CRAY CHANNELS

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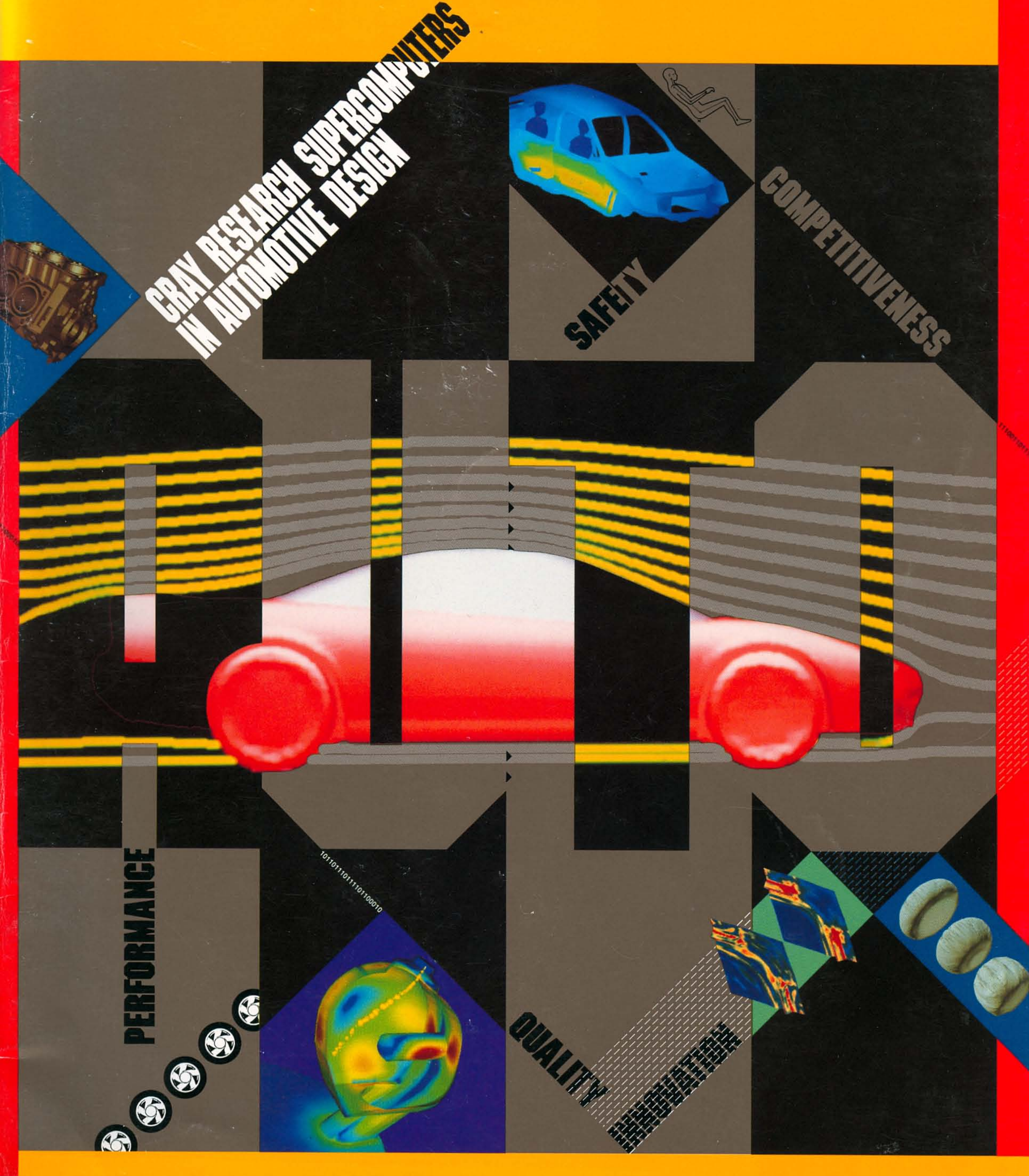


CRAY CHANNELS

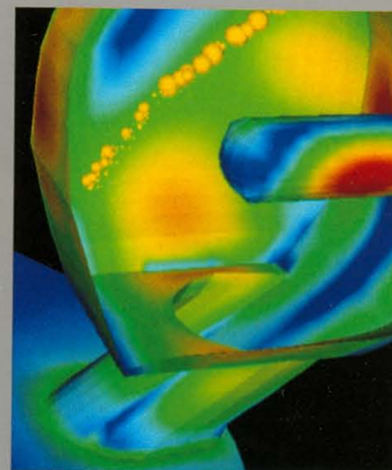
In this issue

Automotive engineers face an incredible challenge: to design clean-burning, fuel-efficient, durable vehicles that are economical and provide maximum safety to their occupants. This issue of CRAY CHANNELS highlights computational approaches to several of these problems, including efforts at Mercedes-Benz AG to improve vehicle safety and at Kia Motors Corporation to predict physical fatigue over a vehicle's service life. Efforts underway at Altair Engineering, Alcan International Ltd., and Computational Mechanics BEASY also aim at solving practical engineering and design problems in vehicle development. To help engineers design cleaner and more efficient engines, Cray Research now offers the CRI/*Turbo*Kiva combustion modeling software environment. The CRI/*Turbo*Kiva environment is an easy-to-use package for modeling fuel injection and combustion in internal combustion engines.

This issue also introduces Cray Research's newest supercomputers, the CRAY Y-MP C90 and CRAY Y-MP EL systems. These systems expand the range of supercomputer performance at the high and low ends, enabling Cray Research to offer more computing power to a broader range of engineers and scientists than ever before. This issue also showcases the Regional Computer Center of the University of Stuttgart, Germany. Our regular departments report on modeling the effects of the Kuwait oil fires and a close-up view of Antarctica.

The engineering of safer, longer-lasting vehicles that are fuel-efficient and clean-burning benefits consumers and automotive companies alike. The automotive industry accounts for about 9 percent of Cray Research's customer base, and Cray Research will continue to serve these customers by offering the most cost-effective solutions to their most challenging technical problems.

Features



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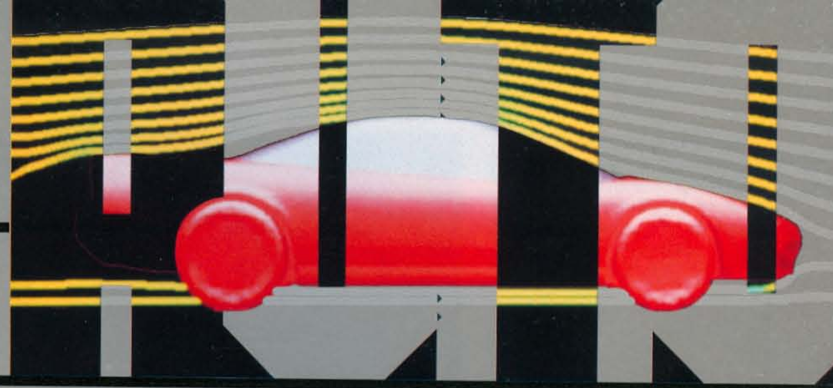


Numerical simulation of frontal impact and frontal offset collisions

Thomas Frank and Karl Gruber
Mercedes-Benz AG, Sindelfingen, Germany

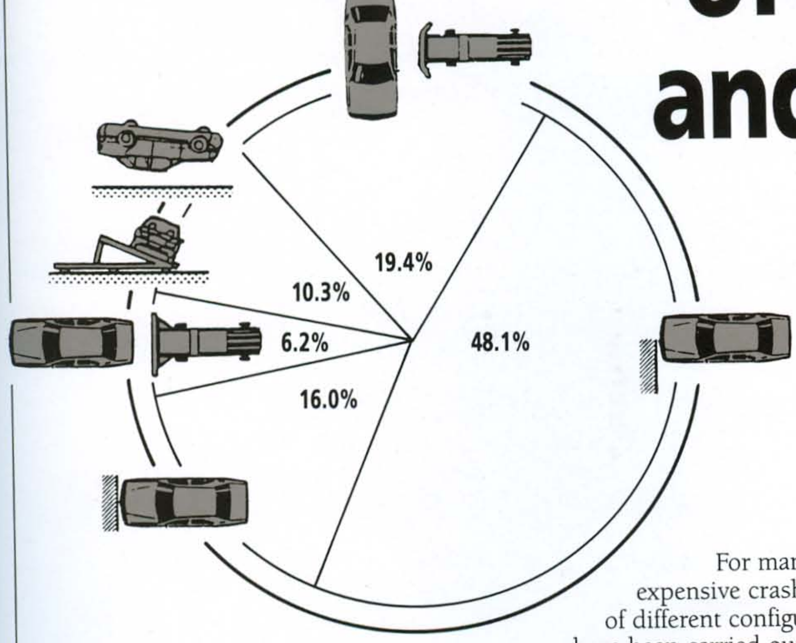


Figure 1. Distribution of real-world severe passenger car accidents by type of collision.

For many years, expensive crash tests of different configurations have been carried out at Mercedes-Benz to improve passenger car safety. The distribution of real-world accidents (Figure 1) shows that frontal impact is the most frequent collision type, accounting for more than 60 percent of all severe passenger car accidents. For that reason U.S. legislation prescribes standard test FMVSS 208, a 30 mph (48.3 km/h) frontal impact against a rigid barrier with full overlap. In this configuration, kinetic energy can be converted to deformation energy at the full frontal crush zone. However, a closer look at Figure 1 reveals that the asymmetric frontal impact with partial overlap of the car width accounts for the majority of real-world frontal accidents with severe injuries.

To accommodate this fact, Mercedes-Benz defined the so-called offset crash test with 40 percent overlap on the driver's side against a rigid barrier. This crash simulates a car-to-car crash during which the rigid engines do not hit each other. To meet this offset crash test requirement, as well as several other internal Mercedes-Benz requirements for every new car under development, a large variety of time-consuming crash tests must be performed. Because of the rapid growth in speed and performance of supercomputers and the availability of efficient computer codes (especially finite element programs) it has become possible to simulate highly nonlinear structural dynamic problems such as a full car crash.

The numerical method

The explicit finite element code DYNA3D[1] is used for analyzing nonlinear dynamic crash events. DYNA3D uses an explicit central difference operator for time integration, requiring a limitation in the time step size. To obtain numerical stability during the crash simulation, the time step size is typically on the order of one microsecond. For the discretization of the structure, shell elements, various solid elements,

Figure 2 (below). Finite element model for simulation of the 50 km/h frontal impact with full overlap.

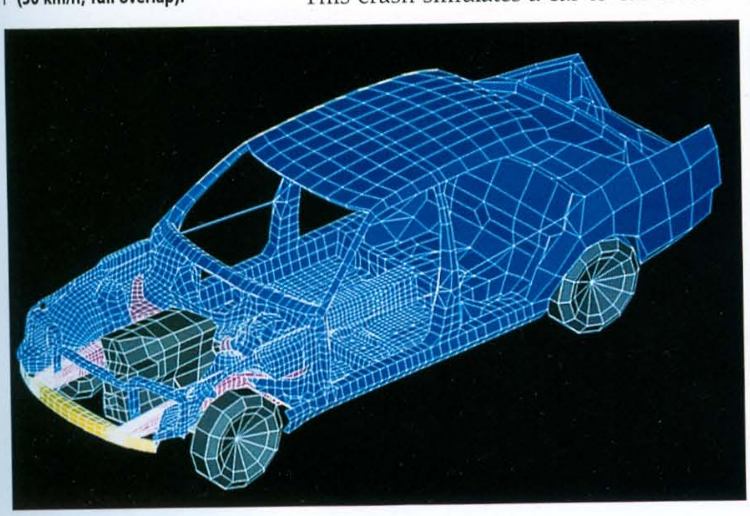
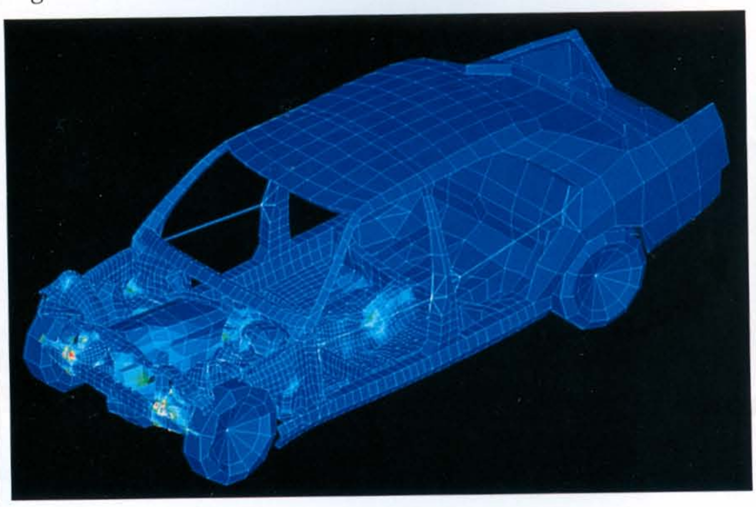


Figure 3 (below right). Distribution of effective plastic strain on the deformed shape at $t = 80$ ms (50 km/h, full overlap).



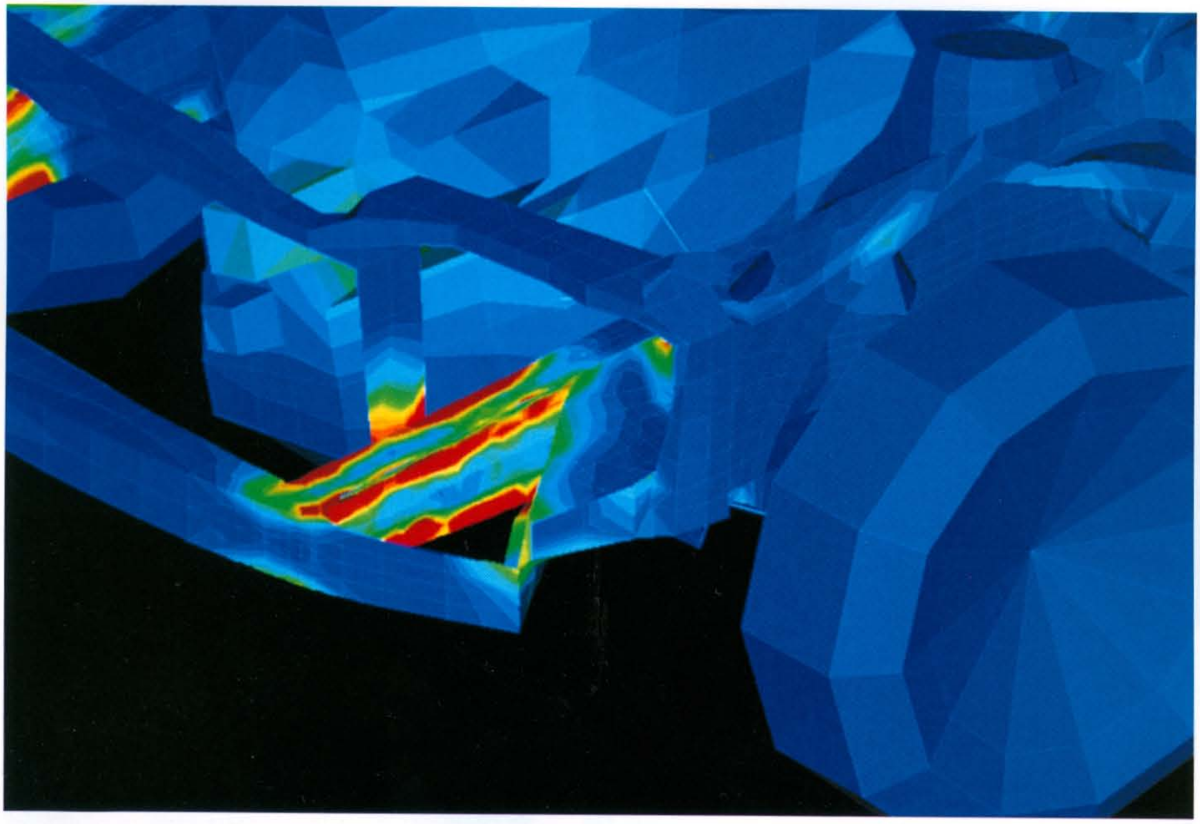


Figure 4. Distribution of effective plastic strain at t = 80 ms shown on the undeformed shape of the longitudinal member (50 km/h, full overlap).

and beam and bar elements are available to handle large displacements, rotations, and large strains. A variety of complex contact conditions can be modeled using the different contact algorithms based on the penalty method to avoid penetrations of structural parts during the crash process. To describe the material behavior, a large number of material laws and constitutive equations are available. Additional background information on theory and crashworthiness can be found in the literature.[2]

Frontal impact with full overlap

Early activities in numerical crash simulation concentrated on frontal impact with full overlap, because this type of impact is a legally specified test.

The finite element model for the full car crash simulation (Figure 2) contains 11,000 shell elements, 140 bar elements, and 10,000 nodes. The front parts of the car are meshed in fine detail to represent the significant areas of severe deformation for the frontal impact. The behavior of sheet metal is described by an elastoplastic material model including isotropic hardening. The engine, transmission, drive shaft, differential gear, and rear axle, as the main parts of the power train, are not modeled in detail. The main goal of the idealization of these parts is to obtain the corresponding energy absorption of the engine and the correct force flux of the power train. Nonlinear bars, beams, and springs are used to idealize engine suspension and drive shaft with rubber components. The wheels, modeled with shell elements, are calibrated on the force-deflection behavior determined in tests. According to test regulations the impact velocity of the car is 50 km/h. To achieve results comparable to those of the numerical model, a special test vehicle was constructed without seats, interior equipment, engine hood, or front fenders.

Figure 3 shows the distribution of the effective plastic strain on the final deformed shape at 80 ms. Because the distribution of the internal plastic energy would produce nearly the same picture, Figure 3 can be used to study the energy absorption and the deformation of various structural components. Figure 4 shows the distribution of the final effective plastic strain on the undeformed shape of the longitudinal member. The level of effective plastic strain increases from blue to green and finally to red, revealing that the absorbed energy is concentrated at the edges. In the barrier-force-versus-time curve (Figure 5), several crash events can be identified. The barrier force level

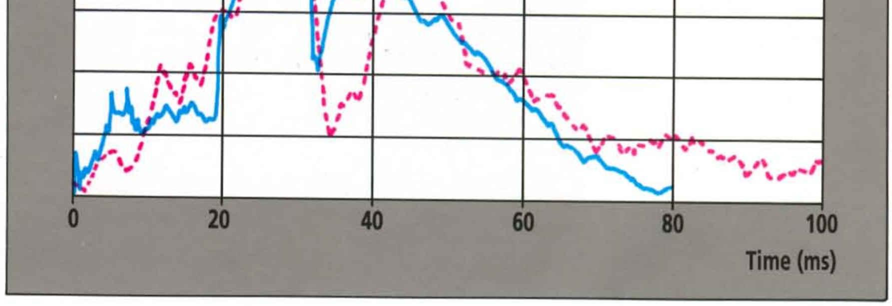
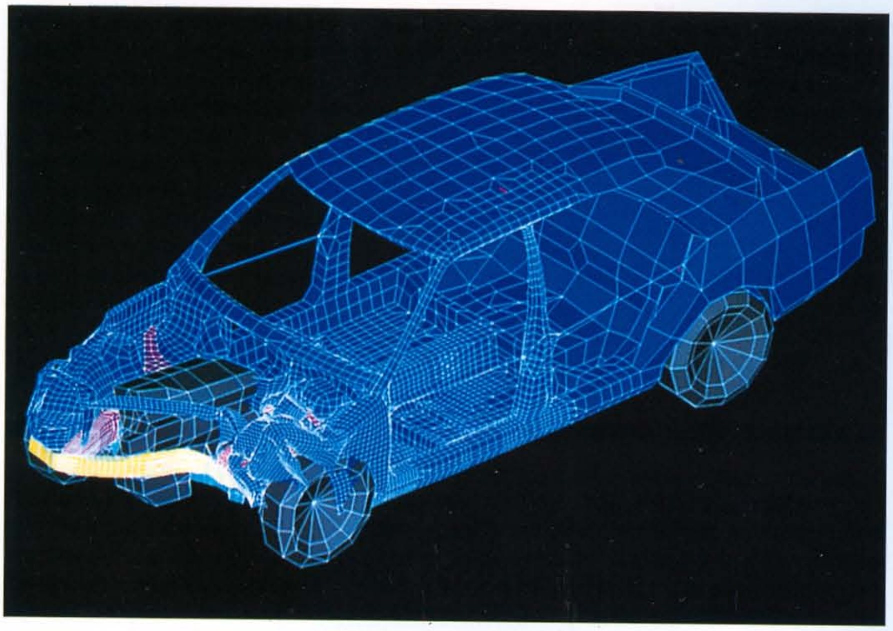


Figure 5. Barrier force versus time (50 km/h, full overlap).



in the time from 0 to 5 ms corresponds to the deformation of the frontal cross member (yellow in Figure 2). From 5 to 20 ms the barrier force is governed by the folding mechanism in the longitudinal members (red in Figure 2). The impact of the engine block against the barrier and the corresponding deceleration are shown in the peak force at t = 25-30 ms. At about 40 ms the contact of the engine with the fire wall results in another peak of the barrier force. The numerical simulation of the crash process up to 80 ms is discretized in 75,000 time steps and requires 3.3 CPU hours on a CRAY Y-MP4/216 system (5.3 CPU hours on a CRAY X-MP/24 system).

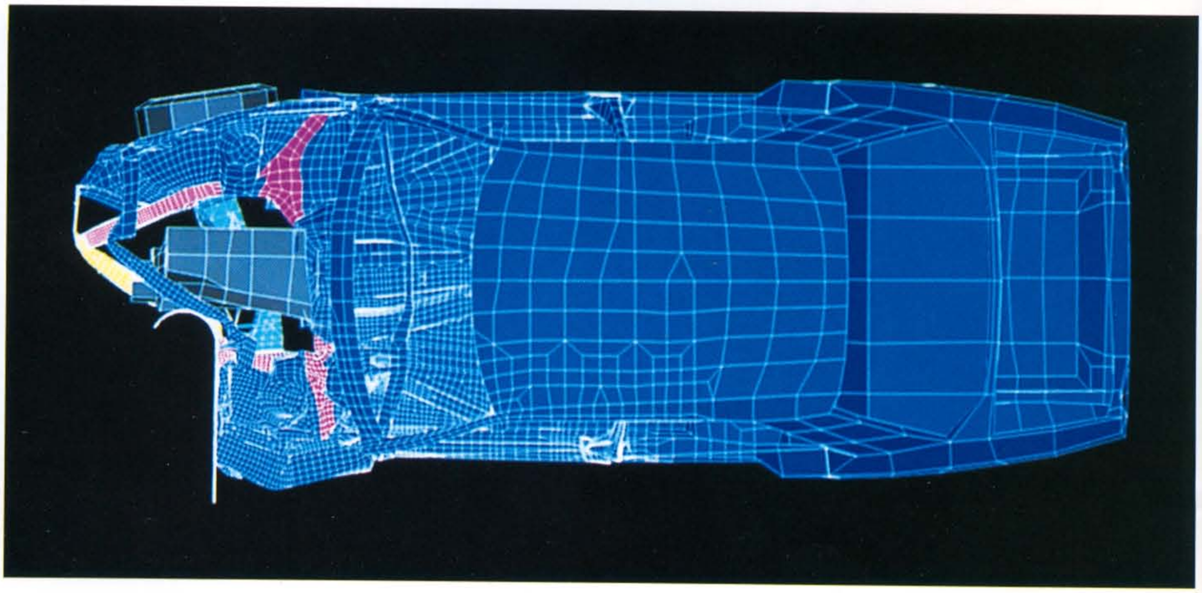
Frontal impact with 40 percent overlap

The 40 percent offset-test procedure was developed to obtain a good approximation of the most frequent real-world accident with partial overlap. In this configuration, additional energy has to be absorbed only by one half of the car width, resulting in severe deformation of the left front of the structure.

Figure 6 (above). Deformed shape of model at t = 70 ms (55 km/h, 40 percent overlap).

Figure 7 (right). Deformed shape of test vehicle (55 km/h, 40 percent overlap).

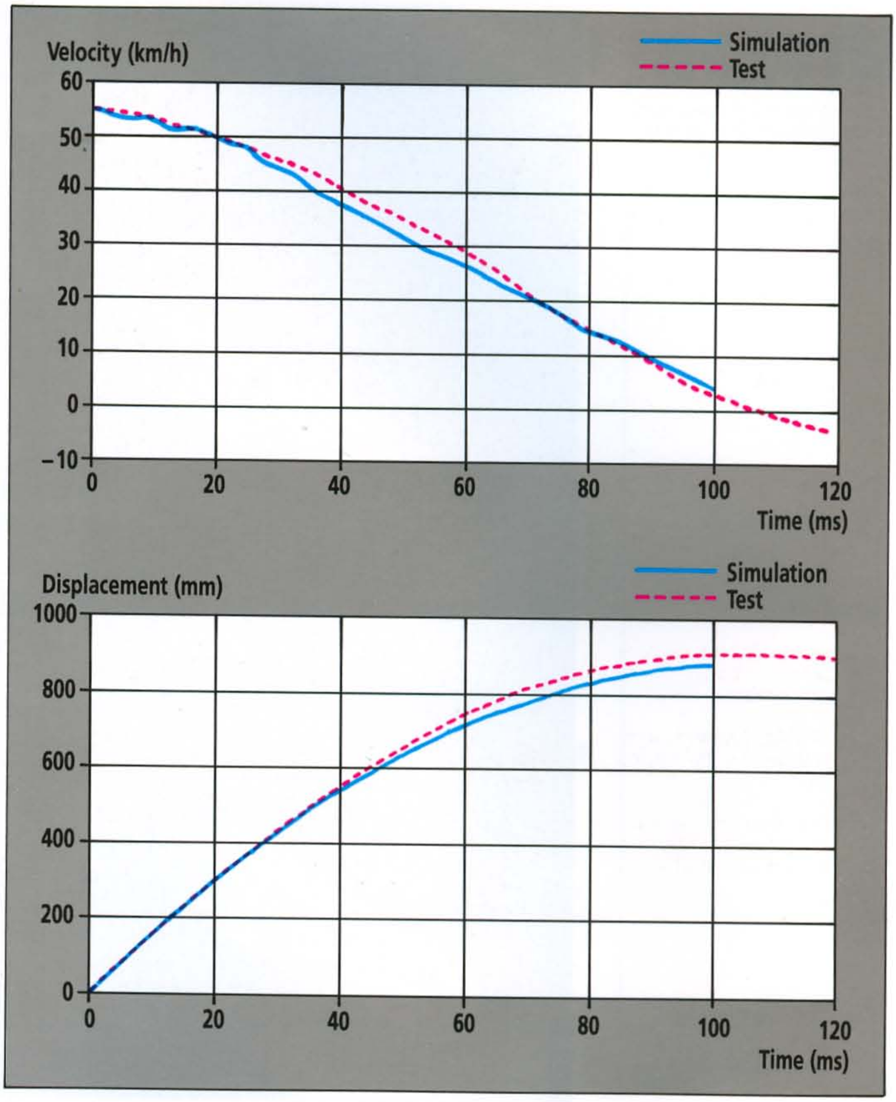
Figure 8 (below right). Deformed shape of model at t = 70 ms (55 km/h, 40 percent overlap).



To simulate the 40 percent offset in the finite element model, the longitudinal member, wheel well, dash panel, passenger compartment floor, side member, front pillar, and roof areas were remeshed in order to resolve the high stress and strain gradients. Additional parts such as the left front fender were added because the energy dissipation of this component cannot be neglected in this configuration. The full model consists of 20,000 shell elements, 140 bars, and 19,000 nodes. To cover a wide range of real-world accidents, the impact velocity of the internal offset-test procedure, and therefore also in the numerical simulation, is set to 55 km/h. In comparison to the 30 mph prescribed in FMVSS 208, this corresponds to an increase of 30 percent kinetic energy. Figure 6 shows the deformed shape at t = 70 ms. The comparison of the crashed test vehicle (Figure 7) with the numerical simulation (Figure 8) shows sufficient agreement in the overall deformation. The velocity and displacement curves (Figure 9) provide more detailed information. In contrast to the full overlap, the engine is not stopped by the barrier in this case. Therefore the kinetic energy of the engine and of the total structure has to be absorbed by only the left front structure, causing large deformations in this part of the vehicle. The simulation of 100 ms within 95,000 time steps requires 15 CPU hours on a CRAY Y-MP4/216 computer system.

Comparison between full and partial overlap

In the case of frontal impact with full overlap, the kinetic energy of the structure is absorbed mainly by both longitudinal members. The engine is stopped at the barrier and therefore its energy does not have to be absorbed by the structure. Additionally, the car body is decelerated due to the contact between engine and fire wall and the supporting effect of the drive shaft. But in the case of frontal impact with 40 percent overlap, energy absorption is concentrated on



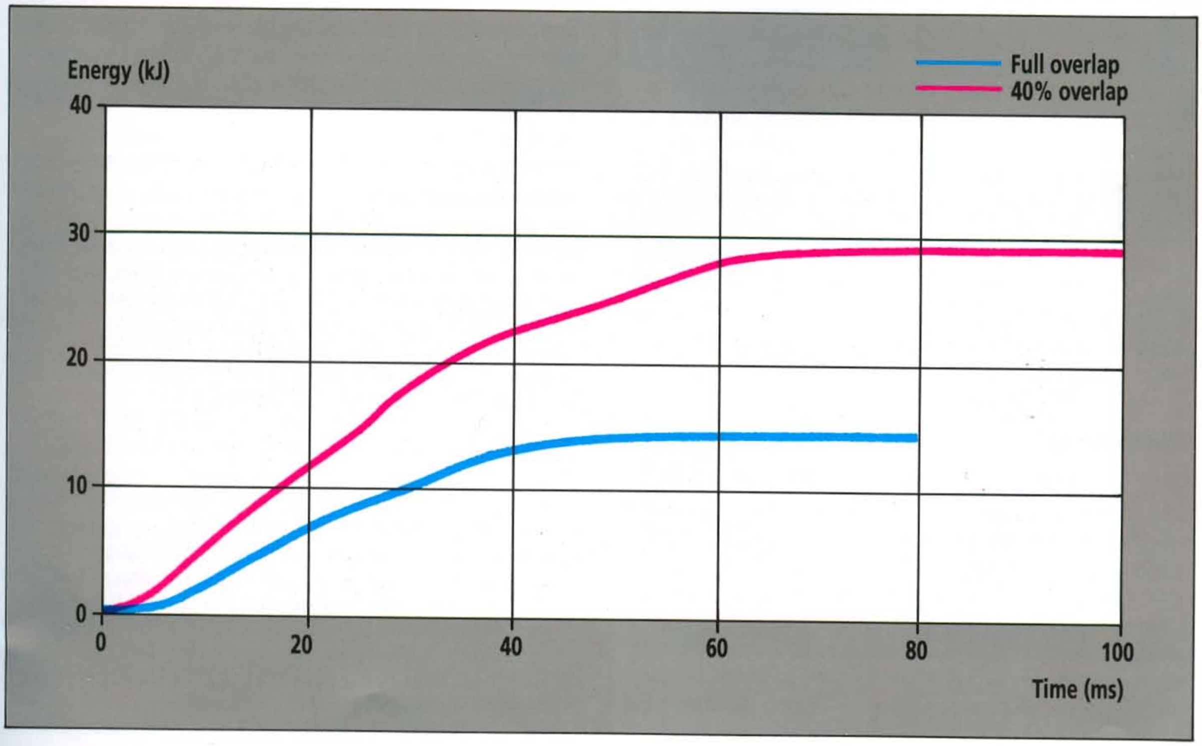
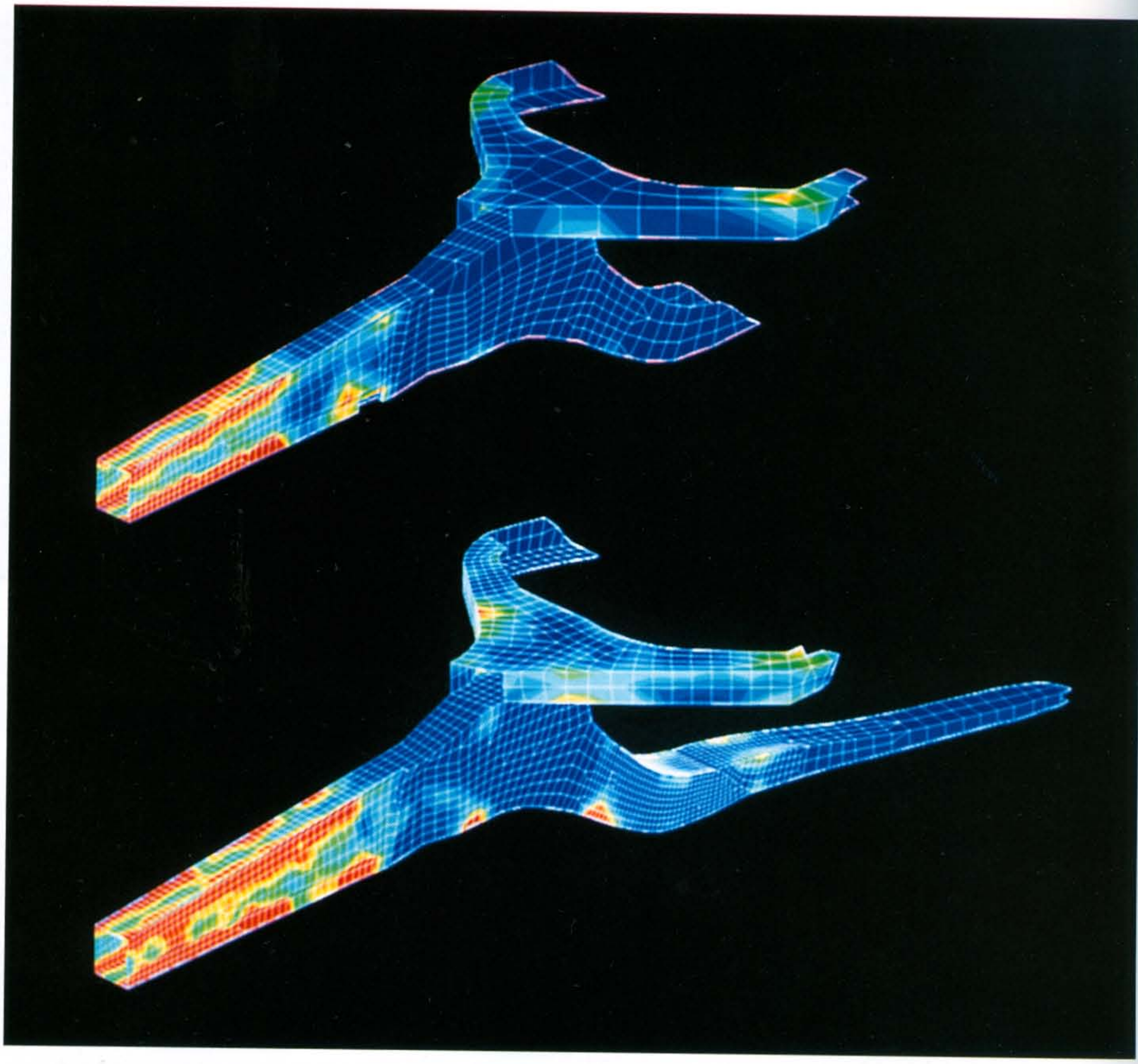


Figure 9 (above). Velocity and displacement versus time (55 km/h, 40 percent overlap).

Figure 10 (left). Internal energy versus time of the left longitudinal member, comparison of 40 percent and full overlap.

Figure 11. Distribution of effective plastic strain at t = 80 ms shown on the undeformed shape of the longitudinal member, comparison of full overlap (top) and 40 percent offset (bottom).



the left side. This effect can be shown clearly by comparing the internal energy of the left front longitudinal member for both cases (Figure 10). Figure 11 shows the distribution of the effective plastic strain as a measure for the absorbed energy for both simulations at a certain point of time. To overcome the high deformations in the case of 40 percent overlap and prevent failure of the passenger compartment, special structural concepts ("three-forked member"[3]) were developed and have been integrated in all Mercedes-Benz cars. If the structure of a car is not designed for this severe impact, great intrusions of the passenger compartment will occur and increase the risk of injuries significantly.

Conclusions

The presented results confirm the feasibility of simulating frontal impacts with full and partial overlap. Numerical simulation provides many results, such as the distribution of locally absorbed energy, that cannot be obtained with conventional crash test instrumentation. Such information is important to understand crash phenomena and to improve the crashworthiness of vehicles. The main point of the simulation is to compare several design variants and to select the optimal structure. Nevertheless, further developments of the code with respect to friction, tearing, fracture, and failure are needed to improve and validate the simulation technique.

About the authors

Both authors are engineers in the car body development division at Mercedes-Benz AG, Sindelfingen, Germany. They are working as CAE analysts on numerical simulation in the analysis department in body engineering. Thomas Frank received his M.S. degree in aviation and aerospace engineering from the University of Stuttgart. Karl Gruber received his Ph.D. degree in mechanical engineering from the University of Stuttgart.

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Integrated fatigue analysis at Kia Motors

Joong Jae Kim, Doo Youl Chung and Myung Won Suh, Kia Motors Corporation, Seoul, Korea

Automotive structural components that are subjected to repeated, fluctuating, or alternating stresses can exhibit fatigue, or diminished physical strength. This can occur even when the stresses are below the ultimate strength or even the yield strength of the components. In general, fatigue is a product of many factors, such as minor defects, the quality of the surface finish, and the chemical or thermal environment, as well as the global integrity of the structure. Defining the operating environment for most automotive mechanisms comprehensively, and thus identifying the various sources of stress, is difficult because structural components typically are subjected to loads from multiple sources and perform very complex duties. In addition, the loads imparted to various structures are influenced by a driver's response to external factors such as traffic, road surface characteristics, corners, and road gradient.

Much research has been conducted to define service loads from the environment and assess the fatigue life of vehicle structures. However, most such studies involved primarily experimental methods because the factors mentioned above were too complex for analytical methods to handle. Recently, advances in computer hardware and numerical methods have encouraged automotive engineers to assess the fatigue life of parts through computer simulation techniques, or Computer Aided Engineering (CAE). Dynamic simulation codes, which have been used mainly for the analysis of multibody dynamics, can help to define the loads that the components of a chassis system, especially of a suspension system, have to endure in service.[1] The finite element method can be used to define a stress/strain history and to calculate the fatigue damage resulting from the input loads obtained by either tests or analysis.[1,2]

FASYS: An integrated fatigue analysis system

KIRD (the Kia Institute of Research and Development) at Kia Motors has developed FASYS (the Fatigue Analysis System), a computational tool for the systematic evaluation of fatigue failure during the prototype and preprototype stages. FASYS includes commercial and proprietary simulation software packages that are run on Kia's CRAY Y-MP4 computer system. FASYS is used primarily for suspension components and body-in-white analysis.

To show how FASYS affects vehicle development, it is worthwhile to discuss briefly the development process. Development generally can be divided into four stages:

- ☐ The concept stage
- ☐ The detail design analysis stage
- ☐ The development (prototype) stage
- ☐ The design modification stage

Most of the important structural characteristics of a vehicle, such as the stiffness and strength of the body-in-white and chassis components, the riding and handling qualities of the vehicle as a whole, and the crashworthiness, are checked and improved at every stage of the procedure by means of CAE techniques and/or tests. Fatigue damage, however, traditionally has not been checked until the prototype stage. FASYS can improve the integrity of the automotive structure by applying fatigue life assessment earlier in the development process. FASYS can predict fatigue damage during the concept and design analysis stages, give useful information to guide tests, and suggest improvements during the design modification stage.

Fatigue damage can be analyzed with a few modifications or small extensions to CAE models created originally for other applications. A model for handling analysis, for example, may be used directly to obtain the time history of the linkage forces of suspension components that experience the loads imparted by a rough road. The finite element model of a suspension component that was created for strength analysis can be an exact model for determining the history of stress/strain in response to the history of the linkage forces previously obtained. In addition, a model used for riding analysis also can be used for dynamic stress/strain analysis of the body-in-white by refining or adding the finite element model of the body. At the concept stage, the riding model may have a rigid body-in-white instead of an elastic or flexible one.

The application of FASYS comprises three procedures. The first is the preparation of the input loads from the vehicle environment. The load data may be obtained by tests, from published sources, or from dynamic simulations. Dynamic simulation is

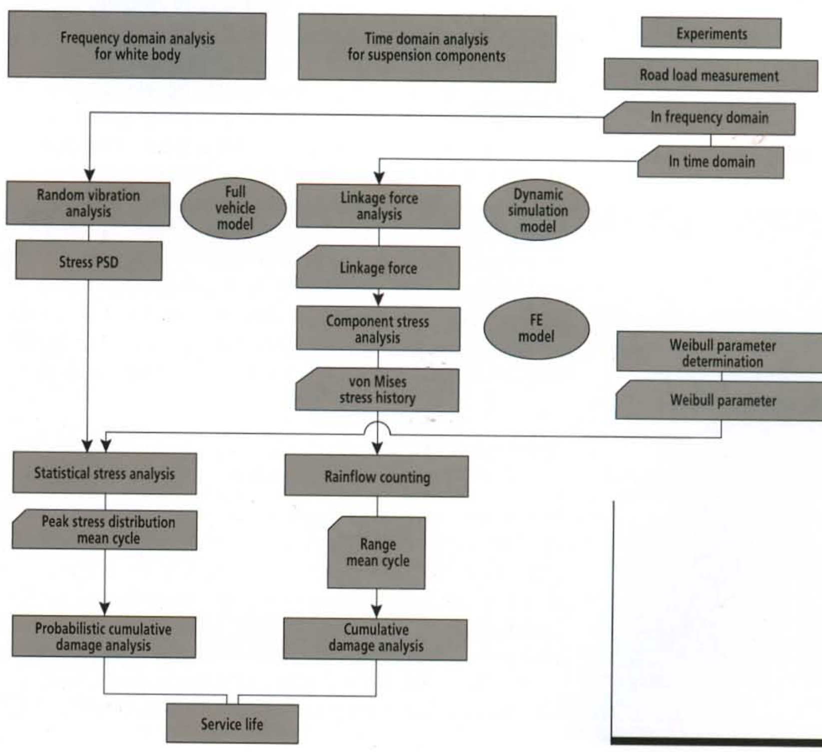

Figure 1. Information flow in FASYS.

used particularly to identify the history of the linkage forces of the suspension components. The second procedure is the analysis of the stress history produced by the loads. Finite element analysis is used to determine the stresses. The fatigue damage and fatigue life are calculated in the third part of the system and are based on the stress history data obtained previously. For the dynamic simulation and the finite element analysis, commercial codes are included in FASYS. Several programs have been developed for the calculations that commercial codes could not support, for transferring the data among the functional programs, and for pre- and postprocessing. The general scheme of FASYS is shown in Figure 1.

Fatigue analysis in the time and frequency domains

Although evaluating the fatigue life or durability of a structure depends on time domain characteristics, the frequency description of the random data is intimately related to the fatigue cycles identified by the rainflow counting procedure in the time domain.[3] In theory, the transformation from time history data to frequency data does not result in any loss of information, and an inverse transformation can be performed to reconstruct the original time history data. Therefore, it is generally understood that the fatigue analysis with the time history stress data and with the stress data in the frequency domain will give the same results. To assess the fatigue life in the time domain, the entire service history of the stress usually is condensed into mean, range, and cycles by rainflow counting. In the frequency domain, the data are summarized in terms of autospectral density, or power spectral density (PSD), which is used to obtain the mean cycle and the peak stress distribution. A simple durability test has shown that the distribution of the rainflow ranges of the structural response in the time domain could be modeled by a Gaussian probability density function for broadband data and by Rayleigh distribution for narrow band data, when the input loads are stationary Gaussian.[3] This means that the assessment of the fatigue life in the frequency and time domains may produce the same results if the peak stress distribution function is modeled properly.

In FASYS, the Weibull function[4] is used for the distribution function. Whether a random process is governed by the Gaussian assumption or not, the distribution of peaks can be approximated by the semiempirical Weibull function. A parameter in the Weibull function makes adjustments according to the test results. FASYS is used mainly for simulation to test the fatigue failure of a vehicle being driven on an endurance road. The test is to ensure the safety of the whole vehicle against fatigue failure after having been driven a certain distance. Therefore, the main input for the system is the road surface data. The road surface data are obtained by driving the vehicle on the endurance road. If the test is not available, previous test data or published data for various roads can be used.

Suspension components and the body-in-white are treated differently in FASYS. The former is assumed to be relatively stiff compared to the frequency range of the significant input loads. The fatigue damage will be assessed quasistatically in the time domain. For the latter, the dynamic stress is solved in the frequency domain because the body-in-white resonates with the input loads.

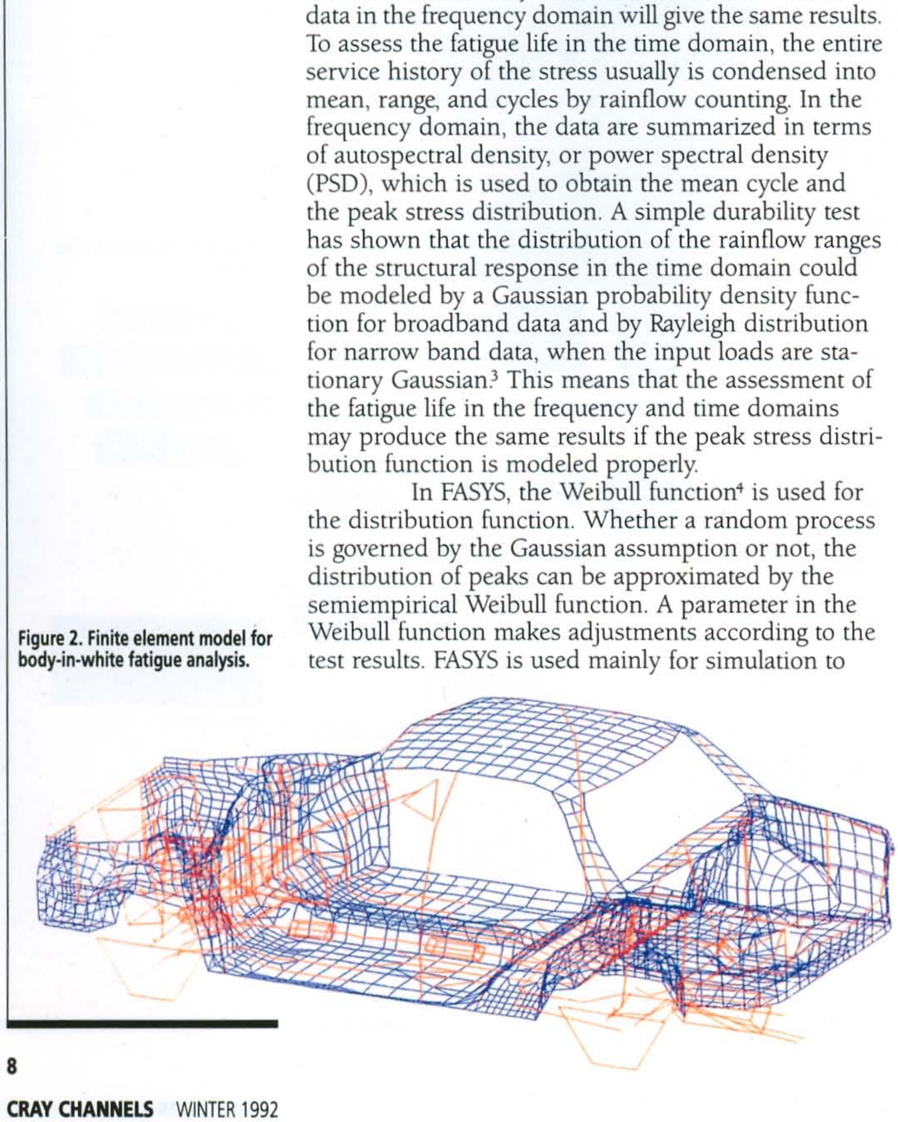

Figure 2. Finite element model for body-in-white fatigue analysis.

Fatigue analysis of the body-in-white: an application of FASYS in the frequency domain

The frequency of the significant tire input loads from rough road surfaces can be expected to lie between 0 and 100 Hz, and the first natural frequencies of bodies-in-white generally are between 10 and 40 Hz. Because the vibrational response of a vehicle body experiencing the loads from a road surface is expected to be highly resonant, the response stress of the body may not be treated quasistatically. An appropriate technique for calculating the response in such cases is one in which the resonant effect can be evaluated. Transient response analysis in the time domain could be a proper technique for this application. In the case of a finite element model with many degrees of freedom, however, this technique may yield huge amounts of output data. In FASYS, bodies-in-white are handled by a random vibration analysis, or PSD analysis in the frequency domain. PSD is the most common statistical function used for random data. Instead of the long time history of stress data, concise statistical or probability data are obtained directly by the analysis.

Under normal service conditions, loads imposed on a vehicle by the road are random and can be assumed to be stationary Gaussian. It also is known that when the excitation of a linear system is a Gaussian process, the response will be in general a very different random process, but it still will be Gaussian.[5] Based on the above considerations, the distribution of the peak values of the responding stress in the structure of a vehicle can be derived theoretically into Rayleigh or Gaussian for narrow and wide band, respectively.[6] In FASYS, however, the Weibull distribution function is adopted and adjusted according to the test results for greater accuracy.

The input loads to FASYS for the body-in-white fatigue assessment are the PSD data of the endurance road surface. The PSD stress response to the road load is obtained at every finite element in the body-in-white through the random vibration analysis. Then, the peak stress distribution is described by the PSD of the stress and the adjusted Weibull function. The mean cycle also can be derived from the PSD of the stress. The cumulative fatigue damage is obtained based on Miner's rule and calculated by mathematical integration of the peak stress distribution function, considering the limit of the fatigue life and the mean cycle. Figures 2 and 3 show a model for the body-in-white fatigue analysis and the result of the fatigue damage. The CAEDS graphics package is used for the plots. The data are edited to be suitable for CAEDS, particularly for the fatigue damage contour plot.

Fatigue analysis of suspension components: an application of FASYS in the time domain

The behavior of the suspension components of a running vehicle is too complex to allow for the definition of the loading and boundary conditions. Because the suspension system cannot be assumed to move infinitesimally in the kinematic linkage system, ordinary finite element analysis codes may not directly solve its dynamic stress in assemblage condition. In FASYS, with the assumption that the suspension components are very stiff, the linkage force histories of the suspension components in response to the wheel center movements are solved by dynamic simulation analysis. The assumption is plausible because the suspension components generally have much higher natural frequencies than the frequency range of the significant loading from a road surface. In addition, the dynamic stress that the component experiences as a result of the linkage force histories can be solved quasistatically, based on the above assumption. The stress histories are obtained by the linear combination of the finite number of the stress data sets, which are solved statically, responding to each degree of freedom of the input loads. In summary, the assumption that the suspension components are very stiff makes it feasible to handle the whole time history data of the loading and responding stresses. This simplicity is the basis for the time domain fatigue analysis of the suspension components.

The whole stress history will be transformed to mean, range, and cycle by rainflow counting. Finally, fatigue damage will be calculated and Miner's rule will be applied to assess the whole fatigue life. Figure 4 shows results after rainflow counting and the damage calculation. The fatigue damage contour plot for the suspension components can be obtained by the same procedure as that used for the body-in-white plot in Figure 3.

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About the authors

Joong Jae Kim is the senior engineer of the Material Test and Evaluation Department of KIRD at Kia Motors. He researches fatigue damage of vehicle systems and metal forming processes. He received a B.S. degree in metallurgical engineering from Seoul National University and M.S. and Ph.D. degrees in materials science from the Korea Advanced Institute of Science and Technology.

Doo Youl Chung is the system engineer of the Computing Service Department of KIRD at Kia Motors and specializes in computer graphics and CAE. He received a B.S. degree in physics from Inha University, Korea.

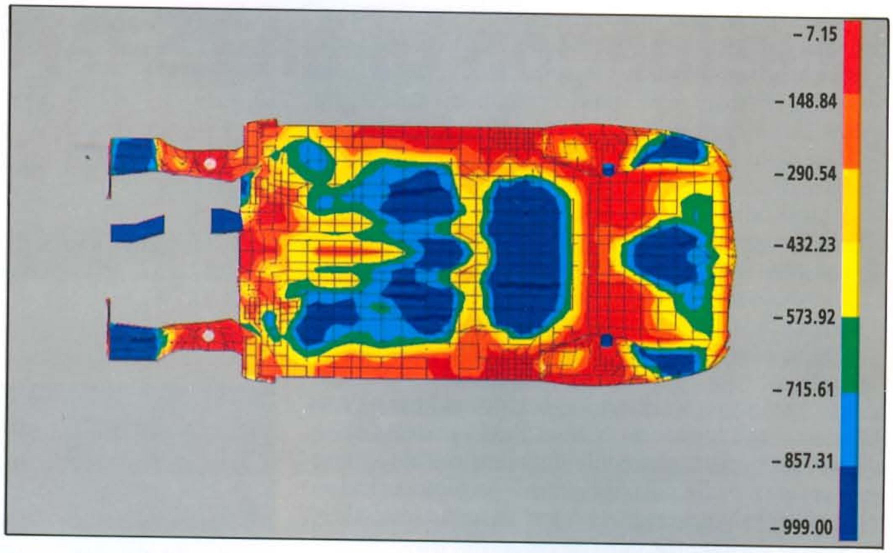

Figure 3. Body-in-white fatigue damage (bottom view).

Myung Won Suh is the manager of the Computing Service Department of KIRD at Kia Motors and works on CAE in vehicle development and structural optimization. He received a B.S. degree in mechanical engineering from Seoul National University, an M.S. degree in mechanical engineering from the Korea Advanced Institute of Science and Technology, and a Ph.D. degree in aerospace engineering from the University of Michigan.

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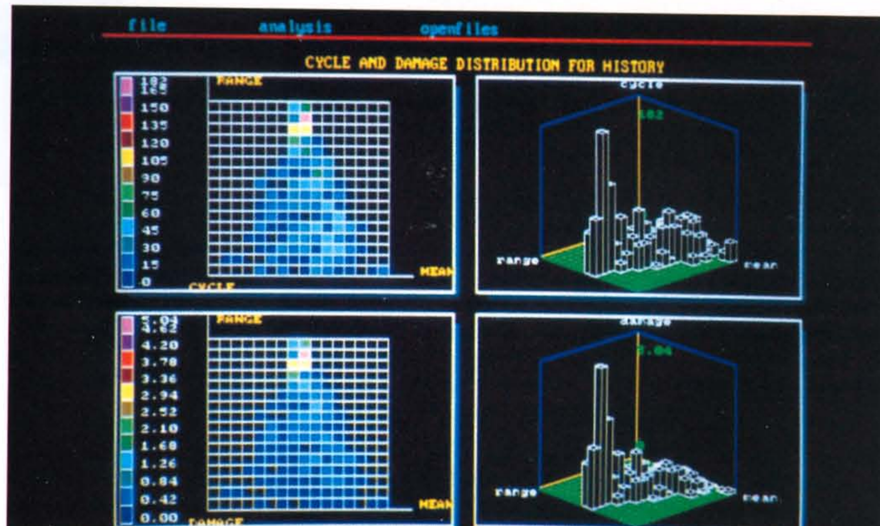
Figure 4. Results of rainflow counting and damage calculation.



Evaluation of an LS-DYNA3D model for deep drawing of aluminum sheet

P. C. Galbraith, M. J. Finn, and S. R. MacEwen
Alcan International Ltd., Kingston, Ontario, Canada

Although attempts to understand the physics of sheet metal formation span at least five decades, computer modeling has only impacted metal forming processes over the past five years. The motivation for replacing trial-and-error testing with mathematical modeling is clear: the current process of die design by an iterative, handcrafted procedure is expensive and time consuming. Many authors have stressed the potential benefits that would accrue if artisanship were replaced by reliable models. According to a recent paper by Honecker and Mattiasson,[1] a successful model must replicate correctly all of the tooling, and especially the drawbeads, and should be able to predict not only final shapes but also details of strain distributions, wrinkling, and springback. In addition, the codes used for analysis should be reliable, robust, and run in an acceptable time, which Honecker and Mattiasson define as an overnight run.

Because the analysis of sheet metal forming is by its very nature one of contact and sliding interfaces, the computer resources needed to handle a real problem rigorously and correctly are formidable. Perhaps for this reason the majority of analyses attempted to date have been relatively small (a few thousand elements) and/or have been two dimensional, with the general feeling in the stamping industry being that computer modeling is too slow and unreliable for "real" problems. It is not surprising that the answer to Keeler's question in 1988, "Has science replaced art?"[2] is "Yes and no; the transition has begun." Leading this transition is the development of new algorithms to handle contact on a large scale, the emergence of workstations with superb graphics capabilities as platforms capable of handling large finite element problems, and the accessibility of supercomputing facilities to the analyst at an acceptable cost.

Although the emphasis on computer modeling has been primarily on the analytical aspects, the importance of material characterization, including the development of appropriate constitutive laws for yield, strain hardening and friction, and the experimental validation of model results cannot be underestimated. Developing a model with true predictive capability requires a blend of material characterization, numerical analysis, and experimental validation. The work described here demonstrates that a realistic finite element analysis of a deep-drawing problem, including the full three-dimensional representation of drawbeads, is feasible. We have chosen to use LS-DYNA3D, an explicit code developed originally by J. O. Hallquist and coworkers at the Lawrence Livermore National Laboratory. It has been used extensively worldwide for simulations of nonlinear, dynamic impact, but only recently for metal forming problems.

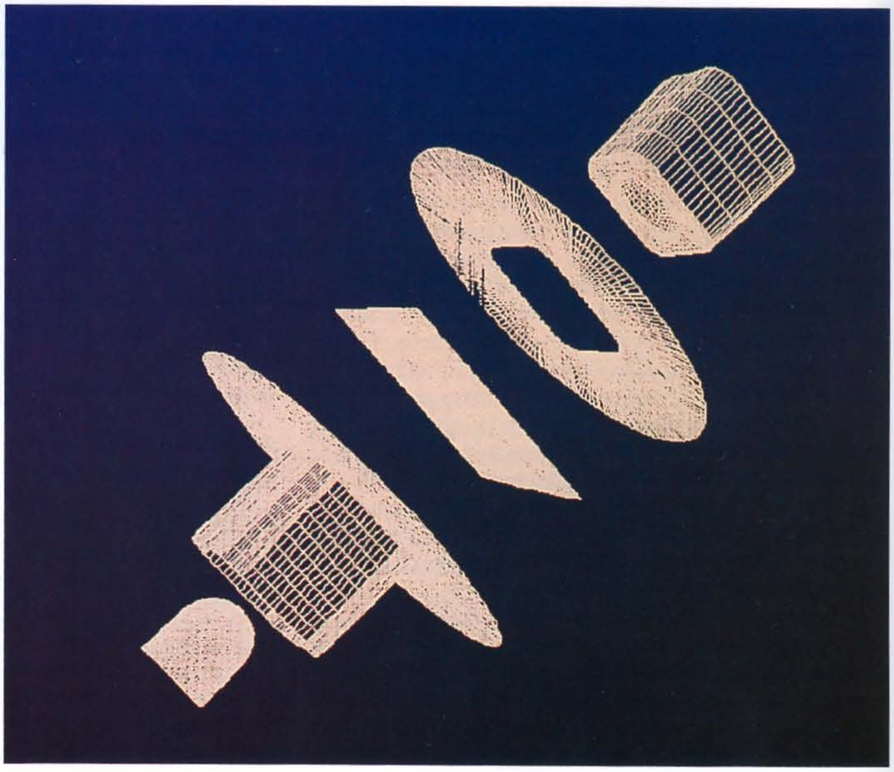
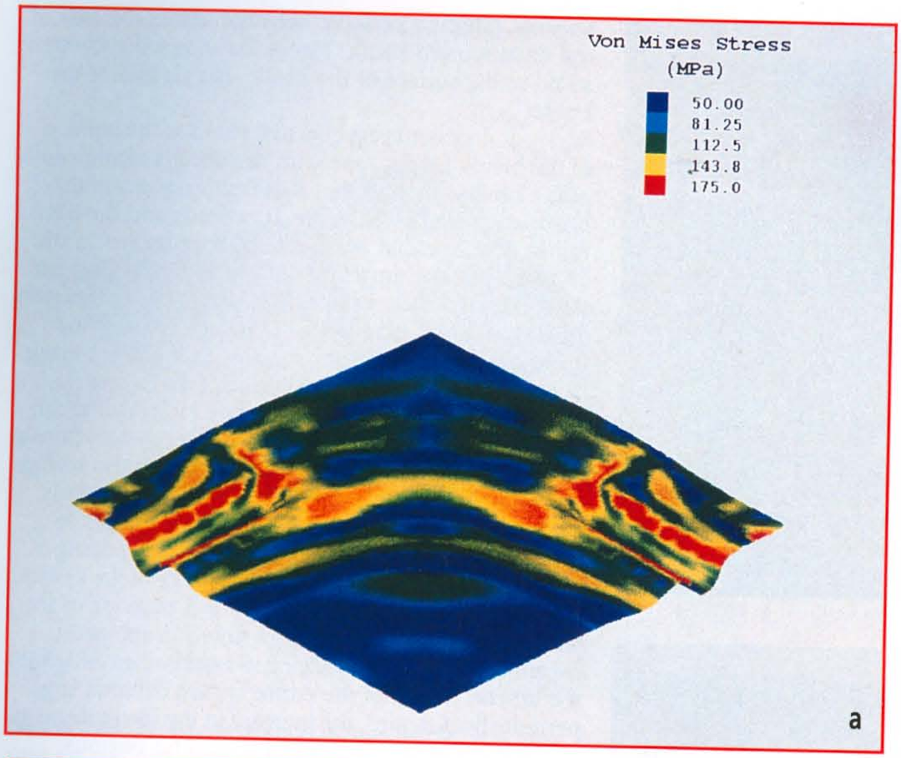


Figure 1. Geometry and mesh of the press tooling and blank.

Honecker and Mattiasson, in assessing the relative merits of implicit (ABAQUS) and explicit (DYNA3D) codes, summarize the current situation precisely. Implicit codes would appear to be ideally suited for metal forming problems; however, their inherent sensitivity for convergence has, so far, made them unusable for all but very small models involving sliding interfaces. Explicit codes are inherently unsuitable for metal forming problems due to the very small time step (microseconds) required to ensure convergence. To model a forming operation taking about a second would require several orders of magnitude more steps per solution than is practical on any current computer system. The resolution of the impasse is to model the operation in a process time that is 100 to 1000 times shorter than the actual process time. Deep drawing of the square pan considered here requires an actual time of about 1.8 seconds; in the model it is assumed to occur in 3.6 msec, a factor of 500 speed-up.

The public domain version of the LS-DYNA3D code used for this analysis has been modified exten-



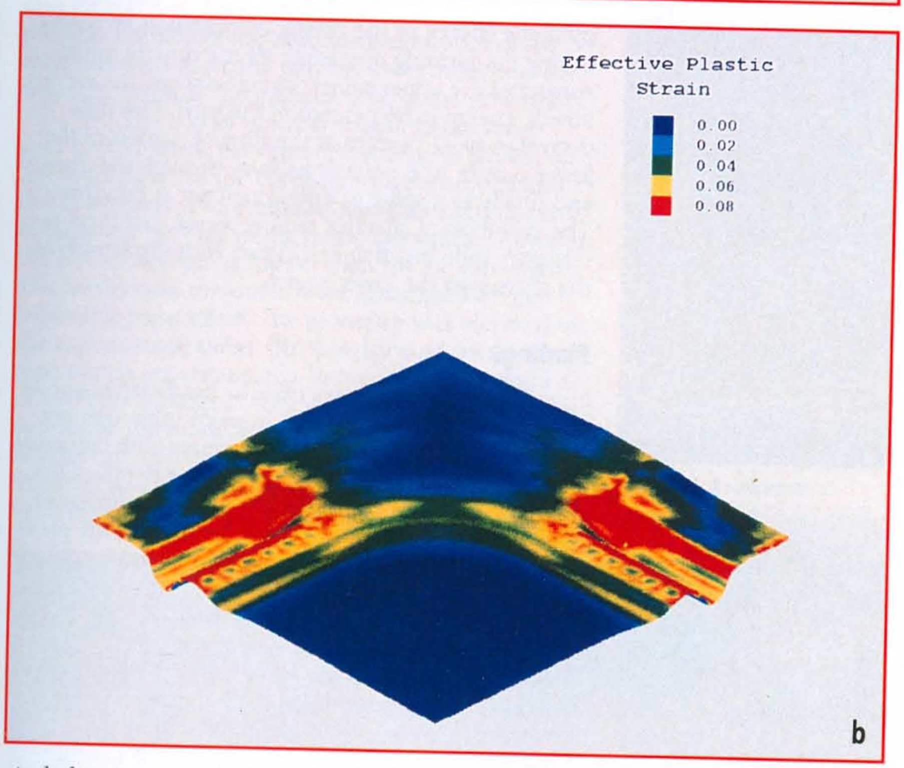


Figure 2a. Effective stress in the blank, at the top surface, after the binder has closed.

Figure 2b. Effective strain in the blank, at the top surface, after the binder has closed.

sively by Livermore Software Technology Corporation. The objective was to evaluate LS-DYNA3D as a tool for modeling large metal forming problems. Particular emphasis was paid to identifying dynamic effects originating from the explicit nature of the analysis that are not features of an actual deep drawing operation.

The test part is a square pan, with a spherical dome at the center. This part, although not representative of any real automotive component, was chosen because its forming involves all of the major modes of deformation found in a stamping operation. Tooling to press a pan 275 mm square with a 150 mm diameter central dome with drawbeads to control metal flow, was cast (to simulate the manufacture of real automotive dies) for the Alcan International Banbury Laboratory press. Experimental pressings were made from an aluminum alloy sheet, 1.6 mm thick, precoated with a lubricant. Polyethylene sheets, 0.10 mm thick, were inserted between the blank and the tooling to further reduce friction. Prior to forming, the blanks were scribed with 2 mm square grids in the regions where high strain gradients were expected, such as near drawbeads, and with 5 mm square grids elsewhere. A three-dimensional coordinate measuring machine was used to create the initial grid pattern in precise detail. The same apparatus was used after forming to determine the displacement of each grid point, with a precision of ±0.0005 mm, from which the major and minor surface strains were computed using an analysis developed by Sowerby, Duncan, and Chu.[3] This exercise provided a principal source of validation for the model. Samples were taken from the press after the binder had closed and after the pressing operation. In this work, the sheet was deformed by various amounts by rolling (assumed to be plane strain only), and the curve of 0.2 percent offset tensile yield versus the effective (Mises) strain produced by the multi-pass rolling operation was used to define the flow law for the finite element analysis.

The geometry of the tooling and the blank, shown in exploded view in Figure 1, was modeled precisely using LS-INGRID. The components illustrated are as follows: the upper punch, the lower surface of the binder, the square blank, the die, and the lower punch. Note that the upper punch has a hemispherical cavity into which the lower punch fits. Details of the drawbeads were obtained by making and then measuring replicas of the actual beads on the experimental binder. All tooling was modeled as rigid surfaces. Particular care was used in optimizing the mesh of the blank. The element size was adjusted over the surface of the blank according to the severity of the deformation expected. In anticipation of including a full description of the anisotropy of the sheet, a quarter symmetry of the component and tooling, rather than only one-eighth, was modeled. In total, the model contains 10,437 elements, 17,615 nodes, and approximately 36,000 degrees of freedom.

All preprocessing and debugging runs were done on a single processor of a Silicon Graphics 4D360 Power Series or on a Personal IRIS workstation. A complete run of the entire forming problem required 35.8 CPU hours on the SGI Power Series 4D360. The run time for the complete problem on a single processor of a CRAY Y-MP8 supercomputer was 1.53 hours, a factor of 23.4 faster than on the Power Series workstation.

Results

Mises effective stress and equivalent strain illustrate the evolution of the forming operation. Because the analysis is dynamic and has been accelerated by a factor of 500 for computational efficiency, the plots of stress, strain, and displacement may exhibit dynamic effects.

Figure 2a shows the effective stress at the top (punch side) surface of the blank after the binder has closed but before the punch has made contact.

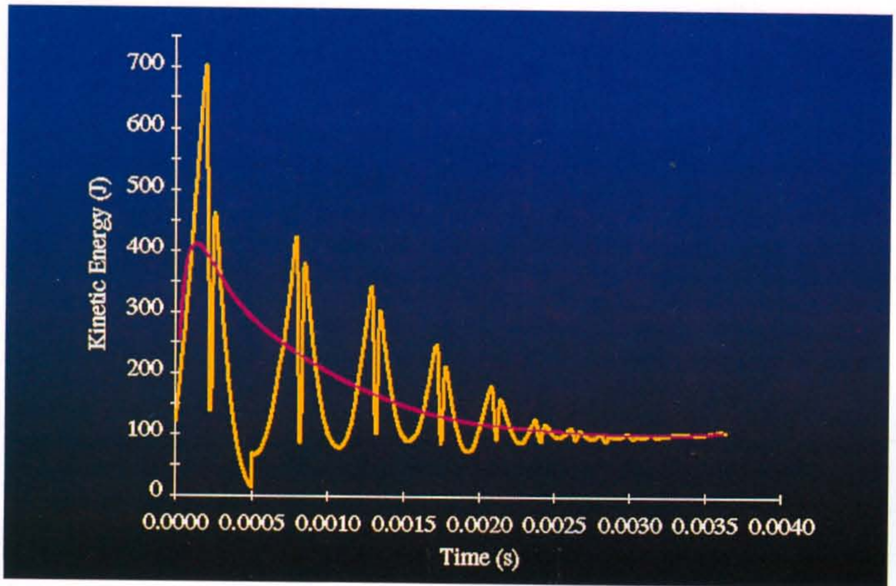


Figure 3a. Kinetic energy of the tooling.

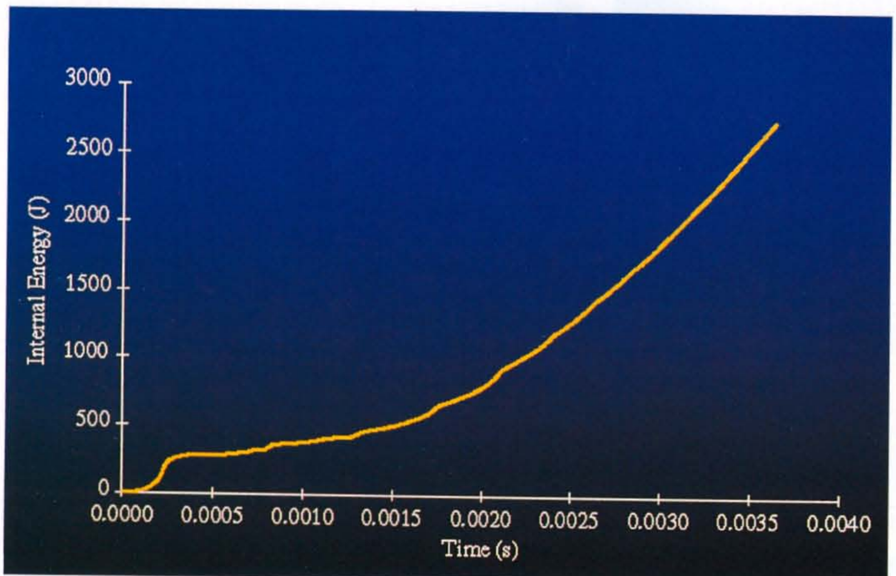


Figure 3b. Internal (elastic plus plastic) energy of the sheet.

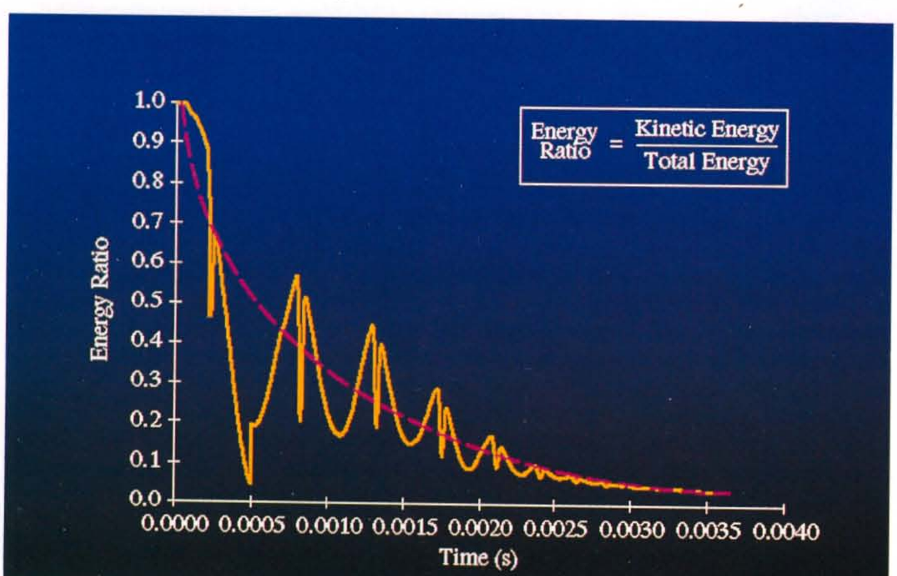


Figure 3c. Ratio of the kinetic to the total energy of the system.

Stresses exhibit a periodic behavior across the area of the unsupported blank. Figure 2b shows the effective strain at the surface of the blank after closure of the binder.

In examining effective strain at the surface of the blank, for the case with drawbeads after closure of the binder, we find that significant regions of the blank, in particular near the drawbeads and the die radius, have yielded plastically. Surface strains in the 15 to 20 percent range are present in the region near the end of the beads; midplane strains in the same region are a maximum of 11 percent. At the corner of the die, the surface strains are in the 4 to 6 percent range.

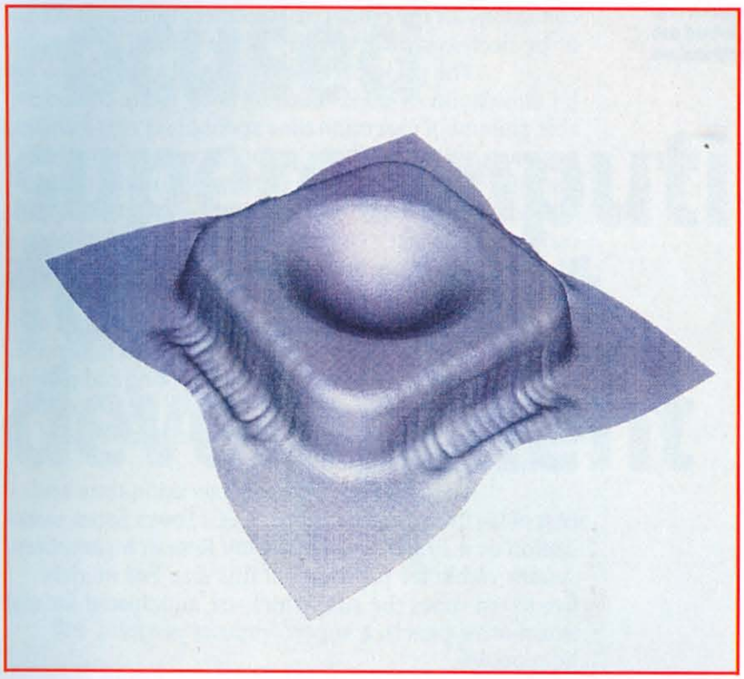
Dynamic effects, illustrated in Figures 3a, 3b, and 3c can be seen most clearly by following the kinetic, internal, and total energies of the system during the forming operation. The data show that the average kinetic energy of the binder decreases continuously as the oscillations damp out. The punch begins to move with a constant velocity at 0.5 msec, adding a constant increment to the kinetic energy of the system. The internal energy of the system is a measure of the total elastic plus plastic energy stored in the sheet, because the tooling is modeled as rigid bodies. Although the kinetic energy of the entire system exhibits large periodic fluctuations, the increase in the internal energy of the sheet increases smoothly, without obvious dynamic effects, as the plastic deformation increases during the forming operation. At the time of initial contact of the upper punch with the sheet, the average kinetic energy is 34 percent of the total. The ratio decreases to 22 percent at the time of contact of the lower punch, to 8 percent halfway through the draw, and finally to a value of only 3 percent at full draw. The evolution of effective strains shows that there is relatively little bending associated with the stretch of the sheet over the lower punch.

Findings

Figure 4a shows that the predicted shape of the pan, with the tooling still in place (although not visible), is in almost complete agreement with the actual drawn pan, as shown in Figure 4b. The depth of the draw, the shape of the dome, the shape of the flange, particularly in the vicinity of the beads, and the presence of wrinkles in the corners and over the drawbeads are in reasonable agreement with the experiment. Closer examination, however, reveals an apparent discrepancy in the details of the wrinkling. Figure 4a plots the deformed geometry as a shaded image and shows a short-wave periodicity that appears to represent wrinkles. However, these have an amplitude of less than 0.1 mm and follow the lines of the mesh. The overemphasis of this minor feature is a consequence of the rendering of the image. In addition, the model does not predict the wrinkles observed at the corner of the flange.

The predicted force on the upper punch is low by about 10 percent for most of the draw and initially has oscillations that are not seen experimentally (see Figure 5). Predictions on the force of the lower punch are in total agreement with the experiment throughout the entire operation.

In comparing measured surface strains at full draw, the agreement between model and experiment



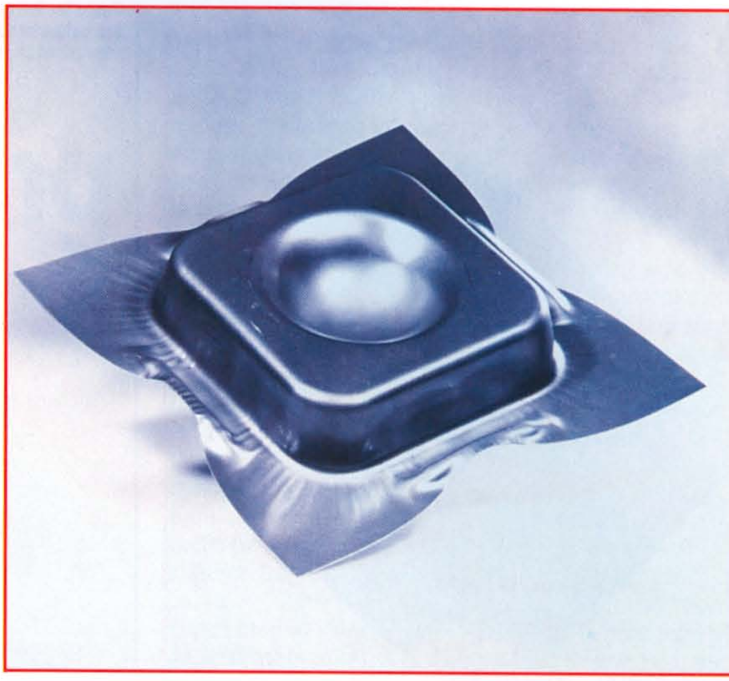


Figure 4a (above left). Calculated shape of the drawn pan.

Figure 4b (above right). Photograph of the drawn pan, showing wrinkling and the shape of the flange.

concerning the corner radius is reasonable (see Figures 6a and 6b). The gradients in strain match those predicted, although the absolute magnitudes of the measurements are a few percent lower. A serious discrepancy exists at the inboard edge of the drawbeads.

The model predicts strains in the range 0.45 to 0.50, while the measurements give strains on the order of 0.1 in the corresponding positions near the drawbeads. The predicted and measured patterns of strain up the side of the dome are similar; however, the former is about 0.5 lower than the experimental. The model data presented were obtained with no adjustable parameters. The geometry was identical to the experimental press; the flow law and friction were determined experimentally. From a materials point of view, the principal weaknesses are the lack of anisotropy in the model for the yield surface and the assumption that a combination of prestrain by rolling followed by uniaxial tension to define yield gives a valid representation of hardening. The simple model of constant Coulomb friction is also an oversimplification, though the presence of a polyethylene sheet is expected to improve the approximation over the case of sheet with lubrication only. Nevertheless, the performance of the model can be considered very accurate.

The reaction force on the upper punch is related initially to that needed to pull the sheet through the binder. Bounce of the binder would reduce the force, as illustrated in the model results. Towards the end of the draw, as the amount of material under the binder decreases, the force becomes progressively more related to the stretch of the sheet over the dome. The spikes in punch force, which diminish and disappear as the draw proceeds, are consistent also with the dynamic effects related to the bounce of the binder. The force on the lower punch is determined solely by the stresses required to stretch the sheet over the dome, and the influence of binder bounce is expected to be less than for the upper punch, as predicted by the model.

Evaluating a finite element model as a tool for design depends on a combination of the ease and speed of preprocessing, (including the entry of geometry, meshing, and the definition of restraints and boundary conditions), analysis, and postprocessing, as well as on the ability of the complete package to reproduce faithfully the process being modeled. The 36-hour execution time on an SGI Power Series workstation proved to be frustratingly long for model development but probably would be acceptable for production runs. Execution time on one processor of a CRAY Y-MP8 computer system was about 1.5 hours. There seems no question that models up to ten times the present size would run in acceptable times on a Cray Research supercomputer.

Discrepancies between the model and the experiment are of three types: those related to material anisotropy, those related to the mesh geometry, and those related to dynamic effects. Concerning material anisotropy, improved constitutive laws for the sheet are expected to rectify the underprediction of plasticity over the dome. Mesh effects played a role only with

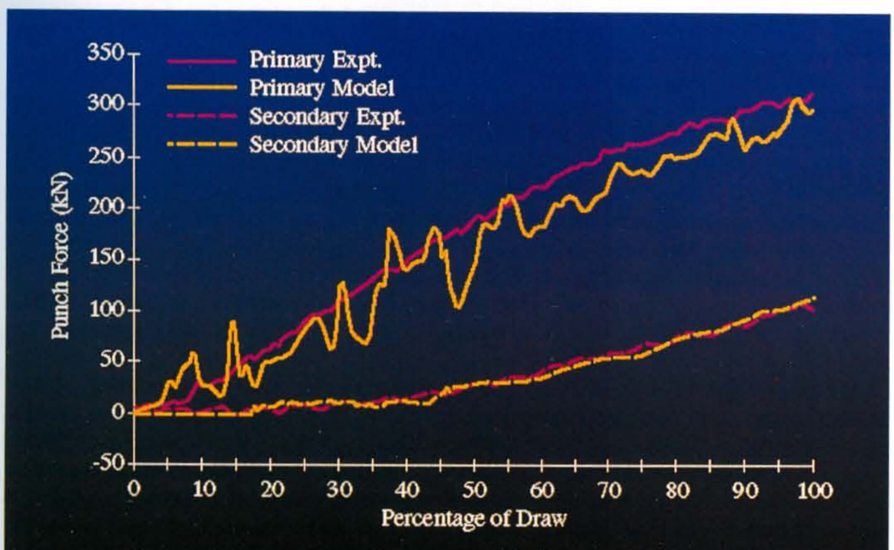


Figure 5. A comparison of measured and predicted punch forces.

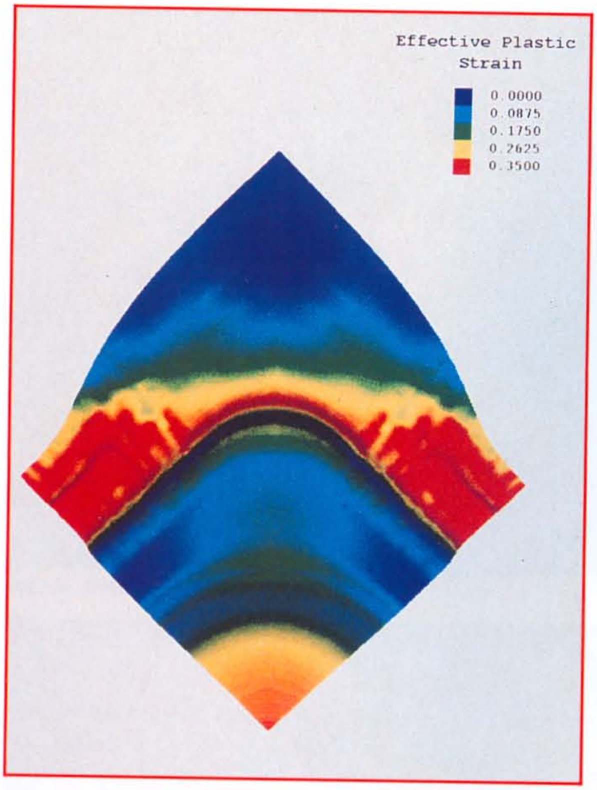


Figure 6a. Surface strains over the surface of the formed pan, determined from grid analysis.

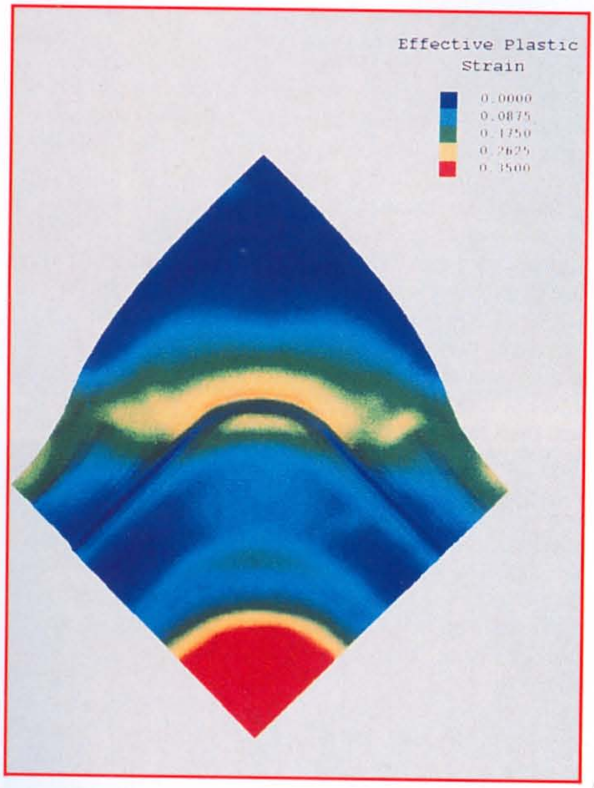


Figure 6b. Surface strains predicted by the model at the end of the draw.

respect to the prediction of wrinkling in the outer corner of the blank; the problem is trivial. Thus, the plasticity around the edge of the die produced by closure of the binder, the underprediction of the force on the primary punch, and the overprediction of the number of wrinkles appear to be the only significant artifacts directly attributable to the dynamic nature of the analysis. The above mentioned limitations all can be reduced or eliminated by choosing boundary conditions for the binder displacement more judiciously or by decreasing the velocity of the punch.

The principal disadvantage of an explicit code for simulation of sheet metal forming is the considerable amount of execution time spent observing features, such as oscillations in stress, or force or position of the binder, that are of little significance to die design. By reducing dynamic effects with the judicious application of boundary conditions and the development of contact damping algorithms, execution time should be reduced significantly.

LS-DYNA3D is suitable for large models of sheet forming operations. Improvements to minimize inertial effects, such as the bounce of tooling and ringing after unloading, are expected to reduce the execution time but not to affect significantly the agreement of the analysis with the experiment.

The trade-off between execution time and cost of hardware makes either an SGI Power Series workstation or a single-processor Cray Research computer system viable for problems of this size. For models five to ten times the size, which are anticipated for real automotive panels, a supercomputer platform will be required.

Anisotropic constitutive laws for plasticity, and possibly for friction, and a criterion for failure will be required before finite element metal forming analyses are completely satisfactory. ▬

Acknowledgments

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About the authors

Chris Galbraith joined Alcan's Kingston Research and Development Centre (KRDC) in 1989 after obtaining a Ph.D. degree in mechanical engineering from Queen's University at Kingston. He currently is working on modeling sheet metal formability for automotive applications.

Mark Finn is employed at KRDC as a researcher investigating finite element modeling of sheet metal formability. He graduated as a mechanical engineering technologist from St. Lawrence College in 1981.

Stuart MacEwen obtained a Ph.D. degree in metallurgy and material science from the University of Toronto in 1969. He worked at the Atomic Energy Canada Ltd. Chalk River Nuclear Laboratory from 1971 until joining Alcan as a principal scientist in 1989. His current work relates to linking the underlying science of deformation and plasticity to finite element models for sheet metal formability.

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3. Sowerby, R., J. L. Duncan, and E. Chu, *International Journal of Mechanical Science*, Vol. 28, p. 95, 1986.

Within this context, two things have not changed since the first application of digital computers to engineering analysis: an ever-increasing demand for raw computational speed to simulate complex physical events, and the ability to manipulate and interpret the input and output data. Before a structural event can be simulated, complex finite element models must be defined that represent the physical, geometric, and mechanical characteristics of the proposed product design. Once the analysis is complete, engineers must be able to extract key information from the results that will underlay the recommendations for engineering decisions. As the complexity of the physical events has increased, these pre- and postprocessing tasks have become formidable.

Adding the computational power of a CRAY XMS system helped Altair reduce the time to solution by decreasing the analysis time as well as allowing Altair's engineers to perform more complex simulations. To further minimize bottlenecks in the design process, Altair developed *HyperMesh,* a high-performance finite element pre- and postprocessing package.

In developing *HyperMesh,* Altair wanted to achieve more than just simple gains in measurable productivity. They wanted their engineers to be able to manipulate input and output easily to encourage them to investigate more design alternatives with greater thoroughness. While traditional finite element pre- and postprocessors were developed to simplify construction of basic models to be processed with the complex analytical codes already mentioned, these processors did not meet the requirements of the contemporary model sizes. *HyperMesh* addresses these issues by providing users with the capability to construct, organize, and manipulate models in excess of 50,000 shell elements on engineering workstations with only 8 or 16 Mbytes of RAM. Plotting speeds, a measure of pre- and postprocessor performance, are in excess of one order of magnitude greater using *HyperMesh* than those achieved using previous modeling tools.

Crashworthiness simulation

Because occupant safety is a primary concern of the automotive industry, crashworthiness issues dominate the design and analysis activities for the automobile companies and their suppliers. Impact events for full vehicle models are simulated to evaluate the performance of vehicle structures for front impact, rear impact, side impact, and roof crush events. Vehicle subsystems such as instrument panels, knee bolsters, steering columns, seats, doors, and other interior systems are also evaluated to study their interaction with passengers during an impact. These simulations are extremely demanding from a computational standpoint, and the presentation of results is critical to an accurate understanding of total system performance. A typical front barrier impact event simulated with LS-DYNA3D, a widely used nonlinear transient dynamic code, is illustrated in Figure 1. The hypothetical automobile, partially modeled with 13,000 elements, has been crashed into a barrier with an initial velocity of 50 mph. The first 40 milliseconds of the event were analyzed in time steps of microseconds. Approximately 40 to

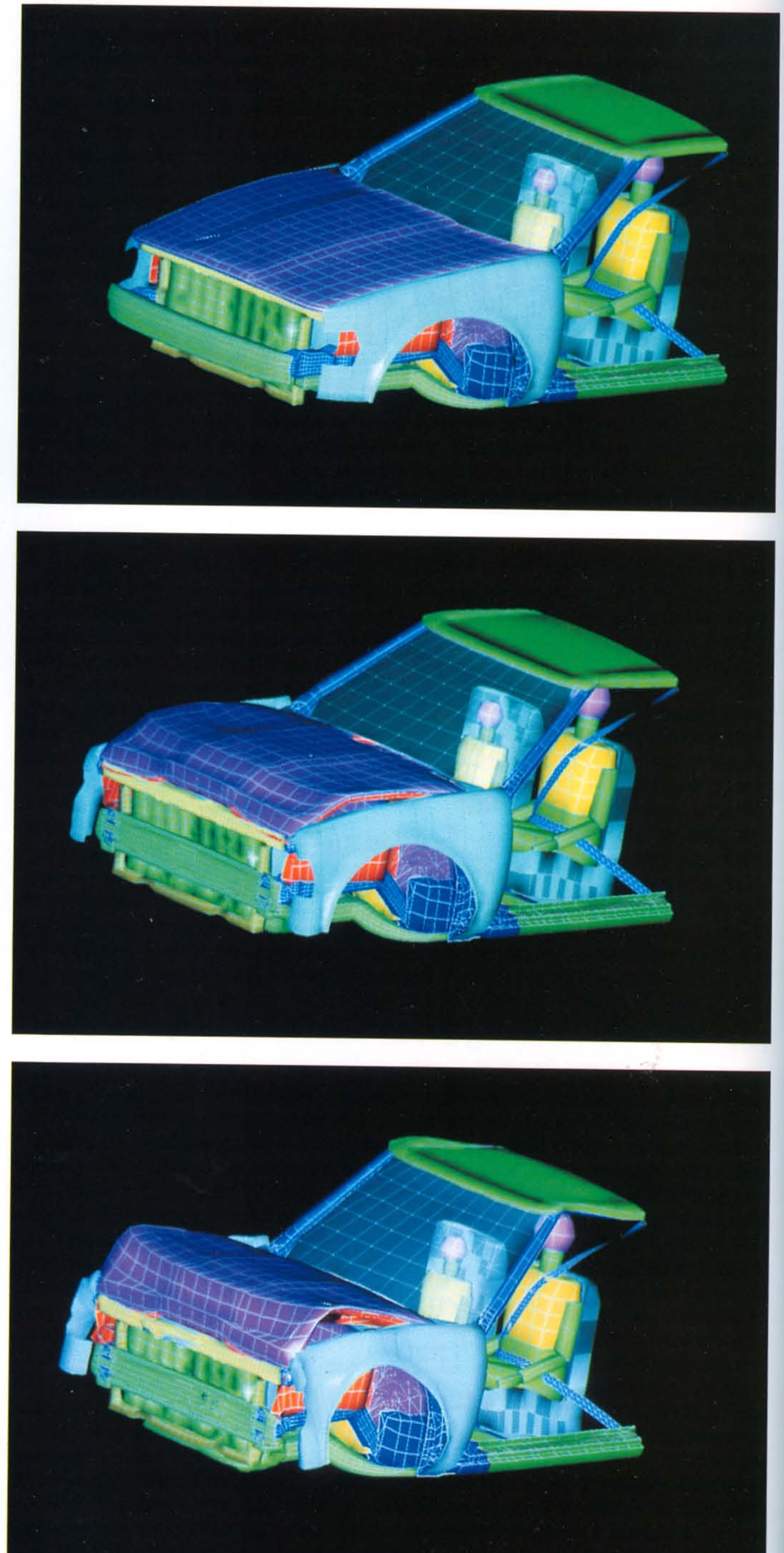

Figure 1 (top to bottom). Successive deformation during a typical front barrier impact at a velocity of 50 mph.

60 Mbytes of output data were generated for post-processing.

Before the introduction of the CRAY XMS supercomputer, the computing power required for this type of analysis would have been effectively unavailable to a company such as Altair. Additionally, pre- and post-processing software features that allow users to explore the animated results did not exist until the introduction of products such as *HyperMesh*. By providing light source shading with the ability to make specific components transparent instantaneously while the animation is in progress, *HyperMesh* enables Altair's engineers a greater level of design insight.

Vibration analysis

Another area gaining increased attention from automotive customers and manufacturers concerns noise and vibration performance of the vehicles and their subsystems, both for occupant comfort and structural integrity. Analysis of vibration modes demands easy manipulation and review of large quantities of output information. Once again, the computational power of the CRAY XMS system in combination with the *HyperMesh* postprocessing speed provides the engineer with the ability to examine a significantly greater number of alternative design iterations than was previously practical within the time constraints of the product development cycle. Figure 2 illustrates a V6 engine block showing displacement due to a natural mode of vibration analyzed with MSC/NASTRAN. In a typical analysis, the engineer would view a number of these displays, individually and sequentially animated, in order to understand the behavior of the design. The freedom to create these displays quickly and review them interactively offers an immense boost to productivity and creativity.

Metal forming

Altair's CRAY XMS supercomputer also has given the company an edge in understanding metal forming processes. The interaction of a punch, binder rings, and die with the sheet metal blank presents an especially difficult analytical challenge. Figure 3 illustrates a quarter model of a typical sheet metal component, displayed at one time step in the forming process. This model, analyzed with LS-DYNA3D, consists of 8700 elements. When combined with light source shading the visualization shows how the blank is formed into the fully drawn part.

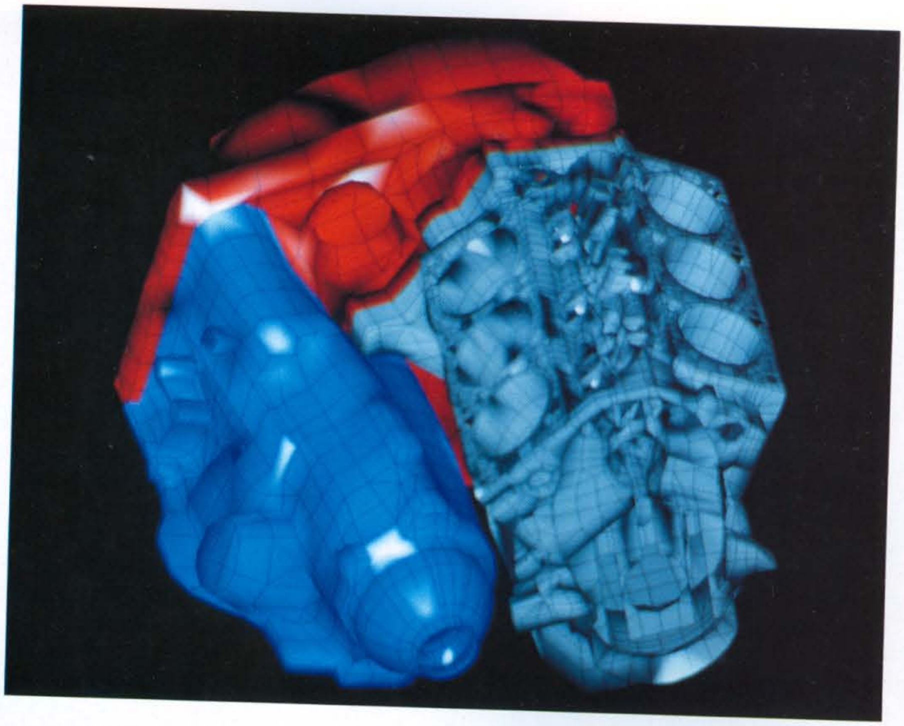

Figure 2. V6 engine block illustrating displacement due to vibration.

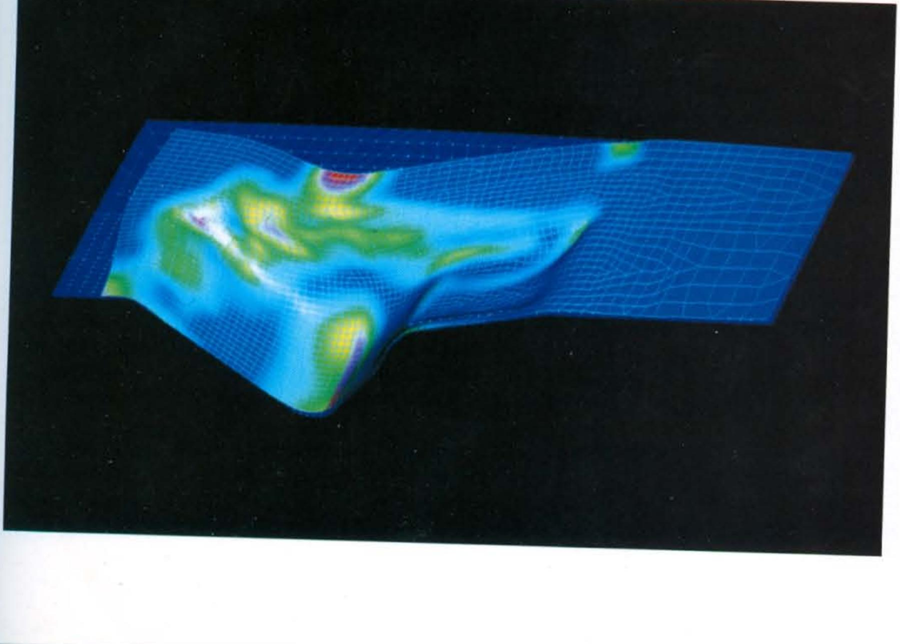

Figure 3. Quarter model of a typical sheet metal forming process.

Future directions

At Altair Engineering, the appetite for analytical power continues to grow. The upgrade of the CRAY XMS system to a CRAY Y-MP EL system will deliver increased computational resources, and version 1.2 of *HyperMesh* will offer another step forward in pre- and postprocessing sophistication. Altair looks to the combined team of Cray Research's entry level products and their own *HyperMesh* pre- and postprocessing package to leverage the talent of their engineers to develop winning products for the marketplace.

Acknowledgments

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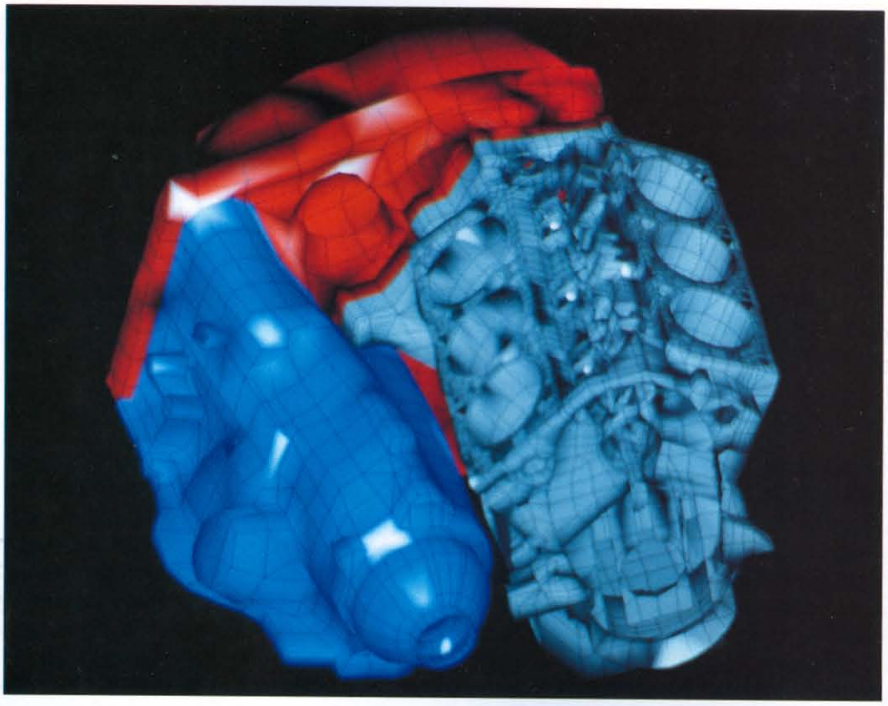

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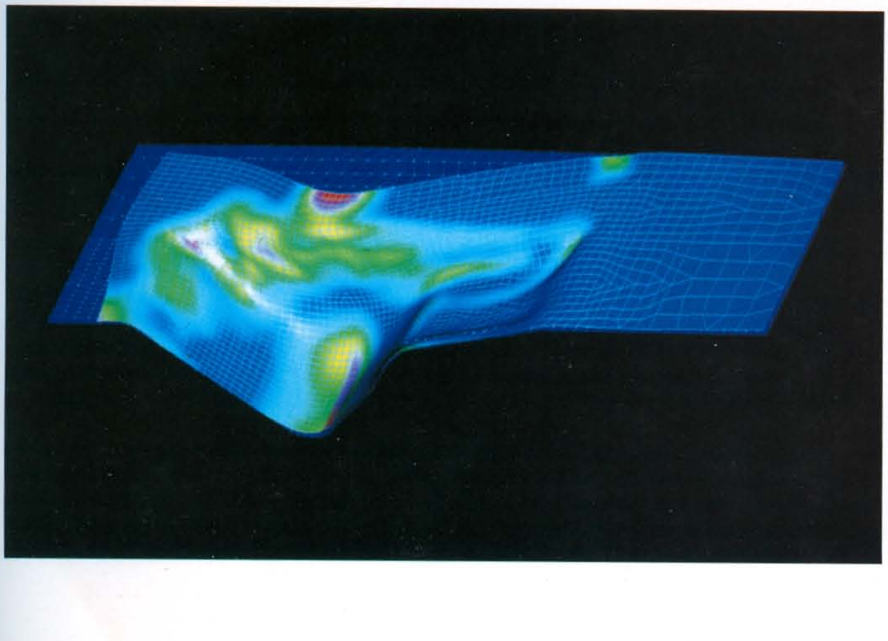

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DIMENSIONS O

The CRAY Y-MP EL Supercomputer System

Cray Research computer systems have given scientists and engineers a competitive edge for more than 15 years by enhancing productivity in diverse technical computing environments. Cray Research now extends these benefits to a broader range of users with the introduction of the CRAY Y-MP EL supercomputer — the most affordable computer system in the CRAY Y-MP family of systems.

The CRAY Y-MP EL system delivers unmatched throughput performance in its price range by incorporating all the advantages of the powerful and balanced CRAY Y-MP architecture. With up to four CPUs working in parallel and up to 1024 Mbytes of central memory, the CRAY Y-MP EL system provides a cost-effective, high-performance pathway to large-scale supercomputing.

Until now, the cost of supercomputing often exceeded the means of many who could benefit from the technology. The CRAY Y-MP EL computer system makes superior performance more affordable by significantly reducing the cost of acquiring, installing, operating, and maintaining a Cray Research supercomputer. Because it is air-cooled and uses less than 6 kW of power per cabinet, the CRAY Y-MP EL system can be installed in an air-conditioned office environment. It has a limited number of connections, making installation quick and easy.

The CRAY Y-MP EL system is compatible with other members of the CRAY Y-MP supercomputer family. All Cray Research computer systems run the UNICOS operating system, a powerful UNIX-based system optimized for maximum performance on production workloads. With outstanding functionality, performance, and ease of use, UNICOS is the most powerful and feature-rich operating system available for technical computing.

Because it conforms to industry standards and supports connectivity to equipment from a variety of vendors, the CRAY Y-MP EL system protects existing network investments. The result is an optimum computing environment with a wide range of resources to improve user productivity.

The CRAY Y-MP EL supercomputer features a powerful and balanced architecture that provides the highest possible performance in its class for scientific and engineering applications. In addition to departmental supercomputing, it can be used

- ☐ As a complementary system for larger Cray Research systems. The CRAY Y-MP EL is ideal for UNICOS application development. Because binaries from the CRAY Y-MP EL system will run on other CRAY Y-MP systems, work can be scaled up easily to larger Cray Research systems.
- ☐ As a secure system. Because it is physically compact and offers removable storage media and multilevel security, the CRAY Y-MP EL system is ideal for secure processing environments.
- ☐ As a high-performance file server. Combined with the powerful data management features of the UNICOS operating system, the CRAY Y-MP EL system is an excellent file server platform. The system can be used as a file server and perform scientific processing simultaneously.

The CRAY Y-MP EL system provides the following benefits along with outstanding performance:

- ☐ Unmatched price/performance. The CRAY Y-MP EL system offers more computing power for the money by offering the highest throughput in its price range for multiuser technical computing.
- ☐ Extensive connectivity. The CRAY Y-MP EL system connects easily to existing networks; it offers connectivity to a wide variety of mainframes, minicomputers, and workstations.
- ☐ Full functionality. The CRAY Y-MP EL system can be a cost-effective departmental supercomputer platform or a node in a heterogeneous networking environment.

The CRAY Y-MP EL system brings supercomputing excellence within the reach of a broad range of scientific computer users. As with all CRAY Y-MP systems, it offers outstanding price/performance. Backed by Cray Research's unmatched experience with total supercomputing solutions, the CRAY Y-MP EL system provides a competitive advantage in scientific computing.

F EXCELLENCE

The CRAY Y-MP C90 Supercomputer System

The U.S. Government Office of Science and Technology Policy has defined a range of technical problems that it considers the grand challenges of science and technology — problems such as the prediction of global climate change, the mapping of the human genome, and the determination of molecular and other physical structures. As scientists and engineers explore these formidable problems, the CRAY Y-MP C90 supercomputer, Cray Research's newest and most powerful supercomputer, will provide them with new avenues to insight and discovery.

The CRAY Y-MP C90 supercomputer sets new standards for high performance computing with six times the peak computing power of the original CRAY Y-MP8 system. The system's processors each provide a peak performance of 1 billion floating-point operations per second (1 GFLOPS). To achieve this performance, each CPU delivers two floating-point results per vector functional unit every clock period with a dual vector pipeline. Using 16 of these powerful processors and 256 million words (2 Gbytes) of central memory, the CRAY Y-MP C90 computer system delivers a peak performance of 16 GFLOPS.

Although some computer architectures offer fast solutions for certain types of problems, the balanced architecture of the CRAY Y-MP C90 system offers the highest possible performance on scalar, short vector, long vector, parallel, and highly parallel problems. The CRAY Y-MP C90 system includes the following capacities to ensure a balanced architecture that delivers maximum performance:

- ☐ More parallelism than any other vector supercomputer available today. The 16-processor CRAY Y-MP C90 produces 64 vector results per clock period. Combined with its mature, production-tested multitasking software, the CRAY Y-MP C90 system makes it easy to apply the highest level of parallelism available on a vector supercomputer to today's most widely used science and engineering codes.
- ☐ Unprecedented memory bandwidth. With four memory ports per CPU and 250 Gbytes/sec of memory bandwidth, the CRAY Y-MP C90 delivers extremely high levels of sustained computing power to users.
- ☐ Unmatched I/O bandwidth. To run efficiently, a high-speed supercomputer requires expansive input/output capabilities. With an aggregate I/O bandwidth of more than 13 Gbytes/sec, the CRAY Y-MP C90 system offers the most powerful and versatile I/O capabilities in the industry. The system also offers unmatched connectivity, with up to 256 external channels.

The CRAY Y-MP C90 system includes new technologies to enhance performance and reliability, including

- ☐ Custom high-speed silicon 10,000-gate-array logic chips — four times the integration level of previous devices — that increase reliability and reduce manufacturing costs
- ☐ Surface-mount component assembly that reduces manufacturing and reliability problems commonly associated with chip leads
- ☐ Multilayer circuit boards with internal pathways that prevent contaminants from corrupting signal integrity

The CRAY Y-MP C90 supercomputer provides an easy upgrade path from other CRAY Y-MP systems. Applications developed on any CRAY Y-MP system can be run on the CRAY Y-MP C90 system. As part of a total system solution, the CRAY Y-MP C90 application support environment includes UNICOS, the world's first and highest-performance UNIX-based supercomputer operating system, as well as a set of powerful compilers, development tools, high-performance libraries, and data storage systems.

The CRAY Y-MP C90 computer system is the most powerful supercomputer available. Its balanced architecture, new technologies, and compatibility with the full CRAY Y-MP series are combined into an unsurpassed scientific computing platform. As part of a complete supercomputing solution, the CRAY Y-MP C90 system provides the capabilities that scientists and engineers need to tackle today's production problems and grand challenges.

Boundary elements on Cray Research supercomputers

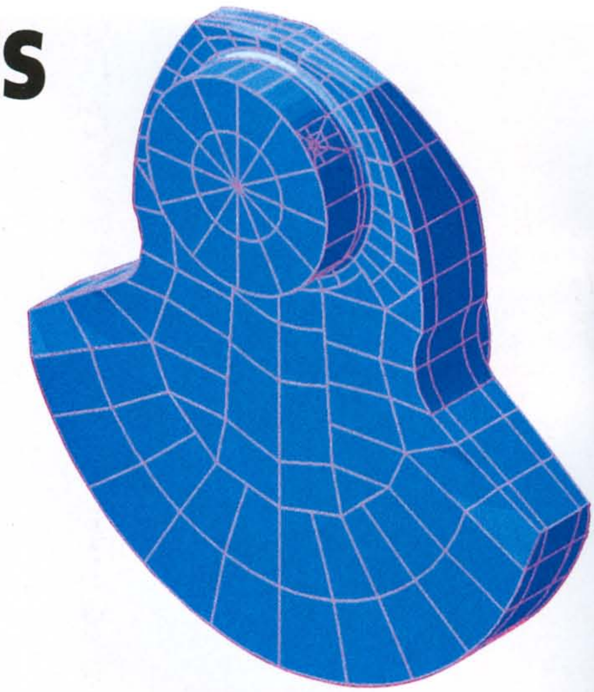

Figure 1. Model of half the crank throw with oil hole used to find bending stiffness.

Abbas Elzein, Computational Mechanics Institute
Ashurst, Southampton, England

The numerical simulation of engineering problems has become a major activity in the design processes of most advanced industries. Until recently, time and cost factors had been divided primarily between the man hours required to build the numerical model and the time needed by the CPU to complete the numerical analysis. However, major advances in supercomputing have altered this equation profoundly. With engineer time demanding the overwhelming share of development monies, industries are searching for a viable means to expedite the model building process.

One solution is offered by Computational Mechanics, developer of BEASY, a boundary element engineering analysis system for stress and heat transfer analyses. Because the boundary element method requires the user to define only the surface of the problem rather than its volume, the amount of time required to build the model is substantially reduced when compared to finite element modeling requirements. A boundary element analysis program running on a supercomputer achieves cheaper and faster design solutions because the speed with which the analysis can be performed is combined with a considerable reduction in the mesh preparation effort inherent to boundary elements.

Because BEASY is optimized for use on Cray Research supercomputers, it can take advantage of new integration and data management algorithms as well as library routines specific to Cray Research systems.[1] The result is substantial reductions in CPU time, wall-clock time, and memory requirements.

In its latest version, BEASY 4.0, stress analysis and steady-state heat transfer analyses of two-dimensional, axisymmetric, and three-dimensional problems can be performed. Linear, elastic conditions are assumed, and a large choice of boundary conditions is available. Nonlinear contact problems featuring gap elements with or without static or dynamic friction also can be analyzed. The stress intensity factors K1, K2, and K3 are calculated automatically for fracture mechanics problems.

A hierarchical element library features constant, linear, and quadratic elements as well as continuous or discontinuous elements (where nodes are inside the element rather than on its periphery). The element library simplifies model generation and improves accuracy in cases of geometrical discontinuities such as corners, or physical discontinuities such as the abrupt jump in stress concentration on a crack tip. Additionally, the user can employ an unlimited number of adjacent elements having nonaligned edges and/or noncoinciding nodes, further simplifying model generation.

In optimizing BEASY for Cray Research supercomputers, three main performance areas were targeted: the CPU time, elapsed time associated with I/O operations, and the memory requirements. The purpose of the optimization was to improve performance and to increase fivefold the size of problems that realistically can be analyzed. Problem size is determined by the number of degrees of freedom.

Because the solver in BEASY was already well vectorized,[2] the optimization effort targeted other areas such as the coefficients assembly, body forces calculation, data processing, etc. A carefully tested

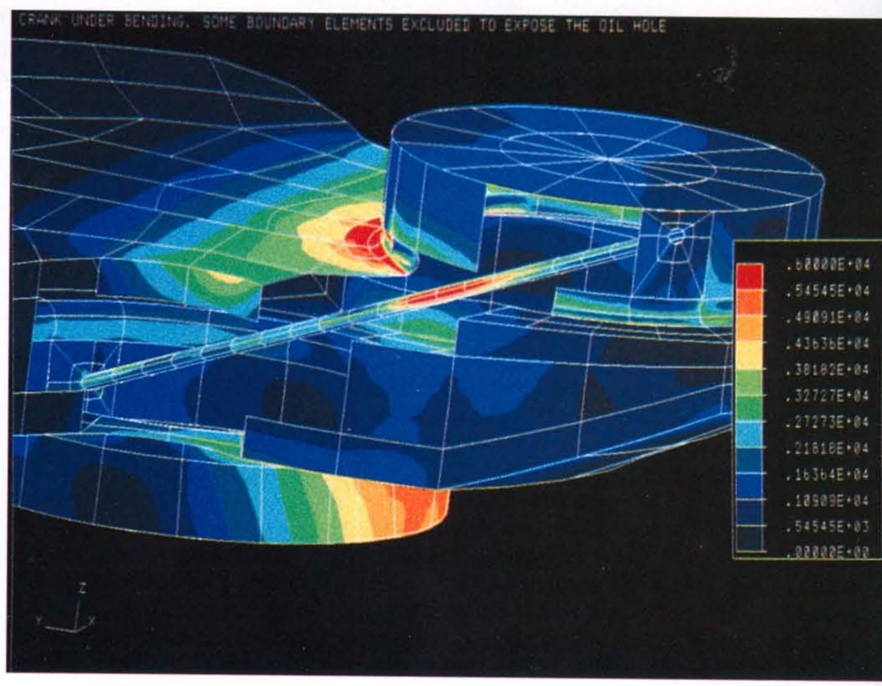

Figure 2. Contour plot of the von Mises stresses on the surface of the crank throw and oil hole.

combination of numerical integration algorithms, data management schemes, and special Cray Research library routines was implemented. The purpose is to reduce the amount of CPU and I/O operations and maximize the ratio of vector to scalar operations while maintaining the accuracy of the results.

The effect of the optimization was assessed by running four sample problems on a CRAY Y-MP system. Memory requirements were reduced by an average of 35 percent. The average reduction of the assembler CPU time was about 42 percent. This is a substantial reduction considering that the operations in the assembler, unlike those in the solver, are essentially scalar. The average reduction in total CPU time was about 38 percent.

The decrease in the amount of data transferred is due to a new data management system that reduces the overall number of I/O operations. However, this reduction does not reflect the improvements caused by the use of word-addressable files and the parametric optimization of I/O variables. These modifications minimize analysis time by accelerating the I/O without necessarily reducing the actual number of I/O operations. The reduction in time achieved by accelerated I/O combined with reduced CPU usage is far greater than the reduction in the amount of data transferred; analysis time decreased by a minimum of a factor of 3.5, while the amount of data transferred was only reduced by an average factor of 2.

To illustrate the capabilities of the BEASY analysis system running on a CRAY Y-MP system, two real-life models taken from the automotive industry have been analyzed using both the optimized and the nonoptimized versions.

Crank throw with an oil hole

Details of solid components are easier to model when only the surface of the solid is to be described. To that end, a crank throw penetrated by a lubrication hole was modeled on BEASY-IMS (Interactive Modeling System) and then analyzed. Figure 1 is a model of half the crank throw. It shows that the oil hole affects only the small number of elements around the two areas where it meets the external surface of the crank. Traction was applied normal to the midsection of the main journal. The purpose of the analysis was to determine the bending stiffness of the crank. No substructuring was made in this instance, and 619 linear elements were used.

The performance of the optimized and the nonoptimized versions of BEASY for this model are shown in Table 1.

Figure 2 shows a contour plot of the von Mises stresses on the surface of the crank throw and the oil hole. Some elements were removed from the plot to allow a view of the oil hole. In addition, the stress range determining the color spectrum was altered to obtain the color variation appearing on the surface of the oil hole where the stresses are relatively low and otherwise would fall into one or two color ranges.

Crankshaft model

A full crankshaft model was built using BEASY-IMS. The problem was divided into eight substructures and contained 1908 quadratic elements and about 10,300 nodes (30,882 degrees of freedom). Vertical bending traction was applied on the surface of four journals of the shaft. The problem required a minimum of two Mwords of memory and ran in one hour and 6 minutes of CPU time and about two hours 30 minutes elapsed time. Figure 3 shows a figure of the crankshaft.

These examples illustrate the value of software optimization in reducing turnaround time for engineering analysis problems. Optimization helps ensure that computational resources are used most efficiently. When optimized and run on the fastest hardware available, boundary element models serve engineers in many industries as powerful and cost-effective analysis tools.

	Nonoptimized version	Optimized version	Reduction (percent)
Substructures	1	1	–
Number of elements	619	619	–
Degrees of freedom	3789	3756	1
Memory required (Mwords)	1.28	0.92	28
Assembler CPU time	9 min. 17 sec.	6 min. 17 sec.	31
Total CPU time	17 min. 3 sec.	12 min. 44 sec.	31

Table 1. Performance of BEASY for crank throw model with an oil hole.

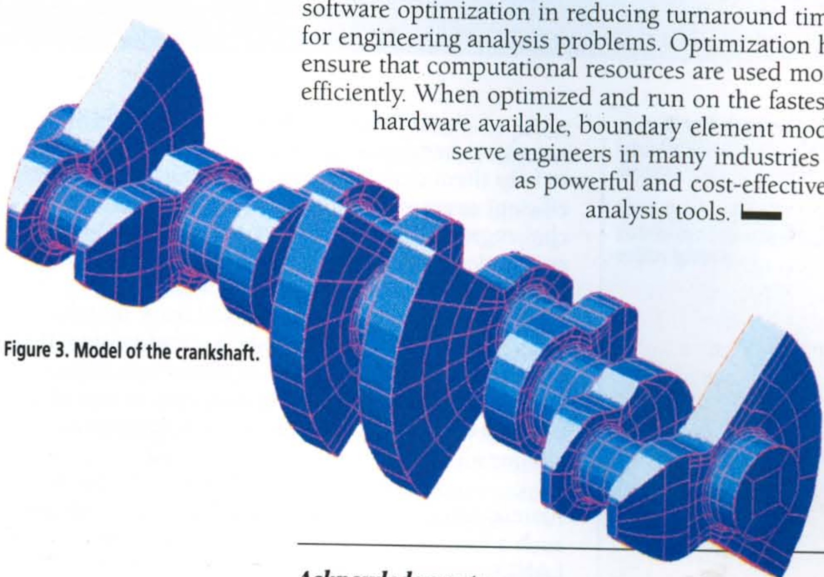

Figure 3. Model of the crankshaft.

Acknowledgments

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About the author

Abbas Elzein is a senior research and development analyst at Computational Mechanics Institute. Elzein received a B.S. degree in civil engineering from the American University of Beirut, a M.S. degree in structural engineering, and a Ph.D. in civil engineering from the University of Southampton.

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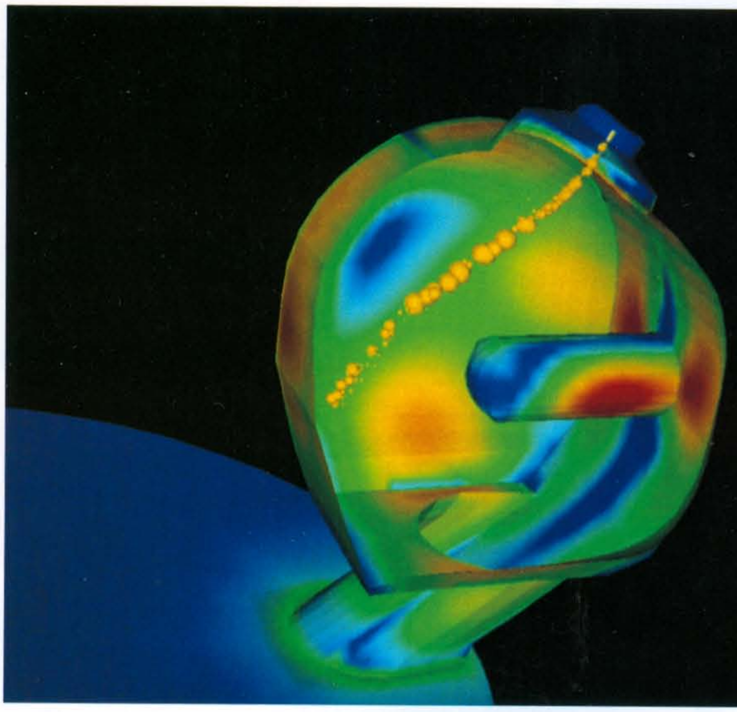


CRI/*Turbo*Kiva delivers the power of insight

by Reza Taghavi, Cray Research, Inc.

Air velocity distribution in an indirect injection diesel prechamber.

Automotive engineers typically rely on expensive handmade prototypes and software models to help them design reliable, clean-burning, and fuel-efficient engines. But today's engineers also are challenged by the competitive environment to cut engine design time by at least half. Meeting this challenge requires a new analysis tool to help engineers choose the right physical tests, thereby reducing the number of prototypes and helping them to better interpret the results of test bench analyses. Such a tool must also be very fast, easy to use, and integrated into the computer aided engineering (CAE) environment.

Cray Research, in collaboration with Los Alamos National Laboratory (LANL), has developed such a tool. Called CRI/*Turbo*Kiva, it is based on LANL's powerful research product, Kiva II. Kiva II has gained wide acceptance in the engine research and design community as a low-cost solution that is generally robust in numerical scheme and modularity, and as such, is the preferred simulation code for cold flow, spray, and combustion modeling in engines.

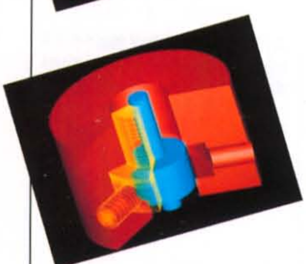
Cray Research's goal in developing CRI/*Turbo*-Kiva was to transform this powerful research code into an engineering tool that can use existing mesh generators to simulate real-world internal combustion engines. Most importantly, Cray Research wanted to make CRI/*Turbo*Kiva easy to use by all automotive engineers — engineers who are interested in designing the most fuel-efficient and environmentally safe combustion engines — engineers who are neither physicists nor computer experts.

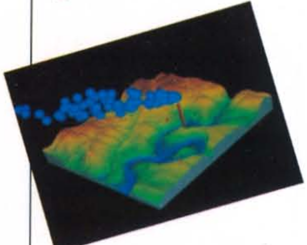
To meet these requirements, CRI/*Turbo*Kiva offers automotive engineers the capability to:

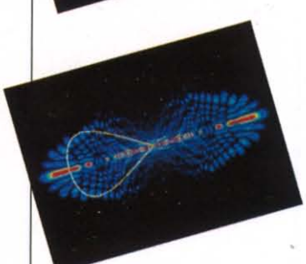
- ☐ Provide a realistic simulation of a combustion chamber in a multi-cylinder environment. CRI/*Turbo*Kiva can simulate a complete production combustion chamber, either spark-ignited or diesel, with up to six intake and exhaust port/valve assemblies with arbitrary valve cam laws. By using the output of in-house, one-dimensional gas dynamic cycle simulation software, CRI/*Turbo*Kiva can deliver a realistic three-dimensional simulation of a combustion chamber in a multi-cylinder environment.
- ☐ Model phenomena accurately occurring inside the combustion chamber. By interacting with the physical tests, and with the help of the Magnussen combustion model or a user-supplied model, CRI/*Turbo*Kiva enables engineers to discover the origin of phenomena such as slow burn duration, knock, low volumetric efficiency, soot, nitric oxide and carbon monoxide emissions, combustion instability, and misfire at low RPM.
- ☐ Interact constantly with experimental work. CRI/*Turbo*Kiva allows engineers to read initial in-cylinder velocity profiles and to specify initial swirl and tumble numbers to provide the appropriate initial flow condition at inlet valve closure. CRI/*Turbo*Kiva output then can be used to build graphs of average pressure, as well as instantaneous and cumulative burn rates. By comparing these results with traditional diagnostic graphs obtained from physical testing, engineers can make more informed decisions when choosing various combustion, auto-ignition, or initial laminar flame growth constants. CRI/*Turbo*Kiva does not replace physical experiments; instead, it helps engineers choose the right experiments, thereby reducing the number of experiments and the overall engine design cycle.
- ☐ Assess and improve mesh quality before simulation. Because mesh quality directly influences the performance, accuracy, and overall success of a simulation, CRI/*Turbo*Kiva assesses the quality of the mesh, and if necessary, improves it. Using

The Regional Computer Center of the University of Stuttgart (RUS)

A showcase of supercomputer applications







The Regional Computer Center of the University of Stuttgart (RUS) was the first German university to install a CRAY-1 system, in 1983; a CRAY-2 system, in 1987; and to use Cray Research's UNICOS operating system. RUS also pioneered the network supercomputing concept in Europe, installing the first Gbit/s network, in 1989, and achieving a world record data transfer speed of 95 million bits per second over a distance of several hundred kilometers.

A history of firsts

In 1990, RUS demonstrated high-speed, wide-area Open System Interconnection (OSI) connectivity to supercomputers for the first time in the world, transferring data between the CRAY-2 system in Stuttgart and a workstation in Berlin via the German Science Network WIN at 64 Kbit/s, as well as via the fiber-optics-based broadband network, VBN, of the German Postal Service Telekom (140 Mbit/s).

In May 1991, RUS continued its series of supercomputing firsts by installing a CRAY Y-MP 2E system as a dedicated file server.

Looking back on the center's history of firsts, K.-G. Reinsch, executive director of the computer center, credits both the "organic growth" of RUS from the early days of supercomputing in the 1960s (the University of Stuttgart's first supercomputer was a CDC 6600), and the "synergistic effect" resulting from the continuous exchange with its growing circle of users, for RUS' achievements in the three key areas of supercomputing: compute power, networks, and visualization. "We were engaged in an intensive dialogue with our users right from the start, and we consistently based the structure for our computer center on user needs," says Reinsch.

Before installing the CRAY Y-MP 2E supercomputer as a file server, RUS was suffering a problem common among large computer centers: a compute server bogged down in file access and data management. "If computing power is available, and fast networks are in place, but data access creates a bottleneck, the whole concept of speed and power falls on its face, and we lose our advantage. The dedicated file server is the perfect third building block in this infrastructure," said Reinsch. Since its installation, the CRAY Y-MP 2E system has taken over both mass data storage and high-speed data access, functioning as an extremely fast, large data buffer.

In addition to managing the data produced on the RUS CRAY-2 system, the CRAY Y-MP 2E system acts as a buffer for three networks that function at different speeds: an Ethernet, at 10 Mbit/s; a Hyperchannel, at 50 Mbit/s; and an Ultra Network, at over 800 Mbit/s.

Professor Roland Rühle, a former user at RUS and now its scientific director, sees data access as the key ingredient in today's supercomputing environment. "The CRAY Y-MP 2E system is a kind of 'speed-dial' for data, allowing the fast interpretation of those massive numerical graveyards," explains Rühle, referring to the data sets of several gigabytes created routinely on the CRAY-2 system. "The quick visualization of large amounts of data, and the time savings achieved in the process translate into significant increases in productivity for RUS and its users."

RUS applications: A medley of scientific disciplines

Over 1000 workstations tap into the CRAY-2 system's power at RUS. Among the users are German universities, such as Heidelberg and Tübingen; research institutes, such as the Alfred Wegener Institute in Bremerhaven; and industrial research center clients such as Porsche and Bosch. Following, researchers and engineers working in diverse areas describe their supercomputer applications.

Direct numerical simulation of transition to turbulence

Ulrich Rist, Markus Kloker, and Horst Bestek
Institute of Aerodynamics and Gas Dynamics
University of Stuttgart, Germany

Understanding transition from laminar to turbulent flow remains one of the major challenges in fluid mechanics and aerodynamics. Due to the different behaviors of laminar and turbulent boundary layers with respect to skin friction and resistance to separation, transition heavily influences the performance of aerodynamic vehicles. Thus the accurate prediction and control of boundary-layer transition to turbulence is vital to aerodynamic research and design.

Direct numerical simulation of the disturbance that develops during laminar-turbulent transition has become an increasingly effective tool for transition research.[1] During the past few years, the Transition and Turbulence group at the University of Stuttgart[2] has developed combined finite-difference/spectral codes for the solution of three-dimensional Navier-Stokes equations for incompressible and compressible flow.

The codes allow scientists to investigate the spatial propagation and development of all types of two- and three-dimensional waves in unstable shear flows. The example presented here shows the results of a numerical simulation of a periodically forced flat-plate laminar boundary layer where a two-dimensional, so-called Tollmien-Schlichting, wave and pairs of counter-rotating longitudinal vortices are introduced at the disturbance strip. As the wave travels downstream, three-dimensional disturbances get amplified due to secondary instability. Spanwise peaks and valleys in the disturbance signals, aligned Λ-vorticity, instantaneous high-shear layers and hairpin vortices also develop. This kind of scenario is called "K-type" transition.

The transition simulation with the best resolution to date used 32 spanwise Fourier modes together with 121 points in the y-direction and initially 1900 grid points in the x-direction which finally were increased to 4600 points as the disturbances traveled downstream. Twelve disturbance cycles have been calculated in 7100 time steps, requiring 400 hours of CPU time and all the available memory (220 Mwords) of the CRAY-2 system in the final stage of the simulation.

The evolving dynamic processes are displayed in Figure 1. The z-component of vorticity is shown at the spanwise position $z = 0$ for three instants. Only a part of the integration domain, consisting of 1400 points in the x-direction, is shown. The formation and subsequent breakdown of instantaneous high-shear layers into smaller vorticity concentrations leading to a flow that resembles that of a turbulent boundary layer can be observed.

The spatial distribution of the spanwise vorticity component is shown in Figure 2. Only those

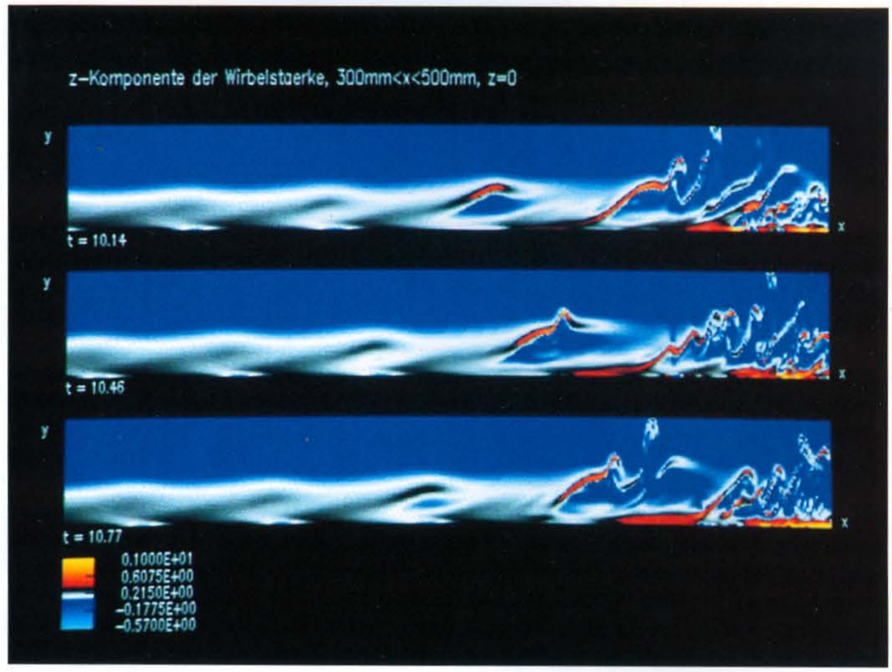


Figure 1. Instantaneous spanwise vorticity (ω_z) contours in x-y plane at so-called peak station ($z = 0$) for three time instances during the breakdown of the high-shear layer.

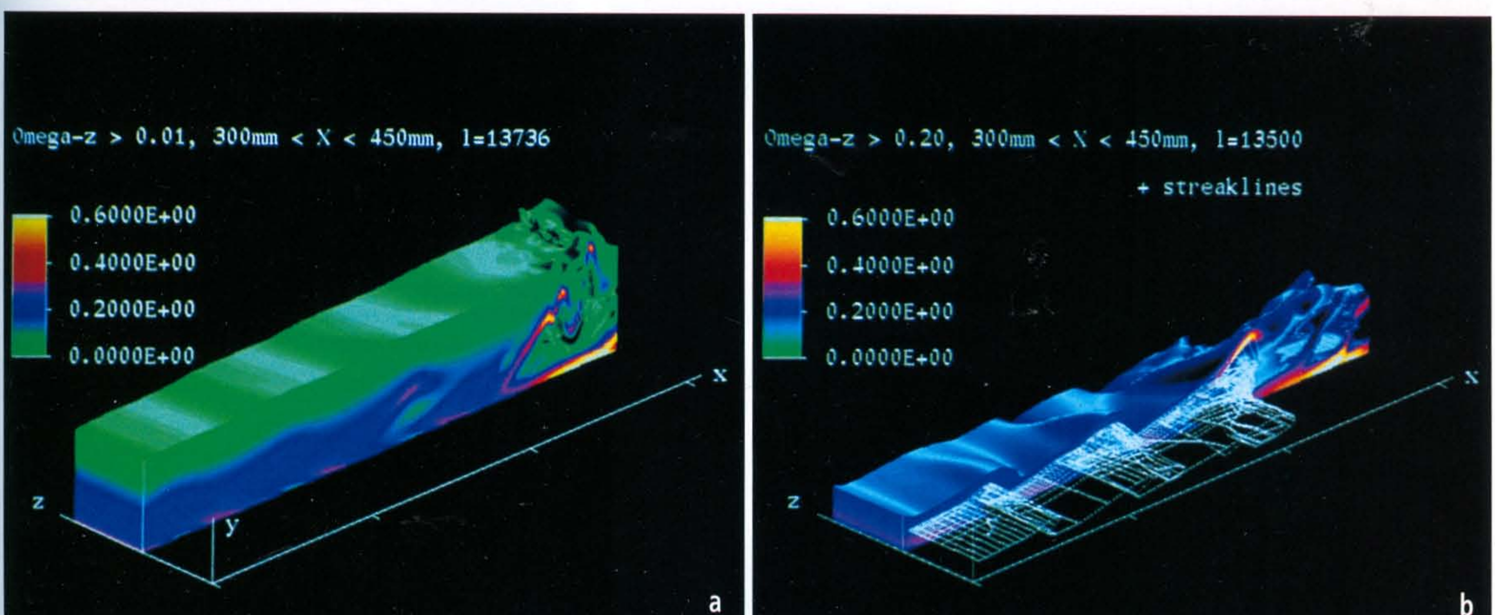


Figure 2. Perspective view of instantaneous ω_z vorticity field bounded by cuts at $x = 300$ mm, $z = 0$, and an isosurface. (a) Isosurface at low ω_z (b) Isosurface at high ω_z compared with time- and streaklines.

data that exceed a certain threshold are displayed ($\omega_z \geq 0.01$ in Figure 2a, $\omega_z \geq 0.20$ in Figure 2b). The three-dimensional structure of high-shear layers observed in Figure 1 is apparent in these perspective views. High-shear layers appear as triangular structures that gradually evolve out of the two-dimensional wave as the disturbance moves downstream.

Timelines, created by connecting all of the particles released at the same time from a horizontal wire, and streaklines, created by connecting all of the particles that have been released at one location, also are displayed in Figure 2b. These lines show the generation of the so-called Λ-vortex, another structure typical of the highly nonlinear transition process. The good correlation of the high-shear layer formation with the Λ-vortex is clearly illustrated.

The realistic simulation of transition phenomena is extremely useful in interpreting transition experiments, providing much more detailed information about the flow field than is observable in the experiments. Direct numerical simulation will become an even more powerful tool in transition research with the next generation of supercomputers, allowing the solution of problems of even greater complexity more economically.

About the authors

Ulrich Rist received a Ph.D. degree in engineering from the University of Stuttgart in 1990. He developed the numerical method described here in cooperation with Uwe Konzelmann.[3]

Markus Kloker, who holds an advanced degree in aeronautical engineering, improved the efficiency of the code considerably and performed the simulation presented in this article.

Horst Bestek is a senior research scientist and head of the research group Transition and Turbulence. He received his advanced engineering degree from the University of Stuttgart in 1980.

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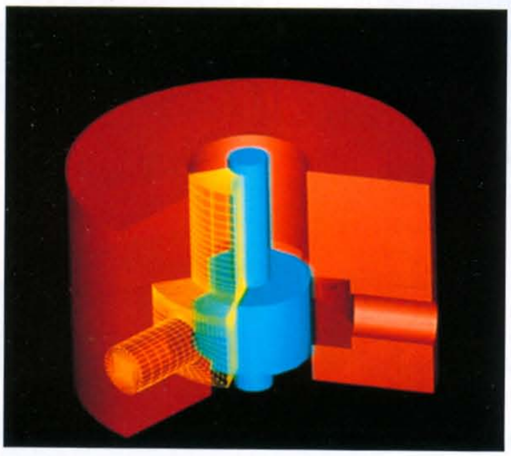
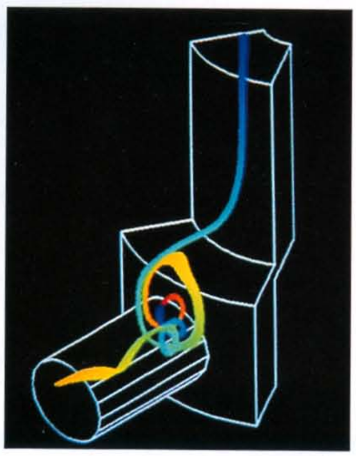




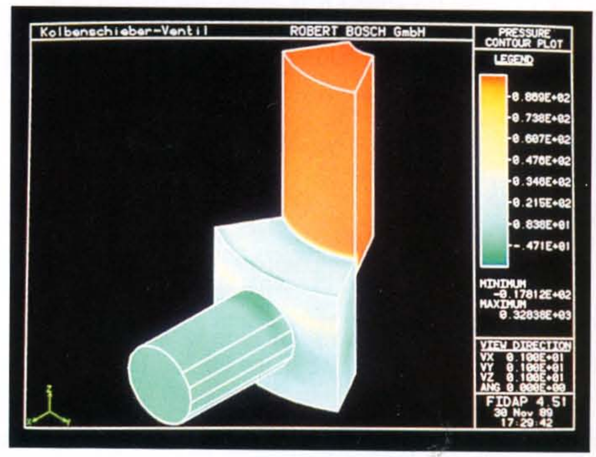


Figure 1 (above). Cross section of spool valve with overlaid finite element grid.

Figure 2 (above right). Path of volume element through spool valve segment.

Figure 3 (above far right). Pressure distribution in spool valve segment.

A three-dimensional fluid dynamics simulation using FIDAP

Christian Döring, Thomas Grauer, and Christer Jansson
Robert Bosch GmbH, Dept. K-EVA1, Stuttgart, Germany
Martin Winter, Regional Computer Center of the University of Stuttgart, Germany

The simulation of fluid dynamics in viscous fluids remains one of the most computationally intensive processes. Traditionally, the fluid dynamics of hydraulic components was investigated experimentally and described with the help of empirical formulas. However, the availability of supercomputers has led to the increased use of numerical fluid dynamics as a tool in product development.

Researchers at Robert Bosch GmbH are investigating the degree to which experimental process can be replaced by numerical simulation. A three-dimensional fluid dynamics computation was performed on a typical spool valve to determine flow coefficients and hydraulic forces, using the FIDAP program from Fluid Dynamics International.

Figure 1 shows the finite element grid of a segment of this valve. The simulation was rendered with the PATRAN preprocessor and consists of about 13,000 grid points. Flow speeds and pressure distributions were computed using FIDAP. Figure 2 depicts the path of a volume element which — as it passes across the inlet through the narrow throttle — is forced into a complicated rotation and finally arrives at the outlet. The resulting pressure distribution along the walls is shown in Figure 3.

For the computation of one parameter case, one processor of the CRAY-2 system requires about two CPU hours and 80 Megawords of memory. By comparison, the computation would require about 150 hours on a VAX 8810 computer from Digital Equipment Corporation. The results were visualized with the FIDAP postprocessor on a Silicon Graphics IRIS 4D-20 workstation.

The Stuttgart TERA project: defining the future of supercomputing

Fritz Schmidt, Institute for Nuclear Energetics and Energy Systems, University of Stuttgart

As a candidate for the first European teraflops computer — and in keeping with its tradition of firsts — the University of Stuttgart and four of its research institutes have initiated the Stuttgart TERA project, a multidisciplinary effort that combines the resources of supercomputing, high-speed networking, computational engineering, environmental research, and satellite remote sensing.

The Stuttgart partners are developing an interdisciplinary model for the simulation of the dispersion of air pollutants over the metropolitan area of Stuttgart. The model fulfills the prerequisites established by the group:

- ☐ The application is so complex that it justifies the use of a teraflops computer.
- ☐ Its methods and results can be communicated clearly within the group and to the general public.
- ☐ Each collaborator has made independent contributions in complementary areas that can be integrated easily into the example.
- ☐ The knowledge gained from the initiative can be applied in other areas.

"On the basis of this model," explains Schmidt, "we intend to explore frontiers in the participating disciplines, to derive interdisciplinary solutions based on the most advanced teraflops computer techniques, and to install computing environments which allow us to turn these solutions into engineering products."

The Institute for Nuclear Energetics and Energy Systems (IKE) is responsible for the physical and numerical models. They are based on models provided by the German climate model FITNAH developed through a joint effort of several meteorology institutes.

The Institute for Navigation (INS) is furnishing the boundary data for the model by processing satellite images. From this data, surface roughness, humidity, and daily temperature variations are correlated. Infrared photos of the Stuttgart area are used to deduce the temperature correlation.

Boundary conditions toward the open atmosphere are adopted from data supplied by the German Weather Service (DWD) following typical Stuttgart weather conditions (based on the Europa model at the present time).

The Institute for Computer Applications (ICA) is providing the visualization model. At the present, it is based on the Multipurpose Graphic System (MPGS) from Cray Research which was also used to generate the visualization of transient particles over the Neckar valley topography (see Figure 1).

The Institute for Chemical and Boiler Engineering (IVD) is providing stationary and mobile air pollution measurements and meteorological data in the studied region and is developing the validation model. RUS is managing the networks and providing access to its CRAY-2 and CRAY Y-MP 2E supercomputers.

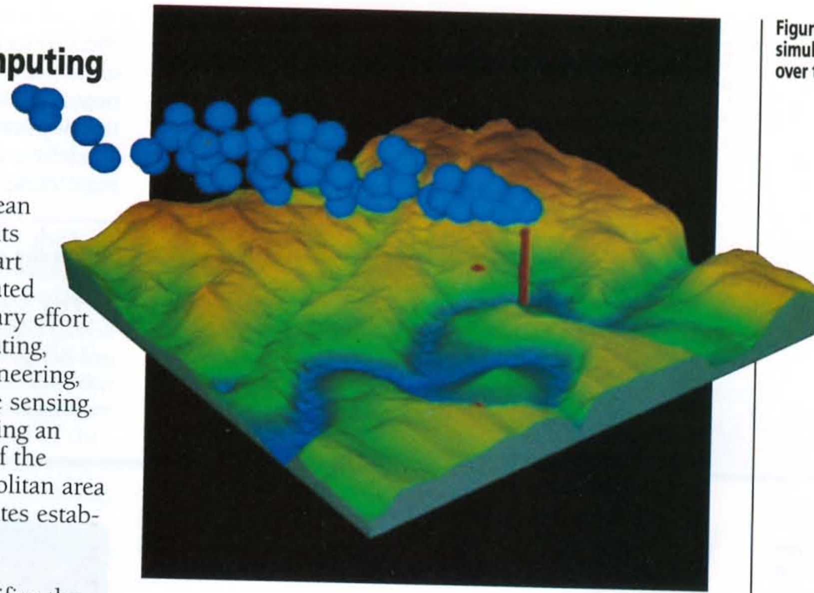
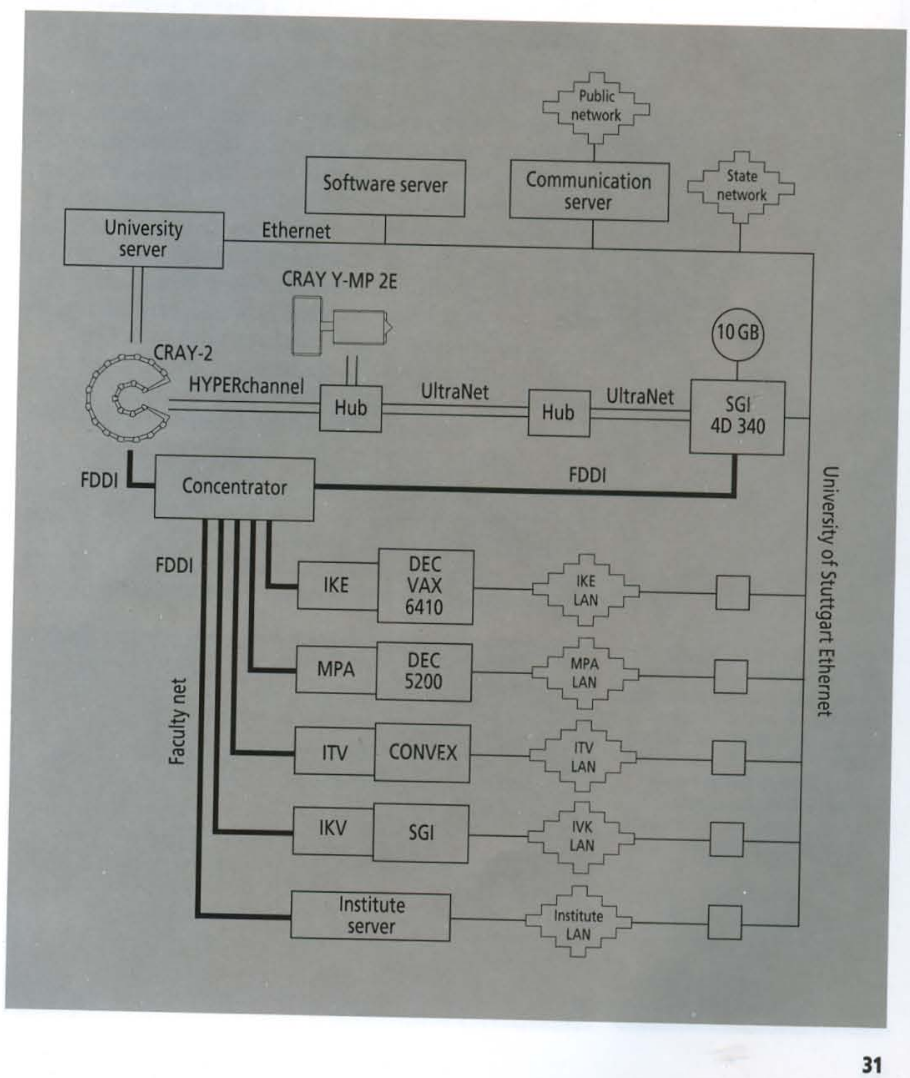


Figure 1. Stuttgart terrain simulation: transient particles over the topography.

In addition, industrial partners, such as Silicon Graphics, DEC, Ultra Network, Microtechnology, and Cray Research are supporting the initiative by establishing the computational environment shown in Figure 2.

The numerical model used in the initiative involves three steps: from mega-, to giga-, to tera-sized problems. For the mega-sized problem currently being

Figure 2. High-speed network available for the TERA project.



worked on, the proposed resolution is about 500 m between grid points. Approximately 60,000 volume elements and 700 iterations are required to simulate a 24-hour period. Problems of this magnitude require about one hour of computing time on one processor of the CRAY-2 system.

For the giga-sized problem, the mesh size will be reduced to 100 m between grid points, the axial mesh width will be cut in half, and the number of node points will increase by a factor of 50. The solution for this type of problem requires the memory and computational capability of the entire CRAY-2 system. Intensive parallelization and vectorization efforts are required. The giga-sized problem will be tackled in 1992 and 1993.

The tera-sized problem will use a grid with 10 m between grid points — the optimal size obtainable by interpretation of satellite images at this time. The 10 m resolution will require changes in the physical, mathematical, numerical, and analytical modeling, as well as the power of a next-generation supercomputer.

About the author

Dr. Fritz Schmidt heads the department of Knowledge Engineering and Numerics of the Institute for Nuclear Energetics and Energy Systems at the University of Stuttgart. His research is focused on computational engineering, in particular numerical methods and the modeling of complex systems.

Visualization in atomics and astrophysics

Hanns Ruder, Department of Theoretical Astrophysics (TAT), University of Tübingen, Germany

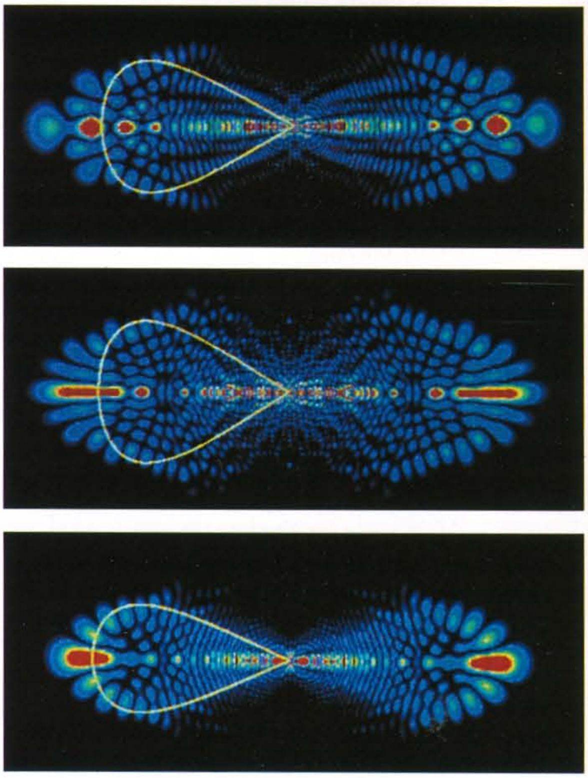


Figure 1. Probability of presence of the electron in highly excited (Rydberg) states of the hydrogen atom in a magnetic field of 6 Tesla. These atomic structures have a spatial extent on the order of 10^{-3} mm.

The high-speed computer link betweeen Tübingen and Stuttgart allowed several research groups at the department of theoretical astrophysics (TAT) at the University of Tübingen to compute atomic and cosmic phenomena on the CRAY-2 supercomputer at RUS, visualizing the results on graphic workstations in Tübingen. In this research the computer serves as a supermicroscope, a giant telescope, and even a space ship.

Using the supercomputer as a supermicroscope, the atomic physics group at TAT studied the effect of a varying magnetic field on the shape of an atom. New insights into the physics of compact objects were gained by visualizing the highly excited states — so-called Rydberg states — of a hydrogen atom. The thousand lowest energy eigenvalues and the corresponding state vectors were computed on the supercomputer from matrices with over 170 million nonzero matrix elements. In these states the atom exhibits a delicate and bizarre structure with binding energies of a few millielectron volts and spatial extensions along the direction of the magnetic field of up to one thousandth of a millimeter — comparable to the intended characteristic sizes of chip structures in VLSI technology.

Providing interesting examples for studying the transition from classical physics to quantum mechanics, these structures also are of fundamental significance for questions relating to quantum chaos. In these ranges of magnetic field and energy, the classical system shows a transition from regular to chaotic

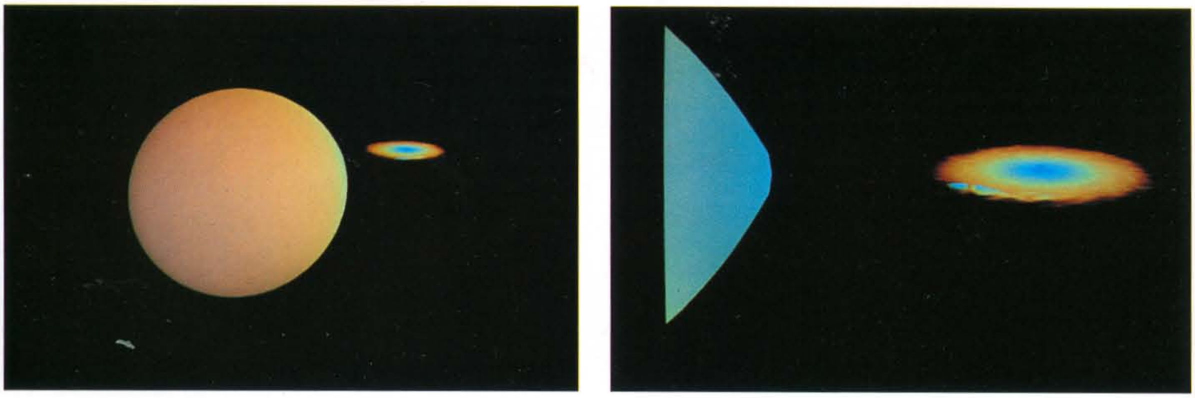


Figure 2. During its "voyage" through space, the supercomputer "flies" past a double star system (normal star and white dwarf). The accretion disk is formed from material flowing from the normal star to the very compact white dwarf. Cosmic phenomena, such as x-ray sources, may be attributable to such accretion disks.

behavior. Classic periodic paths become increasingly unstable; nonperiodic paths become stochastic. The principle of equivalence, however, predicts a tendency for localization of the electron, that is, for an increase in the probability density of the electron, along classical paths. The color coded visualization reveals such localizations along classical paths as "scars" in the structure (Figure 1).

In the study of cosmic dimensions, the computer serves as a giant telescope. Knowledge of the structure of the cosmos and the objects contained in it is derived from careful analysis of electromagnetic radiation reaching Earth, combined with theoretical modeling based on the laws of physics. Astronomical observations today include the radio wave range, the infrared range, the optical and the x-ray range of the spectrum, all the way up to the highest gamma rays.

Advances in satellite and computer technology have provided new insight into highly interesting phenomena such as soft x-rays that originate under extreme physical conditions. The temperature as well as the magnetic and gravitational fields required to produce this radiation are so extreme that they could never be reproduced in laboratories on Earth. Therefore, the material properties and the physical processes occurring under these conditions cannot be observed experimentally; they can only be modeled theoretically, using the supercomputer as a giant telescope.

With few exceptions, cosmic objects are so incredibly far away that they can only be seen as point sources. To be able to observe them as expanded objects one would have to either fly there or develop an optically perfect telescope with a diameter of one million kilometers or more. Table 1 lists the minimum telescope apertures for several typical cosmic distances that are required for the spatial resolution of an object with a size of 10 kilometers. The figures demonstrate that in the foreseeable future, it will be impossible to obtain spatially resolved images of most astrophysical objects outside of our solar system.

Binary star systems often evolve to a state in which one star becomes a very compact star such as a white dwarf or a neutron star while the other is a normal star. At that point, the compact star may pull gas out of its companion by gravitational attraction. This gas forms a disk-like structure (accretion disk) around the compact star.

Using the computer as space ship, the plasma physics group at TAT has been modeling and visualizing theoretical descriptions of the plasma forming the accretion disk. The behavior of the plasma is governed by hydrodynamic equations, taking external forces (gravity) and internal forces (gas pressure and viscous interaction between particles) into account. The equations are solved by a numerical method known as particle simulation. The system itself contains on the order of 10^{25} particles, too many to treat numerically. Instead, it is simulated by an equivalent system containing fewer pseudoparticles. However, it is still necessary to include about 10^4 pseudo-particles to achieve the desired accuracy, presenting us with a problem that is tractable only on supercomputers such as the CRAY-2 system at RUS.

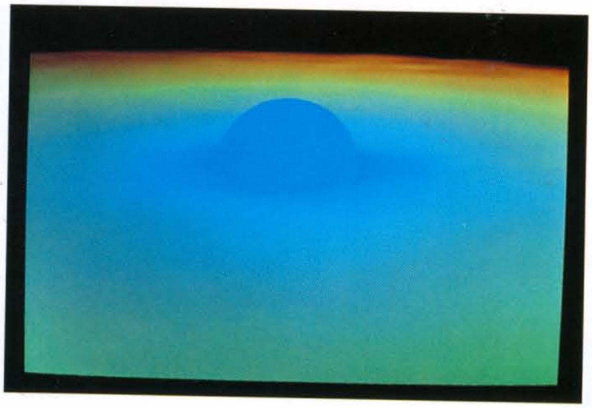
Once the behavior of the accretion disk is modeled, it can be visualized in a variety of ways. For the image sequence in Figure 2, the surface temperatures of the accretion disk and the stars are determined. Assuming that the surfaces emit radiation thermally, the intensity and color at each point can be determined. The pictures show a simulated space flight exploring the binary system. First we circle the system to view it from different sides, then we approach the compact star with the accretion disk, finally ending our voyage near the star.

Distance	Example	Minimum telescope aperture to resolve 10 km object
20,000 km	Germany - Australia	1 mm
400,000 km	Earth - moon	20 mm
80 million km	Earth - Mars	4 m
4 billion km	Earth - Neptune	200 m
4×10^{13} km = 4 light years	Closest fixed star	2000 km
400 light years	Cosmic neighborhood	200,000 km
12,000 light years	X-ray pulsar Her X-1	6 million km

Table 1. The significance of visualization for astrophysics, using the example of spatial resolution.

About the author

Hanns Ruder holds a Ph.D. in theoretical physics. He was professor of theoretical physics at the University of Erlangen from 1973 to 1982. He has been professor of theoretical physics and astrophysics at the University of Tübingen since 1982, focusing on the theory of cosmic x-ray sources, matter in strong magnetic fields, relativity theory, and computational physics.



CORPORATE REGISTER

Cray Research meets customer demand with full product line

Cray Research has received several orders for CRAY Y-MP C90 systems, with one of the first installations to take place at the **European Centre for Medium-Range Weather Forecasts, ECMWF.** ECMWF will use its new system to improve the accuracy of its medium-range (10 day) weather forecasts. Other CRAY Y-MP C90 system customers include **Fleet Numerical Oceanography Center (FNOC),** the United States Navy's primary numerical processing center for global atmospheric and oceanographic predictions, and the **Pittsburgh Supercomputing Center (PSC),** one of the four National Science Foundation (NSF) Centers.

FNOC will use its Cray Research system as the principal computational resource for the Primary Oceanographic Prediction System, a Navy program designed to provide air-ocean prediction capabilities. PSC will be the first non-government lab in the United States to receive the CRAY Y-MP C90 system, which will be used to solve significant scientific and engineering problems.

The **Centre d'Etudes de Gramat (CEG),** a defense and weapons laboratory located in Gramat, France, has ordered a CRAY Y-MP 2E system. The French laboratory will use the new system for research involving detonation simulation as well as electromagnetics and structural analysis applications.

Volkswagen AG (VW) has installed a CRAY Y-MP8 system at the automaker's Research and Development Center in Wolfsburg, Germany. The new system, which replaces a CRAY X-MP system, will be used to shorten the development cycles for new car concept and component designs. The CRAY Y-MP system will be applied to simultaneous engineering activities for product development, including structural analysis, crash simulation, engine design, and aerodynamic computation.

With production of more than three million vehicles in 1990, VW is the leading car producer in Europe, retaining this ranking for the past six years. The company is the fourth largest automotive producer worldwide, with its products sold in nearly every country under the names of Volkswagen, Audi, and Seat. VW employs 270,000 people worldwide, with 174,000 employees in Germany.

The **MacNeal-Schwendler Corporation (MSC),** Los Angeles, a leading developer of finite element analysis software, has ordered a CRAY Y-MP EL system to serve as the main development platform at MSC's subsidiary in Gouda, the Netherlands.

The CRAY Y-MP EL system will be used primarily by software developers working on MSC/DYTRAN, the company's new software for modeling highly nonlinear transient fluid-structure dynamic problems. Future versions of MSC/DYTRAN will improve its current capabilities for occupant safety and crash analysis for the automotive industry, foreign object ingestion by aircraft turbine engines, hard-landing problems of aircraft, and accident analysis.

British Aerospace has ordered a CRAY Y-MP EL system and a CRAY Y-MP4E system, which will serve as the main supercomputing resource for a new TCP/IP and DecNet supercomputing network that links multiple British Aerospace sites throughout the United Kingdom and internationally. The speed and memory of the system will allow the company to simulate larger, more complex problems in computational fluid dynamics, structural analysis, crash simulations, and electromagnetics applications related to British Aerospace's commercial and military aircraft, automotive, and defense businesses. British Aerospace will continue to use Cray Research's Multipurpose Graphics Systems (MPGS), a software tool that enables users to quickly visualize their results.

New executive appointments reaffirm Cray Research as a technology-driven company

In September, Cray Research's Board of Directors approved a new senior executive organization, electing John F. Carlson as chief operating officer of Cray Research, reporting to John Rollwagen, chief executive officer. Carlson joined the company in 1976 as vice president of finance.

In addition to Carlson's position, the Board endorsed the creation of the new post of chief technical officer, responsible for all hardware and software development. The new position is held by Lester T. Davis, formerly executive vice president, Chippewa Falls Operations. Davis will remain based in Chippewa Falls and will continue to serve as a member of the Board of Directors.

Robert H. Ewald, formerly executive vice president, software, was named executive vice president of development, a new position that encompasses both hardware and software divisions. Ewald will relocate to Chippewa Falls and will report to Les Davis. Irene Qualters replaces Ewald as the new vice president of software development, and Mike Lindseth, formerly manager for the Entry Level Systems division, replaces John Carlson as executive vice president of finance and chief financial officer. Dennis McFadden replaces Lindseth as general manager for Entry Level Systems.

In creating the new position of chief technical officer with responsibility for organizing and chairing a new Technical Council, the Board reaffirmed its commitment to keep Cray Research a technology-driven business by providing a technical career ladder that leads to the top of the company.

APPLICATIONS UPDATE

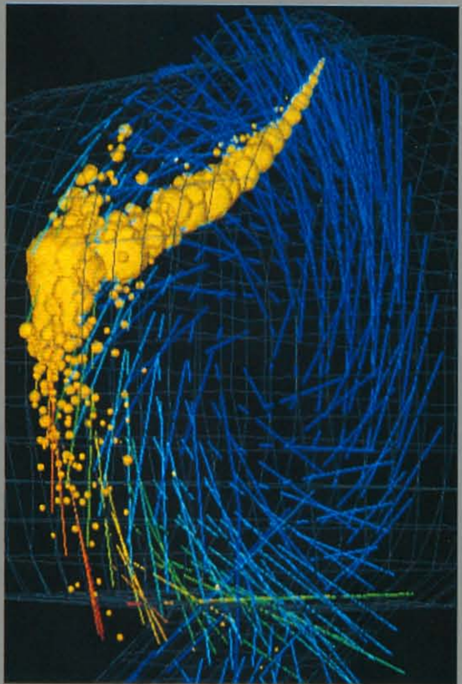
Cray Research announces MPGS Version 4.0

Cray Research's Multipurpose Graphic System (MPGS), is the first advanced visualization tool to offer distributed processing between supercomputers and UNIX-based workstations. While computationally intensive problems are being processed on a Cray Research supercomputer, users can work with their data and visualize the results on their workstation screens.

MPGS Version 4.0 includes the following features:

- ☐ Point-and-click user environment
- ☐ Advanced animation capabilities
- ☐ An auxiliary window that provides dual views of the same image
- ☐ Enhanced on-screen image manipulation
- ☐ Transparent and automatic connection from the workstation to the Cray Research system
- ☐ Online help and enhanced documentation

"Using MPGS, our users have the ability to visualize and animate the results of their analyses interactively," said Brad Comes, program manager of the Scientific Visualization Center at the U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi. "Our users have been able to apply MPGS to a number of situations, and it has been a very productive tool for us. The visualizations allow us to demonstrate research results clearly and concisely to others within our organization. With MPGS, the speed and amount of information transferred between computer and human is remarkable."



Fuel injection and droplet impingement on the wall of a diesel prechamber modeled with CRI/*Turbo*Kiva and rendered with the MPGS visualization package.

MPGS currently is used in the automotive, aerospace, chemical processing, energy, and petroleum industries, as well as at universities and weather research facilities. MPGS has helped engineers visualize the output data from Cray Research systems in diverse applications:

- ☐ Car safety crash tests to optimize automotive design options earlier in the design cycle
- ☐ Airflow circulation around partial or complete airplane configurations for improved aerodynamic design
- ☐ Structural analysis of an engine fan to decrease the number of prototype engines needed for testing
- ☐ Ventilation throughout an aluminum smelting plant to design the plant's ventilation system more effectively

For more information about using the MPGS advanced graphics visualization tool on Cray Research systems, contact Sandra Resnick, Cray Research, Inc., 655E Lone Oak Drive, Eagan, MN 55121; telephone: 612/683-3622.

Application Integration Toolkit (AIT) 1.0 now available

The Application Integration Toolkit (AIT) is a software package for developing and running distributed applications in a Cray Research network supercomputing environment. Initially developed as part of the UniChem network application, AIT now is available as a stand-alone product. Distributed applications improve computing efficiency in several ways:

- ☐ Running several parts of an application in parallel on different platforms reduces the overall time to complete the job.

- ☐ Locating each component of an application on its appropriate platform increases resource usage.
- ☐ Implementing parts of an application on different platforms allows supercomputer applications to distribute output to workstations with graphical interfaces.

AIT provides program developers with the tools to build applications in a heterogeneous network environment, allowing them to distribute applications from a Cray Research supercomputer to a variety of graphics workstations. Through a comprehensive set of library functions, AIT supports applications developers in making the power of supercomputers available to users' desktops.

AIT is intended for applications that follow a one-to-one or many-to-one workstation-to-supercomputer interaction pattern. Examples of such applications include workstation-based job setup interfaces and graphical postprocessing facilities. While AIT is best suited for this type of application, the software also supports other interaction paradigms.

AIT simplifies and accelerates the development and use of distributed applications in several ways:

- ☐ Reduces complexity. Knowledge of UNICOS or workstation operating systems, networking, or windowing systems is not required to use AIT. The application developer is freed from architecture-dependent networking concerns and can concentrate on the application.
- ☐ Provides a uniform interface. An increasing number of supercomputer applications — typically written in Fortran — are augmented by workstation-based user interfaces written in the C language. AIT provides a uniform interface to the Fortran and C languages, eliminating the need to learn and understand the use of different sets of libraries and interfaces.
- ☐ Offers application-independent network supercomputing. AIT works with a wide range of application disciplines and is ported easily to almost any distributed applications environment.
- ☐ Adheres to standards. AIT 1.0 is implemented with the industry standard Transmission Control Protocol/Internet Protocol (TCP/IP). It uses standard external data representation for conversion of data between incompatible hardware architectures.
- ☐ Includes unified product support. Customers deal with one source — Cray Research, Inc. — to license and obtain support for all platforms on which AIT is available, including workstations from Sun Microsystems, Inc., IBM Corp., Silicon Graphics, Inc., and Digital Equipment Corp. (DEC).
- ☐ Appeals to experts and non-experts. AIT provides a simple approach to networking. The network is presented in close analogy to a file, a concept familiar to every programmer. AIT experts can take advantage of the advanced features, such as raw data transfer, to accommodate specific needs.

By shaping AIT to satisfy the requirements of a real life distributed application, Cray Research has ensured that AIT meets the needs of the growing number of distributed applications developers for a comprehensive distributed systems toolkit.

AIT 1.0 provides a high-level interface to the basic UNIX networking facilities and data translation mechanisms that allow binary data to be sent among heterogeneous hosts. AIT 1.0 functions are accessible from the Cray Research CF77 Fortran compiling system and the Cray Standard C Compiler on Cray Research supercomputers and through a C language interface on most popular workstations.

The AIT 1.0 release is available for any Cray Research, Inc., supercomputer system running the UNICOS operating system, release 5.1, 6.0, or 6.1. The workstation portion of AIT 1.0 will be supported on Sun Microsystems, Inc., Sun-3, Sun-4, and SPARC workstations running SunOS 4.1; Silicon Graphics, Inc., 3-D workstations running IRIX 3.3 or 4.0; IBM Corporation's RISC System/6000 computer system running AIX 3.1; and Digital Equipment Corporation's DECstation and VAX computer systems running ULTRIX 4.1. Cray Research fully supports AIT and all its components and offers complete documentation.

AIT 2.0 will enhance the functionality of release 1.0 with extensive job monitoring facilities, a set of job steering primitives, and the capability to run interactive and batch jobs remotely. It also will implement extensive user validation and access control mechanisms for remote access to Cray Research supercomputers.

For more information on AIT contact Steve Schewe, Cray Research, Inc., 655E Lone Oak Drive, Eagan, MN 55121; telephone: 800/284-2729.

MSC/DYTRAN models high-speed fluid-structure interaction

The MSC/DYTRAN software package from the MacNeal-Schwendler Corporation (MSC) combines structural and computational fluid dynamics technology in a commercially supported, three-dimensional code. The program analyzes short-lived events involving the interaction of fluids and structures, or problems involving the extreme deformation of materials. Typical applications include the inflation and unfolding of airbags, bird strikes on aircraft, chemical and nuclear plant safety studies, and defense equipment studies.

MSC/DYTRAN is particularly suitable for crash analysis. Using this code, automotive experts can analyze all aspects of automotive airbag deployment, from initial inflation and unfolding, to the subsequent protection of the occupant. The reduction in occupant injury realized by various designs and fold patterns can be assessed without incurring the expense of physical testing.

The code also solves complex, three-dimensional fluid-structure interaction problems through a combination of Lagrangian and Eulerian techniques. Lagrangian techniques in MSC/DYTRAN use conventional finite elements to model a constant mass of material in simulating structures and solid components. The finite element mesh distorts to follow the motion of the material. To model material or fluid flow, MSC/DYTRAN has an Eulerian processor that uses elements fixed in space, with material moving from one element to the next. A finite volume formulation allows users to create elements of arbitrary shape and general connectivity. Eulerian meshes are particularly suitable for simulating fluid flow, but structural materials such as steel also can be modeled. Eulerian and Lagrangian meshes can be coupled, which allows the simulation of fluid-structure interactions.

The technology used in MSC/DYTRAN is an extension of the proven technologies used in MSC/PISCES and MSC/DYNA. MSC/DYTRAN uses explicit time integration that does not involve the expensive decomposition of matrices. The code is almost completely vectorized and uses subcycling techniques to make it efficient on modern computer architectures.

MSC/DYTRAN is input-compatible with the MSC/NASTRAN structural analysis package. The program is interfaced with MSC/XL, MSC's graphical pre- and postprocessor. Translators to other widely used pre- and postprocessors also are available.

For more information on using MSC/DYTRAN with Cray Research systems, contact Perry Grant, The MacNeal-Schwendler Corporation, 815 Colorado Blvd., Los Angeles, CA 90041; telephone: 213/258-9111; fax: 213/259-3838 or contact Doug Petesch, Cray Research, Inc., 655E Lone Oak Drive, Eagan, MN 55121; telephone: 612/683-3654.

Effects of Kuwait oil fires modeled at DKRZ

Speculations about nuclear-winter-like effects on global climate resulting from the burning oil wells in Kuwait prompted numerous studies by the international climate research community after the oil wells were ignited on February 15, 1991, during the war in the Persian Gulf.

One study, using a computational model developed by an ad hoc group of 17 German scientists, combined the resources of the German Climate Computing Center (DKRZ), the Max Planck Institute for Meteorology (both in Hamburg), the University of Hamburg, and the Institute for Atmospheric Physics of the German Aerospace Research Center (DLR) in Oberpfaffenhofen. The simulation scenarios were run on the CRAY-2 supercomputer at the DKRZ. The researchers used the existing coupled ocean-atmosphere circulation model previously developed in Hamburg for global warming (greenhouse effect) studies (see *CRAY CHANNELS* Vol. 12, No. 4, Winter 1991), expanding it with an interactive tracer module to record the transport and injection of soot into the atmosphere.

Adopting a worst case scenario philosophy, the researchers based their study on the assumption that approximately 440,000 tons of oil is being burned per day, or 160 million tons per year — twice the amount produced by Kuwait before the war — with a soot production rate of 10 percent.

The atmosphere component (ECHAM) of the coupled general circulation model has 19 vertical layers, including the diurnal cycle and standard physics such as cloud radiation interaction. The ocean component consists of an 11-layer large-scale geostrophic (LSG) circulation model that includes a model of the ocean carbon cycle.

Several factors were of particular concern in the study. For example, the injection height of the soot determines its residence time. If contained in the tropospheric level, the soot is rapidly washed out and removed by dry deposition. However, if transported into the higher stratospheric level, the soot would remain there for several years resulting in climatic and ecologic effects comparable to those of intense volcanic eruptions. The self-lofting of soot — an uplift caused by the absorption of solar radiation in the layers of high soot concentration — also had to be calculated in the model. The cooling of the Earth's surface caused by solar radiation being absorbed by the soot layers raised concerns about climate changes. Most feared was a weakening of the Indian monsoon which would threaten crops in Southern Asia.

The DKRZ scenarios cover a one-year period from February 1991 through January 1992. The relatively coarse resolution of 500 km between grid points limits the study to large-scale climate changes, excluding regional changes in proximity to the wells as well as other trace gas or ozone effects. The model was initialized by a 100-year integration that already existed from other experiments studying global warming.

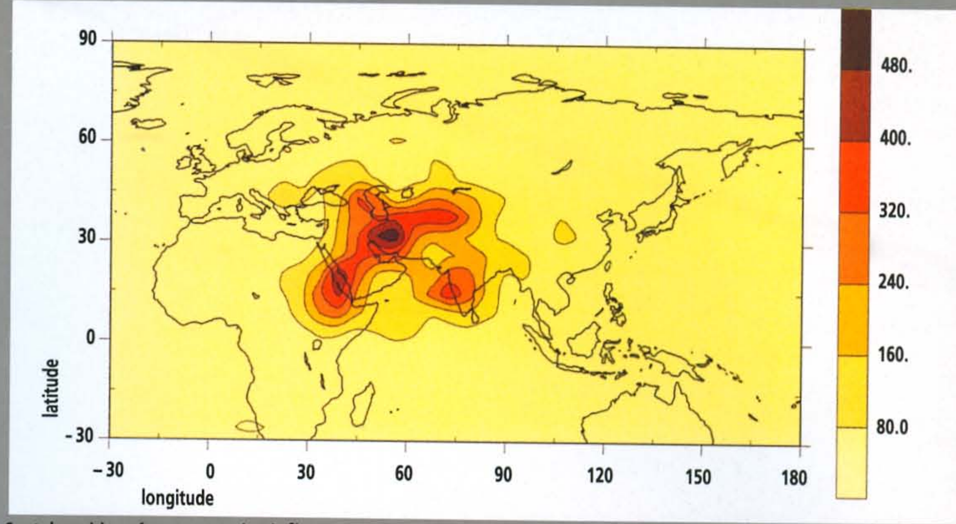
The whole experiment was an ad hoc exercise. The circulation model and the tracer transport module were new and had been tested individually. The extensive memory of the Cray Research system made it possible to couple the components without having to think about restraints imposed by the computing resource. Additional efforts to optimize or multitask the program were carried out quickly in the hope that this would be a one-time event, and that the simulation runs could be finished within a few weeks — certainly well before the end of the war. The simulation of one entire year took 30 CPU hours. The data, consisting of 440 Mbytes per year simulated, have been stored on IBM cassettes.

The computations revealed that the soot does not rise significantly higher than three kilometers (as confirmed by satellite observation of the soot plume over Kuwait on February 24), with very minimal injection into the stratospheric layer (approximately 0.3 percent of the soot is transported into the stratosphere). Even with increased solar radiation during the hottest summer month (July), during which convective activity and the self-lofting of soot increase, the injection height did not change drastically.

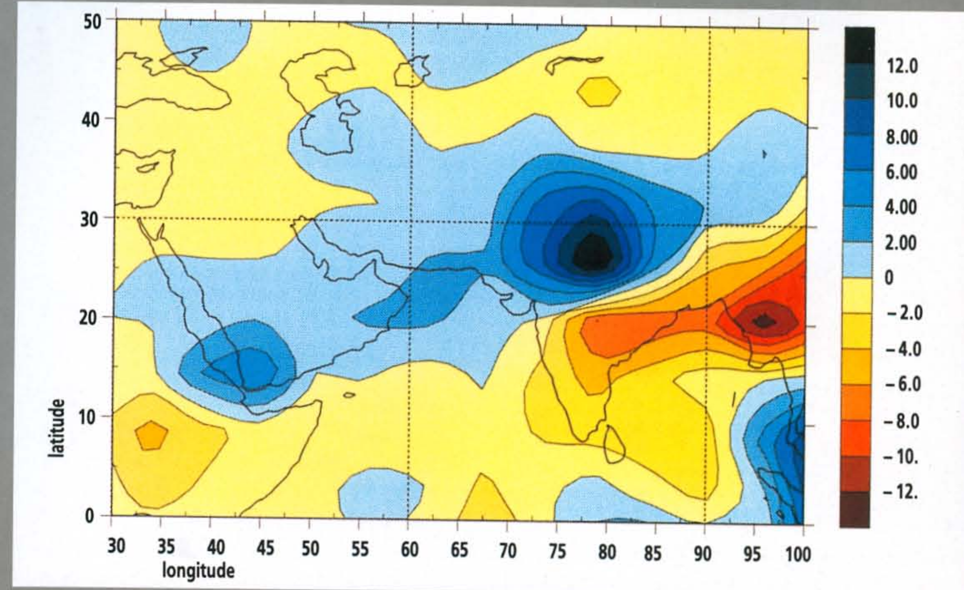
As most of the soot emissions are contained in the atmosphere, the particles are rapidly washed out and removed by dry deposition. The computations assumed a 20-day atmospheric residence time of the soot — which is short compared to the typical aerosol residence times of several years in the stratosphere but large compared with subsequent observations. The total atmospheric soot content was computed to be 7×10^8 kg.

The atmospheric heating of the solar radiation-absorbing soot layers is accompanied by cooling of the Earth's surface. While cooling by up to 4 °C was recorded for July, the overall cooling rate is shown to be approximately 2 °C. However, greater anomalies were observed on a regional scale within a few thousand kilometers from the source. Also, additional sensitivity experiments that assumed four times the amount of soot predicted significant temperature anomalies of 5 to 10 °C near the source region.

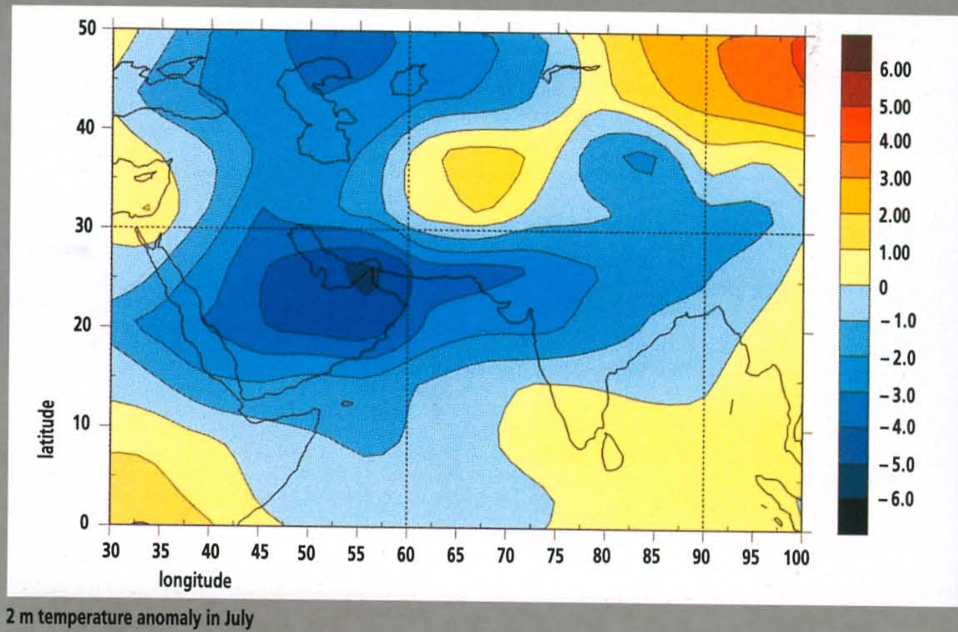
Overall, while significant temperature anomalies have been documented near the source region, the DKRZ scenario revealed no large-scale climate changing structure



Soot deposition after one year (mg/m²)



Precipitation anomaly in July (mm/d)



2 m temperature anomaly in July

in the temperature or precipitation fields outside of the interannual variability of the model. A weakening of the Indian monsoon was not confirmed.

Simulation of multiunit structure deployment

The need has long existed for mobile, reusable structures that can be erected and dismantled easily and quickly. The advantages offered by such structures hold particular promise for industries ranging from temporary construction to aerospace, with uses that run the gamut from recreational camping to emergency sheltering.

Such structures include prefabricated space frames consisting of straight members that can be stored in a compact, folded configuration and can be deployed easily into a large-volume, load-bearing configuration. In the past, deployable structures either behaved as mechanisms during deployment and required external stabilization to carry loads in the deployed configuration, or had curved members with residual stresses that decreased their load-bearing capacity.

A new type of deployable structure recently developed by Massachusetts Institute of Technology researchers Charis Gantes (currently a structural engineering consultant in Athens, Greece), Jerome J. Connor, and Robert D. Logcher, offers the advantage of being stress-free and stable in either straight or curved configurations.

The researchers carried out initial analyses on a DEC MicroVAX computer for simple deployable structures consisting of one unit. The computations became lengthy and expensive, requiring several hours for completion. Once this numerical model had been refined to give reliable results, the researchers turned to a CRAY-2 computer system running ADINA R&D, Inc.'s ADINA finite element program to simulate the deployment process of multiunit structures.

During deployment, stresses develop due to compatibility requirements among the member lengths. These stresses increase gradually, with geometric incompatibilities causing a nonlinear response which results in a "snap-through" phenomenon that "locks" the structure in its deployed configuration. The members were modeled with two-node isoparametric beam elements. Eight elements per bar provided sufficient accuracy. Both the automatic load incrementation algorithm and a displacement controlled Newton-Raphson scheme were used to trace the complete load-displacement path. The final, fully refined numerical model included the effects of discrete joint size and geometric imperfections. Friction was taken into account by introducing nonlinear rotational springs that produced resisting moments at pivotal connections. A series of experiments on physical models provided a basis for comparison with the numerical results, and the final finite element model was in excellent agreement with the experiments.

Tracing the complete load-displacement path of a flat slab consisting of nine units required 433 steps; approximately half of those steps traced just the last 10 percent of the load-displacement path. This fact, combined with the proximity of the limit point to the beginning of the curve, means that considerable cost savings are possible in future analyses by simulating only the first part of the dismantling process. "The accurate simulation of the response of these structures during deployment is an integral part of the design process. The nonlinearity of the response and the complicated geometry and connection details make an analytical solution impossible," explained Gantes.

Cray Research system helps bring the Antarctica to IMAX

The newest IMAX film, an instructive documentary on Antarctica and its impact on the environment, features first-ever footage from the remote Arctic and computer-simulated visualizations of the ozone layer over Antarctica. Producing high-resolution animations on an eight-week deadline was a formidable challenge; one that the filmmakers say they could not have met without the power and speed of a CRAY Y-MP computer system.

Video simulation experts at the Ohio Supercomputer Center (OSC) needed over 750 hours on the CRAY Y-MP8/864 system to create two minutes of computer animation for the 45-minute documentary. A staggering 0.5 terabytes of data were calculated, passed through an Ethernet network and loaded onto 80 Exabyte tapes; each frame required about 38 Mbytes, some texture maps demanded 200 Mbytes, and many of the jobs ran 16 Mwords and more.

"We needed the computational power of the Cray Research system due to the size of images and length of sequences," said John Donkin, OSC supercomputer graphics specialist and the film's artistic director. "At 24 frames per second and 38 Mbytes per frame, you're talking lots of disk space and lots of data," Donkin said, adding that the video simulation team relied on both the power and the speed of the CRAY Y-MP system. "We were under severe time constraints," said Donkin, musing that in eight weeks the Cray Research supercomputer deftly accomplished what would have taken an entire year on a dedicated workstation and 17 years on a personal computer.

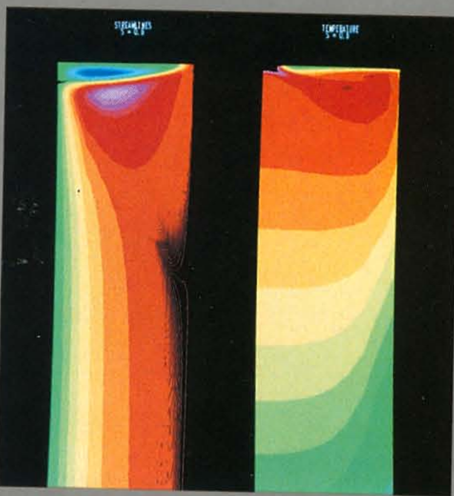
Perhaps the most striking of the sequences is the 31-second video of the "hole" in the ozone layer, a dramatic visualization that illustrates how the ozone layer over Antarctica is being depleted.

The film also features the following animation sequences: a fly-in from deep space showing the location of Antarctica on the globe; the tracking of a penguin's 16-day journey across and under the sea ice; the change in ice over the Antarctic continent over the last few thousand years, as well as the dramatic annual change in sea ice around Antarctica; and a fly-over of the Weddell sea area.

Entitled *Antarctica,* the film was directed by John Weiley and produced by Heliograph Proprietary Ltd. of Australia with funding from the Australian Film Finance Corporation and the Museum of Science and Industry in Chicago. Antarctica premiered at the Smithsonian Air and Space Museum in September.

Researchers study transport processes to improve continuous casting

Continuous casting of steel (and other metals) has emerged as a dominant steel-making technique in recent years because of its economic advantages, which include increased yields and the elimination of intermediate processing steps. Continuous casting technology currently accounts for about 80 percent of the total crude steel production in the world and could account for 95 percent by the year 2000. Almost all Japanese steel is made by the continuous



Colorized contours of streamlines and temperature field in a continuous steel casting mold, modeled on a CRAY X-MP/24 supercomputer.

CUG reports

Users of Cray Research computer systems established the Cray User Group (CUG) in 1977 to provide a forum for the exchange of ideas related to Cray Research systems and their applications. The group holds two general meetings each year. Its second meeting of 1991 was held September 23-27 and was hosted by the Los Alamos National Laboratory. Below, CUG president Karen Scheaffer, of the Sandia National Laboratory, offers her comments on the meeting and other CUG-related business.

The 28th CUG conference set an attendance record, with over 500 attendees from the 183 member sites. The conference also reached new heights in technical quality and overall organization thanks to our hosts, Charlie Slocumb, Bill Dorin, and Jan Hull, and the Special Interest Committee (SIC) and Mutual Interest Group (MIG) chairs.

Organizationally we have added two new MIGs: the Massively Parallel Processor (MPP) MIG, chaired by Kent Koeninger of Apple Computer; and the Security MIG, chaired by Gary Christoph of the Los Alamos National Laboratory. The User Services MIG is now the User Services SIC chaired by Jean Shuler from the Lawrence Livermore National Laboratory. Unfortunately, we must say good-bye to three SIC chairs: Carol Hunter, the Graphics SIC chair; Anna Pezacki, Communications SIC chair; and Bob Baynes, Operating Systems Chair. The CUG Board of Directors extends its appreciation to Carol, Anna, and Bob for their volunteer effort in leading and organizing their SICs. Eric Greenwade from the Idaho National Engineering Laboratory will now chair the Graphics SIC.

While CUG has done an excellent job of representing members' issues and concerns to Cray Research, we have not been as aggressive in representing our members in other organizations concerned with various aspects of supercomputing, such as standards. I want to increase CUG's formal participation in these activities. As an important first step, Fred Crowner from the Ohio Supercomputer Center has been appointed the Cray User Group Institutional Representative to POSIX for one year. Fred will represent CUG at POSIX meetings and on standards ballots, as well as update CUG members on POSIX via the CUG Newsletter and at the biannual conferences.

The Cray User Group Directory of User-submitted Software (CUGDUS) is now operational. This software shareware system maintains a directory of available software and the sites to contact for the software. I want to thank the San Diego Supercomputing Center for its two-year commitment to maintain CUGDUS.

CUG has requested that Cray Research address three issues regarding support:

- ☐ Currently, only those Cray Research customers who have the new model E IOS can take advantage of Cray Research's new I/O peripherals. Cray Research was requested to address I/O support for sites that do not have a model E IOS.
- ☐ CUG requested that Cray Research review the decision not to support UNICOS 5.1 in Eagan.
- ☐ Cray Research was asked to consider establishing a formal mechanism to monitor sites during released product upgrades so that any problems and solutions discovered can be made available to other customers.

Lastly, Cray Research will present its software unbundling plan at the Berlin CUG Conference, April 6-10, 1992.

casting process, while about 50 percent of steel in North America is produced by this process.

Continuous steel casting involves the pouring of liquid metal first into a container tundish and then through one or more nozzles into a water-cooled mold, where the metal begins to solidify. As the strand of steel moves through the casting machine, a shell of hardened steel forms along the walls of the mold, and the metal continues to solidify inward from this shell. The casting emerges from the mold with a solid shell and a liquid core. The casting then is sprayed with cold water to hasten solidification before the casting is cut.

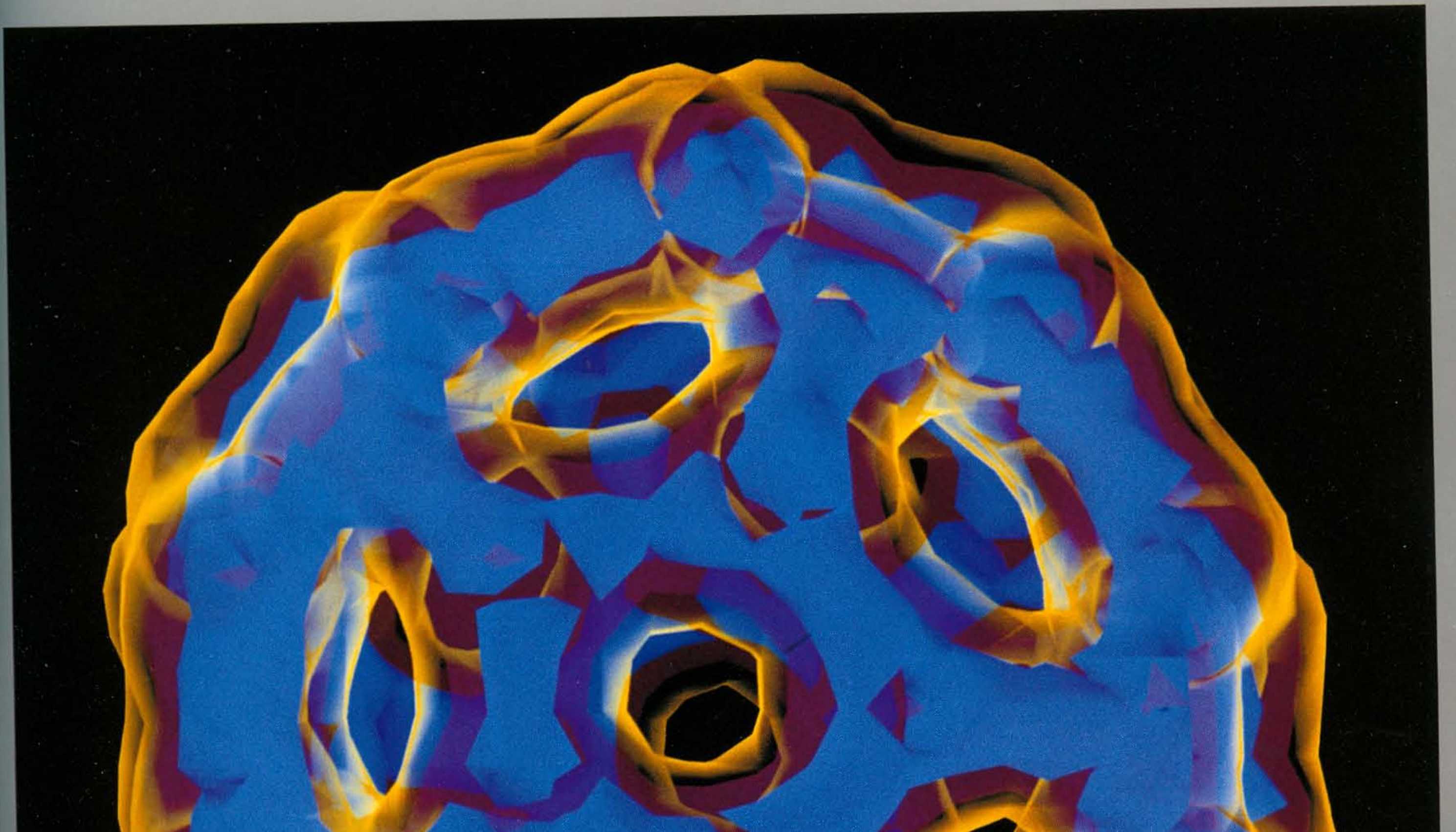
The quality of metal castings is affected by a number of parameters directly related to the turbulent transport processes in the mold region, such as the nozzle shape, the penetration depth of the jet, and the relative size of the separated flow region. For instance, the most common nozzle shape currently used is that of the radial-entry nozzle. This nozzle produces highly turbulent three-dimensional flow in the upper mold region, followed by unidirectional flow farther downstream. Another type of nozzle, the straight-through nozzle, imposes a swirl on the flow of liquid metal that exhibits trends similar to those of the radial-entry nozzle.

Professor Jay Khodadadi of Auburn University and Ph.D. candidates Feng Shen and Xuekui Lan have been using the Alabama Supercomputer Network to access the CRAY X-MP/24 computer system at Huntsville, Alabama, to study the transport processes in the liquid metal pool. An understanding of transport processes in the pool is necessary to develop ways to control the growth rate of the solidified shell that affects the microstructure of the final product. The transport processes also control the formation of various defects that can hamper subsequent steel processing. Examples of defects formed in this region are surface irregularities, such as cold folding and oscillation marks, and more serious defects such as longitudinal or transverse cracks. A more catastrophic problem that can occur is "breakout," in which the shell ruptures and molten metal is discharged uncontrollably.

Khodadadi's CCFM code models the turbulence flow and heat transfer generated when the stream of liquid metal from a straight-through swirling entry nozzle enters the mold. His studies have shown that turbulent flow characteristics similar to those produced by radial entry nozzles are observed. The solution of the transport equations is based on a combination of an iterative, finite difference numerical procedure using primitive dependent variables and a two-equation turbulence closure model. After looking at preliminary results from 16 by 15 and 70 by 60 grid densities, Khodadadi calculated solutions on a 35 by 30 grid that accommodated tolerable numerical diffusion and memory limitations. The test cases chosen ranged from nonswirling to strongly swirling flow, with the model computing from 26,000 to over 35,000 iterations of sets of six equations, with a CPU time of 0.081 seconds per iteration.

The model produced streamline patterns of the liquid steel for different jet swirl intensities, enabling Khodadadi to see what happens to steel formation as the liquid steel is introduced into the mold at different swirl velocities. His studies have shown that some turbulence characteristics are desirable. In an industry that tries to balance productivity with quality, studies such as Khodadadi's help avoid costly production mistakes by describing the processes before they have begun.

"Six years ago," said Khodadadi, "I couldn't have dreamed about doing these kinds of problems. I could only speculate about what we could not calculate." Now with the help of a Cray Research supercomputer, he is able to spend more time analyzing results and less time wondering about the unknown.



Color contours show three electron-density iso-levels for the C_{60} molecule (Buckminsterfullerene). The calculations were performed on a CRAY Y-MP computer system at the North Carolina Supercomputing Center by researchers Qiming Zhang, Jae-Yel Yi, Charles Brabec, and Jerzy Bernholc of the Department of Physics at North Carolina State University. Visualization by Tom Palmer, Cray Research, Inc.

CRAY RESEARCH, INC.
Marketing Communications
1440 Northland Drive
Mendota Heights, MN 55120
612/683-7215