this challenge through the mechanistic modeling of the failure process of constituent fibers. These models of individual fiber strength and life will help us to predict the strength and life of entire composites.

The mechanics of composite reliability are based on structural redundancy. For the same reason that a multistrand cable is stronger than a solid rod, composites derive their strength from the microstructural redundancy provided by a large number of minute fibers. It follows that the behavior of the composite (e.g., strength distribution) is the integrated sum of the individual fiber behaviors modified by the mechanics of redundant load sharing. Already, this is consistent with our observations in Kevlar composites, where the strength characteristic of a composite is manifested by fibers strength-tested at a lower load level, and the life of a composite is manifested in the fiber life over a shorter time. Research to establish a model which can quantitatively capture such a fiber-composite relationship will:

- Provide high resolution of the extreme lower tail of the distribution with a fewer number of samples.
- Provide an accelerated characterization of long-term composite behavior.

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- Distinguish between fiber properties and matrix properties, thus reducing the possibility of data-base obsolescence from changes made in matrix materials.

This research will contribute to the design of the composite structure and to the assessment of its reliability. It will help meet the need for a certification methodology by providing a means of screening fiber strength before fabrication. This method is a practical means of solving the difficult problem of certification because the large number of fibers (100 miles of fiber in a vessel) precludes the use of many conventional inspection techniques.

Contact with the Outside Community

The author conducted two seminars, *Fracture of Composites and Strength of Composites*, as a 1983-1984 Distinguished Lecturer at the NASA-Virginia Polytechnic Institute.

Technical Status

We started this project in November 1983. During this reporting period, we completed the work in single-fiber-filament characterization technology, and we thoroughly characterized two spools of graphite fiber. These two spools were then made into graphite-aluminum composites and characterized. The combined results show an unambiguous relationship between fiber properties and composite properties. We are also refining the bundle-strength test method. These achievements are discussed in detail below.

Fiber-Characterization Technology. We improved the technology for measuring fiber diameter. The quantitative measurement of diameter permits precise calculation of fiber stress. Current high-performance fibers have very small diameters, typically less than 10 μm . Mechanical-contacting measurement introduces potential damage and cannot provide the needed accuracy. We use laser diffraction to measure fiber diameter. A laser beam directed at the fiber filament produces a diffraction pattern of light and dark lines. We use the wavelength of the laser and the measured

distance between the diffraction nodes to determine, by Bragg's Law of diffraction, the fiber diameter to 0.01% accuracy. We completed a manually operated fiber-measurement instrument, and are contemplating a computer-automated instrument.

Results of Fiber Characterization of Two Graphite Spools. We selected two graphite spools of VSB64—a pitch-base graphite—and extracted filament samples at the beginning of the spools. Each sample was then made into graphite/aluminum composite wires. Then we took graphite filament samples from the end of the spools. This program allows us to assess the variation in strength characteristics within the spools, and to show the unambiguous relation between the graphite fiber and its composites. For data interpretation, we used the Weibull distribution for modeling the single-filament strength, on the physical grounds that single-filament strength is truly governed by the weakest-link-of-chain process.

In the two-parameter Weibull distribution, the probability of failure F is given by

$$F(\sigma) = 1 - \exp\left[-\left(\frac{\sigma}{\beta}\right)^\alpha\right],$$

where σ is the applied stress, β is the location parameter relating to the mean strength, and α is the shape parameter relating to the variability.

Filament-Strength Variability Within the Spool. Figure 1 shows the strength variability within the spools. The confidence contours of the Weibull parameters are calculated from the sample tested. Heuristic and analytical interpretations of the results are possible. From the two- and three-dimensional contours of the Weibull parameters in Fig. 1, we observe that the strength at the beginning of the spool, where $\beta = 20$, is slightly less than at the end of the spool, where $\beta = 22$. Less scatter is evident, however, at the beginning, where $\alpha = 5.2$, than at the end, where $\alpha = 4.7$. Since the graphite/aluminum composites are made in the middle of the spool, we are assured that the fibers in the composite are bracketed by these properties.

Comparison of Filament Strengths of Spools. Figure 2 compares the measurements of strength for two spools. It shows a

representation of the linearized cumulative distribution function of the Weibull distribution. We fitted the parameters to the model by the maximum-likelihood estimate method. From Fig. 2, we observed a good fit of the Weibull model to the data, i.e., a trend appeared to be linear in this transformed $\ln[-\ln(1-F)]$ coordinate. In addition, we noted that there is a

significant strength difference between these two spools. Spool 4245M, with $\beta = 20$, is stronger than spool 3083M, with $\beta = 14$. Both spools have approximately the same variability ($\alpha = 4.6$ vs 4.7).

We are fabricating and testing graphite/aluminum samples from these two spools. We intend to establish a quantitative

Figure 1. Two- and three-dimensional representations of strength variability of graphite filaments at (a) the beginning of a spool, and (b) the end of a spool. Such data on strength are necessary to assess and certify graphite composites used in load-bearing structures.

Materials Characterization and Behavior

relation between weak fibers and weak composites and between strong fibers and strong composites.

Bundle-Strength Test Refinement. The bundle-strength test is intended to make testing single-filament fibers routine. The bundle test of a 1000-fiber bundle may be interpreted as the simultaneous testing of 1000 single-fiber filaments in parallel. We have identified three experimental problems which introduced uncertainties in the data interpretation. These problems are friction between the filaments; the slack, or unequal, length of the filaments; and compliance of the adhesive between the bundle and the clamp.

The major cause of friction is the protective sizing (coatings) applied to the fiber during manufacture. We successfully removed most of the sizing by immersing the fiber in a solvent. Complete removal of the sizing, however, requires vapor extraction, which is impractical on a routine basis. We found that after

immersing the fiber in a liquid extraction solution and applying a lubricant with a volatile solvent carrier, we reduced the friction to an acceptable level.

We removed the slacks of the fibers within the bundle by washing the bundle within a tube, while regulating the fluid flow rate to avoid turbulence. The laminar flow effectively applied hydrodynamic friction uniformly on the fibers and thereby straightened out the slacks. We determined the effectiveness of the friction and slack removal by measuring bundle maximum strength, which turned out to be consistent with the Daniel-Coleman asymptotic prediction. The compliance of the bundle within the clamp has not yet been resolved.

Summary. We refined single-filament fiber testing by introducing fiber-diameter measurement using laser diffraction. Our experimental results and interpretation techniques identify strength characteristic (mean and scatter) variations within a given spool and

Figure 2. Comparison of two graphite spools in linearized Weibull probability plots.

between spools. We made important progress toward the use of bundle-strength measurement as a practical and expedient method of determining the strength of an exceedingly large number of single filaments.

Financial Status

Expenditures for this reporting period were \$106,700. This expenditure rate is 20% above the linear expenditure rate.

Future Work

We intend to resolve the clamp compliance problem and to refine the bundle-strength test methodology and data-interpretation techniques. We will also design and construct a bundle life tester so that we can, in effect, measure an exceedingly large number of single-filament lives in parallel.

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Solid Geometric Modeling

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Weapons Engineering Division
Mechanical Engineering Department

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Computation Department

Solid geometric modeling has great advantages over existing edge and surface modeling. It is the basis of the next generation of computer-aided design (CAD) systems for mechanical engineering. Though many applications exist for solid geometric modeling at the Laboratory, no commercial systems meet all of our needs. This project addresses the Laboratory's requirement for advanced solid-modeling technology, and lays the foundation for the eventual widespread use of that technology at LLNL.

Earlier in this project, we overcame many deficiencies of a developmental solid modeler called TIPS-1. Now, we report the following advances:

- We developed a new ray-trace algorithm for TIPS-1 which performs the calculations for high-resolution pictures five times faster than before. This new algorithm, which is analytical in approach, sets the stage for adaptive ray tracing (calculating more detail around sharp edges) and for generating simulated radiographs.

- We programmed, tested, and verified our three-dimensional curves which degenerate to Wilson-Fowler splines when projected to two

dimensions. This is the first such implementation of three-dimensional curves anywhere. It enables us to model parts containing complicated wiring and cabling, and to insert grooves on complex Wilson-Fowler surfaces.

- We tested our version of TIPS-1 on more than 50 programmatic parts. It completely modeled about 95% of them, compared with only 40% for the original version. We also (1) modified the TIPS-1 data structure to allow the addition of material properties such as density and color, and (2) modified a Monte Carlo algorithm used in the generation of mass properties to give true randomness and variable precision.

- We selected ten objects as benchmarks for use in standard tests of our work and for tracking the capabilities of commercial solid modelers.

- We further tested our new meshing and variable-grid algorithms in an attempt to solve the "missing chunk" problem.

In the rest of FY84, we will test and improve these capabilities further, and continue to optimize solid-modeling algorithms.

Background

Solid geometric modeling, often simply called solid modeling, is the basis for the next generation of computer-aided design (CAD) systems for mechanical engineering. This highly visible technology offers significant new capabilities over existing edge and surface modeling approaches. Solid modeling allows a computer to accurately and unambiguously depict the geometry and topology of three-dimensional objects. Because of the potential value of solid modeling, a great deal of research and development is currently being done in it around the world.

The fundamental idea behind solid modeling is that *three-dimensional* volumes in space are analytically described so that the computer can determine the inside, outside, and surface of an object. The capability to determine the exact extents of an object is vitally important for doing volume-related calculations (interference checking, mass properties, radiograph simulation, etc.), and for calculations involving the surface of that object (tolerance, inspection, group technology, hidden-surface images, etc.)

In contrast, most present-day turnkey CAD systems are based on "wire-frame" and surface-modeling technologies. These systems allow users to model their objects by assembling lines,

Computer-Aided Engineering

arcs, splines, and other similar geometric entities to represent the edges of their object. Some of the advanced systems allow surfaces to be added for more complex constructions. Although such a collection of geometric entities may to a human imply a volume, to a computer it is merely a collection of geometric entities. More information, such as is available in a good solid modeler, is needed to completely describe a part.

Objectives. The goal of our research is to advance the state of the art of solid modeling and lay the foundation for its eventual widespread use at LLNL. Specifically, our objectives are in the following areas:

1. *Algorithm Research.* We seek to (1) understand the underlying concepts and the limitations of existing solid modelers, and (2) investigate and develop algorithms and approaches to overcome these limitations in areas important to Laboratory programs.

2. *Modeler Enhancement.* Our goal is to overcome the deficiencies of experimental solid modelers, specifically TIPS-1 and PADL-2, by adding geometric constructs, modifying data representation, and enhancing graphical output as required at the Laboratory.

3. *Benchmark Development.* Our goal is to develop a set of solid objects and assemblies which can be used as a standard test for our own work and for tracking the ever-improving capabilities of commercial solid modelers.

In pursuing these objectives, we have addressed questions of great local concern about current solid-modeling approaches. (1) Are spline surfaces compatible with constructive solid-geometry modelers or are they better handled by boundary-representation modelers? (2) Can Wilson-Fowler splines be generalized to three dimensions, and if so, what are their limitations? (3) Can the generation of high-quality images by a general computer-based solid modeler be made compatible with the requirement for fast interactivity?

Relevance to Laboratory Programs. Though many applications exist for solid modeling at the Laboratory, no commercially available systems meet all of our needs. This project addresses the Laboratory's requirement to advance solid-modeling technology to meet general and specific programmatic needs. The results of this research will be applicable to all programs.

Solid modeling is a fundamentally different approach to engineering modeling, and will have an enormous impact on the design/manufacturing cycle at the Laboratory and throughout the nuclear weapons complex. Improved models of our designs will significantly increase accuracy and productivity, most probably in the areas of mass-property calculation, interference checking, automated tool path generation, tolerance analysis, technical-illustration generation, part classification, process planning, and finite element meshing.

Solid modelers have many benefits. For example, they help prevent the creation of nonrealizable or ambiguous parts. In addition, the high-quality graphics of some solid modelers clarify many details of parts, including surface inflections and design flaws, that might otherwise be misunderstood. Only with the benefit of state-of-the-art solid-modeling tools will our engineers be able to compete with and communicate with outside engineering facilities five and ten years from now.

Commercial Solid Modelers. Although a number of solid modelers are marketed in this country (Euclid, Medusa, Romulus, Synthavision, etc.), they all suffer from two problems: they do not support all the capabilities required by the Laboratory, and their source codes are considered proprietary and are unavailable for experimentation or enhancement. One exception is Romulus, which has a suggested source-code price of \$1 million. Our own research will help us evaluate progress in the commercial field and strengthen our requests of vendors for the specific features we need. The standard benchmark geometries we prepare should be very helpful in evaluating commercial solid modelers.

The Laboratory's Solid Modelers. Through the Laboratory's involvement with the Production Automation Project at the University of Rochester, and the Geometric Modeling Project of CAM-1, we have acquired two experimental (or developmental) solid-modeling codes: PADL-2 and TIPS-1, respectively. PADL-2 runs on a DEC VAX computer and is being brought up on a CRAY 1. TIPS-1 runs on a CRAY 1. Both PADL-2 and TIPS-1 are the results of major long-term efforts. Each represents scores of FTE-years of research and development.

TIPS-1 and PADL-2 take fundamentally different approaches to solid modeling. The TIPS-1 system uses half-spaces to define volumes and develops a penalty function to describe the object. This penalty function has a value which approaches zero at the surface and inside an object. The PADL-2 system uses primitive elements such as blocks, cones, spheres, and cylinders to develop a large tree-like data structure, from which it also creates a complete, evaluated list of geometric and topological entities describing the object. Although PADL-2 is an extremely powerful and robust code, its approach limits its geometric coverage by demanding that all surface intersections be evaluated. In TIPS-1 these intersections are implied. Because of our desire to add entities with very complex surfaces, we selected TIPS-1 as the starting point for this research.

We made two discoveries in the course of the research that caused us to change direction. First, we found that the meshing algorithm used in TIPS-1 does not work adequately with the thin or tapered parts commonly modeled at LLNL. Second, we discovered that some of our goals would be much easier to reach by using PADL-2 rather than TIPS-1. Accordingly, we added to our list of tasks: (1) substituting a new meshing algorithm into TIPS-1, and (2) bringing up PADL-2 on the CRAY 1 computers.

Contact with the Engineering Community

Our contacts included the following:

- In October 1983 R. Weisinger gave a talk to about 200 people at the Department of Energy Computer-Aided Engineering Symposium at the Laboratory.
- We gave a Laboratory-wide presentation in January 1984. About 20 of the 60 people who attended stayed afterward for a valuable critique session.
- We held six formal meetings with people in L Division and in the Mechanical Engineering Department's Nuclear Explosives Engineering Division who are interested in using or working with us on our solid modeling work.
- At the request of B Division, R. Weisinger wrote a routine which makes use of the Wilson-Fowler spline.
- In November 1983, we hosted an Engineering Research seminar entitled

"Multidimensional Graphics," and invited Dr. Alfred Inselberg, of the IBM Science Center in Los Angeles and Professor of Computing Sciences at UCLA, to speak. About 40 Laboratory people attended, and a great deal of interest was generated by Dr. Inselberg's unique approach to understanding the interrelationship of dozens of simultaneous dependent variables by looking at a single plot.

- M. Kong and K. Spencer of the Mechanical Engineering Department continued to work together on applying our CRAY 1 version of TIPS-1 to actual parts being designed in other programs.

Technical Status

1. Algorithm Research

The New Analytical Ray-Trace Algorithm.

In an effort to decrease the time required to produce a raster image, we sought to replace the ray-trace algorithm in our version of TIPS-1 with a faster one. The algorithm we initially implemented, before Engineering Research funding began, was a straightforward approach which stepped in a uniform fashion along the line of sight (ray) from an observer's point of view toward a tiny square or picture element (pixel) on the image plane, and determined at each step whether the surface of the object had yet been penetrated. The stepping process required a lot of calculation. This whole process of determining the intersection of a ray with the object was repeated for each pixel in the final image—128 × 128 pixels for quick-look video quality, and 1024 × 1024 or 2048 × 2048 pixels for photographic quality.

Producing images with spline primitives was particularly slow. Our initial approach to handling splines was to divide space into tiny cubes or cells, and for each cell, to keep a list of all spline primitives which contained that cell. This required evaluating the list of spline primitives each time a cell was accessed. An attempt to speed the ray-tracing algorithm was made by storing a list of pre-evaluated spline segments rather than the unevaluated spline primitives for each cell. As expected, it took longer to generate the lists with this approach, but totally unexpectedly, it also took slightly longer to do the ray tracing. After unsuccessfully trying to speed up this process, we abandoned it.

In our search for a better ray-tracing approach, we decided to try calculating the exact point of intersection between a ray and the surface of an object by using the analytical description of each part entity. There was a vast amount of mathematical complexity involved in implementing this new algorithm, but our timings showed an impressive factor-of-5 growth in speed over the stepping algorithms. We chose to "spend" some of the increase in speed for greater resolution of our video image. The new resolution is 256×256 , up from 128×128 pixels or raster units. For video pictures, our improvements mean a four-fold increase in image resolution and, still, a slight decrease in the time required to generate the image. We implemented analytical intersections for 16 of our TIPS-1 primitives, including our Wilson-Fowler spline primitives. Still to be implemented are the two-dimensional TUBES and the REVOLVE features.

The new analytical ray-trace algorithm appears to have several benefits. The first benefit was the replacement of the stepping algorithm and the subsequent five-fold increase in speed. A benefit in picture quality is forthcoming. With the new ability to calculate ray-surface intersections, we can also implicitly determine the edges of surfaces. With the edges known, it is possible to create an adaptive ray-trace algorithm which does not cast a ray to every pixel on some square grid, but casts them judiciously, with many rays near edges and surface intersections where detail is important, and fewer rays on flat or slowly changing areas. Another benefit of the new ray-trace algorithm is that it sets the stage for more efficient calculation of simulated radiographs.

Meshing Algorithms/Variable Grid Size.

We tested work done in the spring and summer of 1983 which attempted to avoid "missing" (losing for purposes of calculation and display) small pieces or chunks of very thin entities. To fix the problem, we developed two new algorithms, described in earlier reports:^{1,2} (1) in the spring and summer of 1983 we created a new meshing algorithm in which we forced "on" the bits in memory indicating the presence of material in a given three-dimensional cell—for entities parallel to the three primary axes, and (2) in the fall of 1983 we added the capability to vary the grid size independently along any of the three primary axes.

In our tests, all failure cases which led to the development of the two new algorithms worked, but three actual parts, admittedly complicated or unusual in shape, still exhibited the "missing chunk" problem. Most perplexing is our observation that decreasing the grid size (making a finer mesh) along a principal axis seems to make no difference in finding these missing chunks.

Variable-Precision Monte Carlo. We added two new capabilities to the Monte Carlo or random number algorithm used in determining mass properties. First, we added true randomness by obtaining a random seed or starting value for the random number generator, as opposed to using a table of pseudorandom numbers. Second, we added variable precision to the Monte Carlo algorithm in an effort to save computer time when accuracy is not critical and, ultimately, to get very high accuracy when it is crucial.

PADL-2 on the CRAY 1. J. Kalibjian, a student employee from the University of California, Berkeley, made an effort during Christmas vacation to get the PADL-2 solid modeler running on our CRAY 1. He made some progress, but didn't get the modeler fully running.

Maintenance. Maintenance became more of a burden during this reporting period. We had to modify our version of TIPS-1 twice to accommodate changes in CRAY 1 (LTSS) systems software. Changes in the Computation Department-maintained routines FORTLIB and LDR forced us to change large portions of code. And a change in the defaults to Computation's GRAFLIB convinced us to rely no longer on default parameters in codes maintained by others; now we specify all parameter values explicitly.

2. Modeler Enhancement

Three-Dimensional Space Curves. We stated in our last progress report¹ that we were close to implementing three-dimensional curves which degenerate to Wilson-Fowler splines when projected to two dimensions. That implementation, though not yet incorporated into TIPS-1, is now complete and tested (Fig. 1). We believe that this is the first and only working model of Wilson-Fowler-compatible three-dimensional curves; it is important to the kinds of geometries modeled at LLNL.

In the process of this implementation, R. Weisinger completely rewrote the equations found in a paper proposing the generalization of Wilson-Fowler splines to three dimensions. Informal written comments from a Laboratory colleague about the mathematical basis of Weisinger's work are favorable and supportive. The next step is for him to add these curves as a new entity to TIPS-1.

Assemblies. The T1LIST data array in TIPS-1, which contains attributes of the parts being modeled, has been modified to allow material properties such as color, density, etc. to be handled. This sets the stage for TIPS-1 to model assemblies of parts, a facility crucial to its continued use on LLNL projects. The next steps are to implement a hierarchical data structure, modify the user interface so material properties can be easily specified, and change the mass-properties calculations so assemblies of parts of different densities can be calculated automatically.

User Interface. We modified the user interface to TIPS-1 to allow easy specification of resolution for high-quality pictures. Three levels of resolution for the Dicomex D-48 are allowed: 512×512 , 1024×1024 , and 2048×2048 .

Wilson-Fowler Splines. R. Weisinger wrote a routine which quickly determines, for Wilson-Fowler-defined surfaces of revolution or projection, whether a point in space is inside or outside the object. This small project was requested by B Division as a result of interest generated by our previous accomplishments.

Programmatic Involvement and Benchmark Development

M. Kong and K. Spencer of the Mechanical Engineering Department continued to work together on applying our CRAY 1 version of TIPS-1 to actual parts being designed in other programs. Marv tried to find weaknesses in TIPS-1 by testing it on new and complicated, but real, geometries. Spencer, supported by weapons program funding, continued to model parts of interest to that program. The following items are of interest regarding this effort:

- Spencer came up to speed quickly on TIPS-1 and did not tire of using it during the 45 full days she spent on it in the six-month period. After weeks of full-time TIPS-1 use, Spencer noticed a reduction in her board skills when she returned to pencil and paper, and vice versa.

Figure 1. Views of a three-dimensional curve which degenerates to a Wilson-Fowler spline curve when projected to two dimensions. This is the first implementation of three-dimensional curves with this property.

- Most of Spencer's time was spent not in modeling a part but in modifying the model to keep up with changes in design, verifying the revised model, selecting an appropriate point of view for image generation, and finding "work-arounds" for bugs she discovered in TIPS-1. Roughly 60% of Spencer's time was spent on changes; over 75% of the parts underwent changes after initial design.

- Of the approximately 50 parts modeled, mass properties from TIPS-1 agreed with known or otherwise calculated mass properties to within 1% on all but three parts. We are not yet certain about the cause of the disparities.

- Our current version of TIPS-1 successfully modeled about 95% of the programmatic parts we tested it on. Prior to our modifications, it would only have had a 40% capability. Two examples of parts that appear to be beyond the capability of our modified TIPS-1 are: (1) an object of revolution with a diameter-to-thickness ratio on the order of 10,000:1, and (2) a Wilson-Fowler-spline-defined surface of revolution with a groove having an unusual and nonuniform cross-section. We also discovered that TIPS-1 cannot handle rotational offsets.

- Among the images we generated, Spencer made one multiple-part image of the type used in exploded views or layouts (Fig. 2).

- The typical CRAY 1 time to generate a digital representation of a part is roughly 1 to

3 min. The time to compute mass properties is about 1 to 2 min. It takes about 3 to 5 min per part to generate a 1024 x 1024 picture.

- We found and fixed several indigenous TIPS-1 bugs, including problems with the REVOLVE command, offset values for center-of-gravity calculations, and the ROTATE command.

- M. Kong selected a set of ten parts for use as a standard benchmark test to monitor our progress and evaluate commercial solid-modeling software.

Future Work

The tasks that we expect to accomplish are listed below by person. As expected in a research effort, the tasks may expand or change along the way.

- J. Hersh, a student from the University of Rochester, will be with us for a second summer. Providing his clearance arrives, he will help bring the latest version of PADL-2 up on a CRAY 1 computer and will write a device driver linking the PADL-2 graphics with our high-quality Dicomex color-film recorder.

- J. Kalibjian is joining the lab full time in July and will work with Jay. He has brought an earlier version of PADL-2 up on a VAX computer. He will experiment with PADL-2 and look into generating simulated radiographs using that code.

- M. Kong, with us half-time from Engineering Sciences Division, plans to continue testing TIPS-1 and generate a reliable set of benchmark objects. He is also interested in pursuing assemblies and radiographs on TIPS-1.

- G. Laguna will work on enhancing the visual output of TIPS-1, and will experiment with ray-trace algorithms, trying to find those most appropriate for solid modeling. He is also interested in investigating rapid anti-aliasing techniques and adaptive ray-trace approaches.

- L. Taylor will continue to offer overall technical direction and support to the project.

- D. L. Vickers will continue to administer the project and write the reports.

- R. Weisinger plans to investigate the addition of general three-dimensional space

Figure 2. Exploded view of a sphere and concentric hollow hemispheres, produced with the TIPS-1 solid modeler.

curves to TIPS-1, and speed up and enhance general TIPS-1 performance by experimenting with new algorithms, data structures, and approaches.

Financial Status

Our Engineering Research allocation for FY84 was \$175,000, with \$150,000 of that earmarked for manpower and expenses, and \$25,000 for computer time. As of the end of March 1984 we spent \$59,000 for manpower and expenses and \$11,000 for computer time. We were fortunate to find G. Laguna, who plans to do a Ph.D. dissertation in the area of graphical ray-trace algorithms and who is interested in joining our Engineering Research effort. Along with the planned summer-of-1984 return of J. Hersh and J. Kalibjian, G. Laguna

brings our estimated annual manpower and expenses total to about \$178,000; the \$28,000 increase over the allocated amount has been resolved with the Mechanical Engineering Department. Computer use is on target for the allocated \$25,000.

Our FTE allotment for FY84 was 1.6, and by midyear we had utilized 0.65 FTE. The estimated annual total is 1.7 FTE, which is close to our initial allotment. Again, appropriate arrangements have been made for this slight estimated increase over allocation.

1. *Mechanical Engineering Research Program Quarterly Progress Report, April-June 1983*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19323-83-2 (1983).
2. *Mechanical Engineering Research Program Annual Report FY 1983*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19323-84-1 (1984).

Multivariable Systems Analysis and Design

K. D. Pimentel

Nuclear Test Engineering Division

Laboratory programs often use complex multivariable systems, such as mechanical and electrical systems and their controls. We provide tools with which programs can design advanced structures and controls, and we also use the tools in applications in the programs. Our project is a joint effort with the Electronics Engineering Department.

In this reporting period, we developed a design for the x-ray laser rod pointing system. The work was done using DELIGHT, a

computer-aided design package which we helped research and develop. We also designed an active control system for controlling vibrations in a flexible beam in directed-energy applications. We are starting to pursue a new research direction, large-scale systems, an area of great interest to weapon developers. Contact continues with many programs. Our goal is to establish controls as a viable technical area at the Laboratory.

Introduction

We are continuing with the research and development of a computer-aided control-system design package to meet the need for advanced control systems in Laboratory programs. This research is part of a joint project in the Engineering Research Program of the Electronics Engineering (EE) Department, with C. Herget as principal investigator in EE. From the beginning of the joint project 18 months ago, most of the research and development of computer methods was done in EE, while most of the work on applications was done in the Mechanical Engineering (ME) Department.

Our objectives are the following. (1) To research, develop, and implement advanced methods of analyzing and designing multivariable systems on computers at Laboratory. (2) To begin research in large-scale systems and in combined structures-and-controls problems. (3) To have our research guided by applications in Laboratory programs. (4) To have the applications of our results lead to funding from programs at the Laboratory and outside agencies. (5) To build a cooperative capability in systems and control in the ME and EE departments.

Background

From the beginning, we pursued several lines of work in control systems. In research, we are pursuing optimization-based design of

engineering systems together with research in the control of large-scale systems. We are developing computer-aided methods to facilitate that research, which includes fundamental work on the computer/human interface for control systems, based on our applications experience. We are implementing these methods as extensions of DELIGHT, a computer-aided design package which originated at the University of California (UC), Berkeley, and are beginning a next-generation package which will build on our experience of the past 18 months.

Finally, perhaps the most important area we pursue is applications. From the first, we demanded that applications guide the direction of our research so that useful results would come from our work. Using our ME Engineering Research funding as seed money, we obtained substantial programmatic support this fiscal year, which was one of our goals.

The Research Team

This project is part of a cooperative effort with staff from the EE Department at LLNL and consultants to LLNL. This fiscal year we minimized our work with UC Berkeley on DELIGHT, and focused on work we do at Livermore. We established contact with staff in EE's Nuclear Energy Systems Division, and with W Division and R Program in the applications we are carrying out.

We had useful contact with consultants to the Laboratory. Professor A. Laub at UC Santa Barbara is providing guidance and

assistance in producing state-of-the-art numerical methods for control-system design. Professor D. Siljak at the University of Santa Clara is assisting in our early work in large-scale-systems control. Professor R. Taylor of UC Berkeley helped us in looking at the combined structures-and-control problem.

Technical Status

This section reviews our progress in the tasks given in the FY84 Engineering Research Proposal for this project.

Simulation Module. Two simulation modules were developed by C. Herget and D. Gavel in EE to use in predicting performance of control systems with DELIGHT. There are deficiencies in running the simulators for large, complicated models; more efficient integration methods will be developed in the future.

Applications. This fiscal year we made the first programmatic applications of DELIGHT. The use of DELIGHT in actual control-system analyses and designs is guiding our future research and development. Because initiating and coordinating the applications has been my major responsibility, I will focus on applications in this report. In the case studies detailed below, C. Herget, D. Gavel, and Engineering Research's H. H. Woo provided much of the analytical support.

R Program. We have worked with R Program since January on the analysis and design of x-ray laser rod pointing systems. I will describe two case studies.

a. **Three-Mass System Study.** D. Gavel used the DELIGHT system to analyze the dynamics and to design control systems for a simple three-mass system for R Program.¹ I will briefly describe a case study as it relates to our results in this multivariable systems research. Figure 1 shows the three-mass system, which represents a weapon system in an inertial reference frame. It is desired that masses l_1 and l_2 accurately point at separate targets. Our study assessed the performance of large-scale systems concepts for decentralized control in such an application. In this case, we first developed the equations of motion for the three masses and

two connecting springs using Lagrange's equations. These complicated, highly nonlinear ordinary differential equations were then linearized into the following set of equations:

$$\dot{x} = A \cdot x + B \cdot u \quad x(0) = x_0 \quad (1)$$

$$y = C \cdot x \quad (2)$$

Equation (1) is the "state equation" for the system, and Eq. (2) is the "output equation," typical formulations from modern control theory. The state vector x , dynamic matrix A , and input matrix B are of the form:

$$\begin{aligned} \dot{x} &= A \cdot x \\ \begin{bmatrix} \dot{\theta}_1 \\ \dot{\omega}_1 \\ \dot{\theta}_2 \\ \dot{\omega}_2 \\ \dot{\theta}_3 \\ \dot{\omega}_3 \end{bmatrix} &= \begin{bmatrix} 0 & * & 0 & 0 & 0 & 0 \\ * & 0 & * & 0 & 0 & 0 \\ 0 & 0 & 0 & * & 0 & 0 \\ 0 & 0 & * & 0 & * & 0 \\ 0 & 0 & 0 & 0 & 0 & * \\ 0 & 0 & * & 0 & * & 0 \end{bmatrix} \begin{bmatrix} \theta_1 \\ \omega_1 \\ \theta_2 \\ \omega_2 \\ \theta_3 \\ \omega_3 \end{bmatrix} \\ &+ B \cdot u(t) \\ &+ \begin{bmatrix} 0 & 0 & 0 \\ * & 0 & 0 \\ 0 & 0 & 0 \\ 0 & * & 0 \\ 0 & 0 & 0 \\ 0 & 0 & * \end{bmatrix} \begin{bmatrix} \tau_1(t) \\ \tau_2(t) \\ \tau_3(t) \end{bmatrix} \end{aligned} \quad (3)$$

Here, the state vector is made up of the angular positions and velocities. The first equation, for $\dot{\theta}_1$, says that the rate of change $\dot{\theta}_1 = \omega_1$; this is merely the definition of the angular velocity. The second equation, for $\dot{\omega}_1$, is just Newton's Second Law for the angular acceleration for mass l_1 ; the rate of change of the angle of mass l_1 is equal to the spring constant for K_{12} times the relative displacement in the spring $(\theta_1 - \theta_2)$, plus the input torque on the first mass, $\tau_1(t)$. The other four equations are similar for masses l_2 and l_3 .

The important aspect of the form of the dynamic matrix A is that it is almost block diagonal; in this case, there is very little coupling among the three masses. In particular, there is very little coupling between masses l_1 and l_3 . This fact suggests approaching the control

system design with decentralized control methods.² For the control-system design, D. Gavel formulated the Linear Quadratic Regulator (LQR) using full state feedback.³ Figure 2 shows this regulator.

In the LQR formulation, the state $x(t)$ is used with the "optimal controller" matrix K_{opt} to form a linear feedback control law. This optimal controller matrix is a constant matrix, given by:

$$K_{opt} = -P^{-1} \cdot B^T \cdot R_{ss} \quad (4)$$

where R_{ss} is the steady-state solution to the matrix Riccati equation

$$\dot{P} = R \cdot B \cdot P^{-1} \cdot B^T \cdot R - R \cdot A - A^T \cdot R - C^T \cdot Q \cdot C \quad (5)$$

where the P and Q matrices are used in the design process.

Figure 1. Schematic of the three-mass system used in our case study of an x-ray laser rod-pointing system. The study investigated decentralized control-system design for this application. Masses I_1 , I_2 , and I_3 are acted upon by torques $\tau_1(t)$, $\tau_2(t)$, and $\tau_3(t)$, respectively. It is required that masses I_1 and I_3 point at separate targets. We investigated various control laws using the three angular positions and velocities as feedback data.

This Riccati equation has a constant solution as time approaches infinity; that solution is given to the reduced Riccati equation, where the left-hand side of Eq. (5) is set equal to zero. We used the new numerical software built into the DELIGHT package provided us by Professor A. Laub to solve for R_{ss} .^{4,5} With R_{ss} , the optimal controller matrix K_{opt} is used to form the optimal state feedback from

$$u_{opt}(t) = -K_{opt} \cdot x(t) \quad (6)$$

This completes the feedback loop in the block diagram in Fig. 2.

The control equation using this optimal controller matrix has the form:

$$u_{opt}(t) = -K_{opt} \cdot x(t) \quad (7)$$

$$\begin{bmatrix} \tau_1(t) \\ \tau_2(t) \\ \tau_3(t) \end{bmatrix} = \begin{bmatrix} * & * & * & * & * & * \\ * & * & * & * & * & * \\ * & * & * & * & * & * \end{bmatrix} \cdot \begin{bmatrix} \theta_1 \\ \omega_1 \\ \theta_2 \\ \omega_2 \\ \theta_3 \\ \omega_3 \end{bmatrix}$$

For full state feedback, the optimal controller matrix is full as shown, so that, for example, the optimal input torque to mass I_1 given by $\tau_1(t)$ is a function of all six state variables.

The block-diagonal form of the A matrix in Eq. (3) suggested trying decentralized control instead of full state feedback. First, we tried using the same K_{opt} control law but with isolation of the measurements of mass I_3 from the input to mass I_1 , and the measurements of mass I_1 from the input to mass I_3 .

Figure 2. Vector block diagram for a state feedback control law using the Linear Quadratic Regulator. The Regulator was developed for the x-ray laser rod system analysis shown in Fig. 1.

This Level 1 decentralization had a suboptimal controller matrix of the form:

$$K_{\text{subopt}} = \begin{bmatrix} * & * & * & * & \boxed{0} & \boxed{0} \\ * & * & * & * & * & * \\ \boxed{0} & \boxed{0} & * & * & * & * \end{bmatrix} \quad (8)$$

The next level of decentralization was to say that each mass was isolated from measurements of the other masses; that is, the input to mass I_1 was determined only from measurements on mass I_1 , and similarly for the other two masses. The suboptimal controller matrix for this fully decentralized case is of the form:

$$K_{\text{subopt}} = \begin{bmatrix} * & * & \boxed{0} & \boxed{0} & \boxed{0} & \boxed{0} \\ \boxed{0} & \boxed{0} & * & * & \boxed{0} & \boxed{0} \\ \boxed{0} & \boxed{0} & \boxed{0} & \boxed{0} & * & * \end{bmatrix} \quad (9)$$

The suboptimal control laws in Eqs. (8) and (9) were used in Eq. (6); we used this input in the full feedback system in Fig. 2, and simulated the equations for the six states [Eq. (1)] using the advanced simulation software package built into DELIGHT, based on A. Hindmarsh's LSODE package.⁶ Figure 3 shows the results in the DELIGHT time response graphs. The implication here is that decentralized control for such a three-mass system works adequately, and that full state feedback is unnecessary. This has important implications for applications of results like these in real weapons systems.

This work produced results related to our goals on many levels. First, doing this example demonstrated the power of an integrated analysis and design package like DELIGHT for programmatic applications. The interactive nature of the language, together with the control-systems-specific software tools we are adding to DELIGHT, make it possible to develop the decentralized control-system designs for this problem far faster than any other way known to us. This is a real benefit in control-system design for programs around the Laboratory.

Second, the specific software packages to solve the reduced Riccati equation and simulate the state equation's responses were implemented as part of this research at LLNL, and have made the power of DELIGHT much better for our design problems. Examples like

these show us the shortcomings of the existing DELIGHT package and guide the direction of our research. We are investigating easier ways to do LQR design because the traditional cut-and-try method is laborious. Finally, applications like this are getting us funding and support from the programs.

b. Active Control of a Flexible Beam.

H. H. Woo and D. Gavel did an analysis and design of an active control system for controlling vibrations in a flexible beam. The work was part of a pointing study for directed-energy weapon applications.⁷ A controller had to be designed to damp out vibrations in a flexible beam caused by motions resulting from tracking a moving target.

Figure 4 shows a schematic of the system. We developed a mathematical model for the Euler beam and expressed it in state-space form, similar to Eqs. (1) and (2) in the previous example. We implemented those equations with the LSODE package in DELIGHT. In this example, measurements were assumed to be available down the length of the beam that would provide data to a Kalman filter or Luenberger observer which would produce estimates of the full state for the controller. The LQR approach was used in this example. Figure 5 shows the open-loop and closed-loop poles calculated with the EISPACK eigensystem software integrated into DELIGHT.

The state-space model for the beam was truncated at the third normal mode. The first three mode shapes are shown from the DELIGHT graphs in Fig. 6. While DELIGHT is most often used for lumped-parameter control-system design, the power of its software and language became evident in this application. The mode shapes, being continuous functions of space, not time, were plotted in DELIGHT by developing a macro for the shape of the mode as a function of the modal parameters. In this way, once the macro was built, each mode could be studied through typing one simple macro call statement. The performance of the LQR active control system design was investigated by applying a bang-bang step torque to the feedback system, and simulating the responses of the individual normal modes and of the overall beam with time. The open-loop response of the vibratory beam, and the closed-loop response with the LQR control are shown in Fig. 6 for just the first mode of the

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system. The active control approach chosen here worked well, whereas without control, vibration was excessive.

The results that bear upon this project include the following. Doing this case study opened channels of communication between structures analysts in ME and control engineers in ME and EE; this bridge will be important in future directed-energy weapons work. The case study highlighted limitations in existing methods

of computer analysis and design of structures and controls. As a result of this work, we are developing ways to integrate structural analysis and control-system design methods so that engineering departments can respond in a timely way to needs for structures and control design.

Four-Channel Shaker. We have not actively worked on this control-system design project because of manpower and scheduling changes in W Program and a lack of manpower

Figure 3. Angular responses of each mass in the three-mass system to initial displacement of $\theta_1(0) = 0.001$ rad, for four different feedback control conditions. Top row, open-loop response with no feedback control; note how oscillation is transferred from mass I_1 through mass I_2 to mass I_3 . The second row shows good response for full state feedback control using the Linear Quadratic Regulator. The third row shows Level 1 decentralization; response is still good. The bottom row shows Level 2 or full decentralization; this still yields an acceptable response. (Graphs adapted from Ref. 1.)

on our side. There may be an opportunity to do modal analysis of the shaker itself that could lead to other controls work in the next fiscal year; we have no further plans for this project this year.

Cable Downhole System. Recent contact with Nuclear Testing staff indicates a continuing interest in modeling the Cable Downhole System to test various operating scenarios and the adequacy of the installed control-system design. We are not pursuing this further because of a lack of manpower.

Other Applications. We are in contact with several programs that may need controls work in the future, including the Corsair and Rockfish programs and the filament winding machine and Ultrasonics Test Bed projects. We do not have the manpower to take on more projects. The Laser Isotope Separation Program contacted us to do the analysis and design of the temperature control system for the uranium extractor chamber. C. Herget is going ahead with this project, but I do not have any manpower to devote to it this fiscal year.

Computer/Human Interface. D. Gavel did most of the day-to-day development work on the interfaces for DELIGHT as applications showed what had to be done to make the package easier to use. This work will continue.

VAX/CRAY Link. We did not have enough support this fiscal year to continue this development task. The Engineering Research midyear review of this project found that it was too development-based, lacking the research focus required to fall within the scope of

Figure 4. System used in our pointing study for directed-energy weapon applications. An Euler beam free at the left end is hinged with a rotary spring at the other. Measurements are made at various locations down the length of the beam in the x direction of the beam displacement $y(x)$, in order to provide feedback information to the torquer motor that produces the control torque $M(t)$.

Engineering Research. Charles Herget is proposing the use of EE Thrust Area development funds for FY85 to continue this needed work to make DELIGHT accommodate large-scale systems problems.

Structures and Control. There was insufficient support this fiscal year to do this task. Independent funding for research and development in the Controls/Structures Interaction area was obtained from the ME Department. No further results on this task will be reported here.

Transfer Functions. Staff from ME's Materials Fabrication Division (MFD) and EE's Nuclear Energy Systems Division (NESD) approached us with the need to generate transfer functions for machine-tool structures of interest to the Precision Engineering Program. Transfer functions were needed for designing electronic control systems to control the motions of machine-tool slides, motors, etc. J. Weaver and R. Murray from Nuclear Test Engineering Division got the requirements and did the research and development of a module for calculating transfer functions. The module produces frequency-domain transfer functions between two arbitrary points on a structure, in any spatial direction. It works from data taken from a test of an actual structure or from synthetic data generated by a finite-element structural model. Thus it is useful for many

Figure 5. Calculation of the open-loop poles of the three-mode normal-mode beam model (Fig. 4). The results show that all the poles lie on the $j\omega$ axis; the open-loop response will be completely oscillatory. The closed-loop poles using LQR design show a good pole pattern, with satisfactory damping ratios for all flexible modes. Note that there is still a pair of poles very near the origin that account for the rigid-body mode.

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phases of machine-tool design and development. This small task gained us visibility and credibility in MFD and NESD, and will provide a useful tool to the Precision Engineering Program.

Model Order Reduction. Model order reduction is one of the many techniques being explored for large-scale systems control. Large-scale systems are the principal area of research

Figure 6. First three mode shapes of the state-space model for the beam (Fig. 4.) (a) Torque motor input torque $M(t)$ was a bang-bang shape for this case. (b) The open-loop response of the first mode shows continuing, unacceptable vibration. (c) The closed-loop response of the first mode with the LQR design shows good tracking of the torque and excellent vibration suppression.

we will work on for the rest of this fiscal year. We will begin work with D. Siljak in combining optimization-based design methods with methods of decentralized control-system analysis. These methods could be powerful in future weapons projects at LLNL.

Bond Graphs. Because our funding on this project was less than we requested in FY84, and because this development task is outside the scope of the Engineering Research Program, we will seek other support for adding bond graphs to DELIGHT.

Summary. This section reviewed the progress in the original tasks in our FY84 proposal. We completed some as planned, found others to be outside the scope of Engineering Research, and received support for others from other sources. Only one active research area remains: the work with D. Siljak on large-scale systems.

Financial Status

The spending rate for this project has bounced around a straight-line pattern. Our initial budget for FY84 was authorized at \$100,000. In the first half of this year, we spent \$57,600, a little more than half of the budgeted amount. January was heavily charged because we had several people working on the R Program project before we received funding from R Program for that work.

Future Work

In the second half of FY84, we will begin bringing together methods of optimization-based design with methods of decentralized control analysis, through our work with D. Siljak. We hope to research and develop ways to use optimization as the design process for controllers that are based on decentralized models for large-scale systems. This is a new research direction for us, but a logical one, because enough of our computer tools are now in place and because it complements the research going on in large-scale systems in the EE half of this joint project.

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