Review

Mechanical CAE in Automotive Design

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Abstract

The urgent issues for automobile companies today are how to reduce the time and cost required for developing a new car. CAE (Computer Aided Engineering) has been regarded as an efficient way to solve these issues, and as a numerical experiment to replace prototypes and experiments. CAE was first introduced to reproduce phenomena that are elusive in regular experiments. Now it is even capable of optimizing the design parameters to achieve the desired performances. Moreover, the necessity for FOA (First Order Analysis) is under current discussion. This refers to the CAE that covers processes such as project planning and grand design, which have not been paid much attention so far. This new CAE is expected to help designers create basic design and to reduce eventually the entire production time. This paper will briefly overview how CAE has contributed to vehicle development and address its future applications.

Keywords Automobile, Body, Structure, Mechanism, Design, CAD, CAE, Simulation, FOA

1. The ideal form of CAE

Computer Aided Engineering (CAE) is a concept that was first proposed by J. Lemon in 1980, the founder of SDRC, as a way to provide analytical information in a timely manner in the product development process, and through doing this, products and production processes with great improvement are made possible. Lemon described the ideal in the following words [1)]:

"Technologies to automate computer-aided drafting and computer-assisted N/C tape preparation are available and are beginning to be used widely to help reverse the alarming trends of declining productivity in many industrial economies. However automating isolated tasks in today's "build-and test" product development process, while cost-effective, will not achieve significant time savings, productivity gains and/or strategic benefits, as anticipated by most companies.

The overall mechanical product development process itself must be automated. Products must be developed within the computer. Prototypes should be built to verify and validate computer predictions, instead of being used to find out how a product performs, as is common today.

Extended reaches to improve product performance and quality can be achieved in significantly shorter time through the effective implementation and integration of existing computer-aided engineering and related manufacturing capabilities. Indeed, strategic benefits impacting a company's overall market share, quality image, return on investment and profitability can result from effective CAE implementation."

The nineteen-eighties were the period when CAD began to be used by major manufacturers. It took over a decade, until the beginning of the nineteen-nineties, for drafting boards to be driven completely out of the design engineering departments. It was in that era that Lemon used the term CAE to posit virtual prototyping in terms of the integrated CAD and CAM. A consensus was reached on CAE as Lemon conceived it, where all processes would be executed on computers, after the three-dimensional CAD in the latter half of the nineteen-nineties.

Moreover, we can catch a glimpse of the difference between Lemon's CAE and the today's CAE in the fact that we unconsciously differentiate between virtual prototyping and CAE. That is to say, the greater part of our effort in CAE is devoted to improving calculating precision and making model development more efficient, by the great development of computer hardware, isn't it? Of course, these efforts have led to contributions to numerical experimentation that should be greatly applauded. But does it not look as though the purpose of supporting the creative activity of CAE is not necessarily reflected in these efforts? We are in a period when CAE is considered to be within a new bleed of framework like Lemon's idea.

This paper describes the current states of mechanical CAE used in vehicle development and issues for the future. Specifically, it surveys the changes in the development flow that have been made possible by CAE and offers ideas on how CAE should be used further upstream in the early design stage.

2. What has been made possible by CAE?

It is well-known in Japan that the Vitz™, Platz™, and FunCargo™, as well as the Will-Vi™ and bB™ (**Fig. 1**), are all based on the Vitz. The Platz™ and later models based on the Vitz™ differ in their outward appearence. Even among users, there is a tendency to classify vehicles as being for families or single, women or men. This is not just limited to Toyota. There are more cases of this sort than one can count, such as VW Golf and New Beetle, Ford Lincoln and Jaguar S-type, and so on. These kinds of derivative vehicles of different body design and packaging were developed in less than a year, so as to reflect the market and the forefront of popular taste. So despite the fact that the performance requirements for automobiles have become more demanding and complex, with lighter weight for better fuel efficiency, crashworthiness, etc., recently added to the conventional standards of ride comfort and handling.

3. Technology supporting the acceleration of development

3. 1 Changes in the development flow

The vehicles in the Vitz™ series, mentioned above, share a common platform, that consists of the underbody, suspension, engine, and drive train, on top of which different upper bodies are installed (**Fig. 2**). **Table 1** shows the basic specifications for the Vitz-derived vehicles. Dimensions related to the platform, such as the wheelbase, tread, etc., are almost all the same, but differences in the

Fig. 1 Vitz, Platz, Fun-Cargo, Will-Vi and bB.[2)]

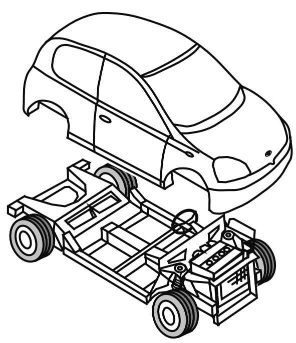


Fig. 2 Passenger car upper-body and platform.

Table 1 Specifications of Vitz, Platz, Fun-Cargo, Will-Vi and bB.[2)]

Main Spec.	Vitz	Platz	Fun-Cargo	WiLL-Vi	bB
Overall Length (mm)	3610	4145	3860	3760	3825
Overall Width (mm)	1660	1660	1660	1660	1690
Overall Height (mm)	1500	1500	1680	1575	1640
Wheelbase (mm)	2370	2370	2500	2370	2500
Tread Width Front (mm)	1450	1450	1440	1450	1450
Rear (mm)	1430	1430	1420	1430	1435
Ground Clearance (mm)	150	150	150	155	165
Interior Length (mm)	1800	1855	1905	1705	1955
Width (mm)	1380	1380	1370	1385	1375
Height (mm)	1265	1265	1290	1330	1355
Suspension Front	Strut/Coil				
Rear	Torsion beam/coil				
Delivery year	Jan/1999	Aug/1999	Aug/1999	Jan/2000	Feb/2000

Fig. 3 Outlines of Vitz, Platz, Fun-Cargo, Will-Vi and bB.[2)]

dimensions related to the upper body, such as the overall height and length, are visible in the outward appearance of the vehicles (**Fig. 3**).

The development of all mechanical products, not just automobiles, proceeds as a series of steps: plan, design, proto-typing, experimental evaluation, and production (**Fig. 4**).

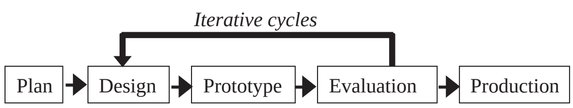


Fig. 4 Conventional development procedure.

That is to say, the basic sequence is that an idea is expressed in a drawing, and a good product is made through repeated failures in experiments. It is obvious that development can be accelerated by repeating the cycle of design, prototyping, and evaluation as few times as possible, but items for evaluation and analysis can not be omitted, and as mentioned earlier, the number of these items has tended to increase in recent years. Therefore, if the design proposal prior to the prototyping stage can be sufficiently completed by CAE studies at an earlier stage, it should be possible to reduce the number of cycles of prototyping and evaluation (**Fig. 5**).

Ultimately, it should be possible to bring the prototyping and evaluation process down to a single step (**Fig. 6**).

Because the role of CAE here is as a substitute for experiments, it will be called "CAE as numerical experiment" in this paper. In the case of automobiles, it is used to simulate crashworthiness, noise, vibration and harshness (NVH), strength and durability, and drivability. The following section provides an overview of these.

3. 2 CAE as numerical experiment

3. 2. 1 Crashworthiness

As reported recently by a number of media outlets, crashworthiness is considered the most critical item according to each automobile company's standards, which are made with reference to the Japanese government assessment[3)] (the so-called JNCAP[4)]), as well as to the assessments of other countries. CAE as numerical experiment, as used here, is coming to calculate a large deformation non-linear analysis that has recently been used in conjunction with human body models[5)]. Crashworthiness is determined by, for example, an elastoplastic analysis that is not just

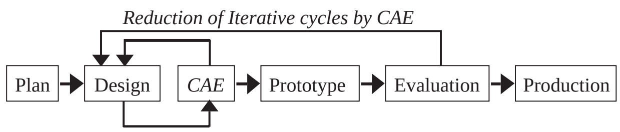


Fig. 5 Development procedure with reduced iterative cycles by CAE.

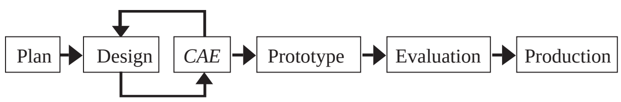


Fig. 6 Development procedure with single prototype step.

a simple matter of calculating that the cabin is rigid and that the front-end crushable zone is soft, so the number of elements and the analytical method used in the calculation are detailed and complex. Also, it is thought to be progressing toward an analysis[6] based on a design that leads to a design proposal that incorporates optimization techniques based on simple evaluation by numerical experiments so as to achieve the desired performance (**Fig. 7**[7]).

3. 2. 2 Strength and durability performance

In contrast to the crashworthiness, which requires an analysis that handles rigidity and elasticity well, the analysis of strength and durability performance requires that the discontinuity of localized rigidity be canceled out. Helping this along is the fact that CAE as an evaluation procedure to replace simple tests, such as stress-strain tests, has become increasingly common since its introduction.

3. 2. 3 NVH performance

NVH is directly related to the everyday use. The range of vibration that can currently be handled by CAE is roughly below 200 Hz, and the objects of study include low-frequency vibration in the ride comfort range, engine idle vibration and low-speed booming noise, and road surface harshness and medium- to high-speed booming noise. Because analysis of NVH requires the calculation of the entire vehicle, the component mode synthesis (CMS) method, which separates the vehicle into multiple partial structures, degenerates their degree of freedom, and then links them together for analysis, has come to be widely used. One important issue is how to evaluate and design to decrease noise and vibration based on degenerated and regenerated models.[8, 9]

3. 2. 4 Drivability

Once in the days of bias tires, the tire force limit was small (the tire would slip immediately), and its input to the suspension and body was also small, so the era of the spring-mass model using simple dynamic equations lasted a long time. At that time, a program developed in-house sufficed to meet our needs. When the market switched over to radial tires, adequate tire force was maintained. And as a result, both a suspension mechanism that could sustain a large tire force and the rigidity of the body had been taken into account. Accordingly, mechanical analysis software is coming popular with multibody dynamics, such as the characteristics of the tires, the mechanism of the suspension, the body structural dynamics, etc.. Full vehicle simulations[10] using the specific software were actively carried out (**Fig. 8**[10]), and our focus was made on how to model actual vehicles and actual driving, for example, how to efficiently couple the rigidity of the body to its dynamics,[11] and how to model the non-linear characteristics of bushings.[12]

3. 3 Toward more efficiency

It has been described how experimental analysis, which entailed prototyping that cost money and

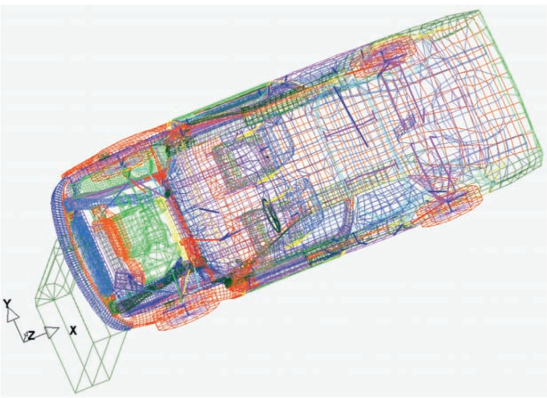


Fig. 7 Crash analysis by FHWA/NHTSA National Crash Analysis Center.

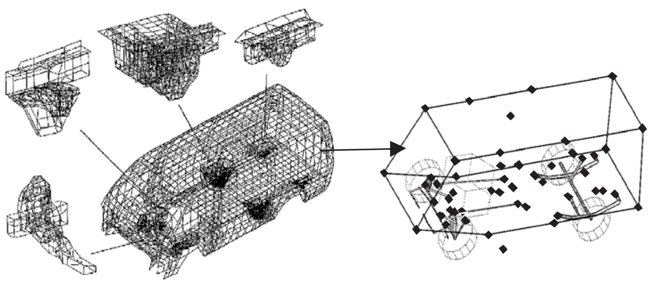


Fig. 8 Multi-body dynamic analysis with body FE model.

time, was replaced by numerical experiment CAE in order to move the development process more quickly. The next issue to arise was how to increase the efficiency of the design (CAD) and CAE loop.

First, let us express the step from design to CAE with the term "automatic modeling" (**Fig. 9**).

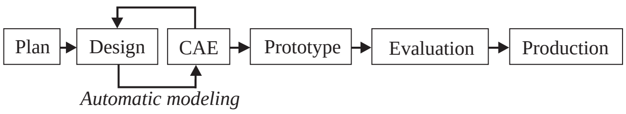


Fig. 9 Automatic modeling function in development procedure.

As CAE becomes more detailed, the automatic modeling requires elaborate mesh data, the technology to create it, and persons called "meshers“ or "mesh modellers” who have that skill. This is the same thing as making an excellent prototype and the skilled technician to create it. Actually, CAD software on the market is equipped with functions that automate the creation of the mesh, moreover functions that reproduce CAD data from CAE mesh data are starting to appear. Today, one could say that the question of how good the CAD/CAE interface depends on the relative merits of the CAD software. However, as CAD has become three-dimensional and the precision requirements have become more stringent, it remains as important as ever to do research on such questions as how to fill the gap in data definition methods between CAD and CAE and how to automatically create mesh model that calculates features that are not flat. This includes not only problems that should be solvable geometrically, but also basic conditions for the development of elements for FEM.

Next, we will call the step from CAE to design "design optimization" (**Fig. 10**).

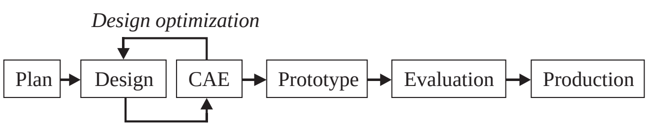


Fig. 10 Design optimization function in development procedure.

Optimization is a major current in recent CAE research. There are two basic approaches, the first of which involves techniques for handling design variables. Specifically, these include a technique called parametric analysis, which leads to better product performance by changing the design variables in sequence, as well as sensitivity analysis that helps determine which of the parameters contributes the most to products. Also in this category are experimental planning methods that determine the scope and combinations of the large numbers of design variables that are used, as well as the response surface methods, which determine the optimum parameters from a continuous map using polynomial equations to approximate the discrete relationships between the design variables and product performance. These techniques are based on the beginnings of experimental analysis, but they are indispensable tools in the world of CAE.

Software for parametric analysis, as well as for the sensitivity analysis and experimental planning methods has recently been incorporated into general-purpose structural analysis software, and specialized optimization software is also widely used. Moreover, if the powerful interface functions of these specialized optimization tools are used to run different types of solvers simultaneously, it becomes possible to do multiphysics analyses for issues like the aeroelasticity problem and others. These things are important for practical use. Basically, this is because when one derives the answer to the governing equation for a certain phenomenon, seeking to improve product performance, it often happens that a contrary phenomenon arises that is related to a separate governing equation. As well known, the aeroelasticity issue developed in the aerospace field. The fact that the multiphysics problem is handled in the ordinary engineering indicates that even with a product that we use in daily life, its performance is ultimated, and the work is not finished just because a single phenomenon has been optimized.

Next are methods of directly determining and optimizing the form of the product we are trying to design. These are topology optimization methods[13, 14)] based on homogenization methods. These techniques have begun to be tested on parts like reinforcing materials that are affixed to the backs of suspension arms and panels, where the direction of the load is already roughly known, weight reduction is strongly required, and the shape has a large degree of freedom. But practically speaking, these functions are currently limited to determining the weight and then maximizing the rigidity. In the same manner as the first optimization methods described above, these creative functions are expected to increasingly be incorporated into general-purpose structural analysis software.

4. Moving to the plan and design stages in the future

4. 1 CAE for design engineer

It has been shown that the number of cycles of prototyping and evaluation is reduced by using CAE as a numerical experiment, and that the design proposal can be refined by using optimization functions. On the other hand, while one can say that the automation and optimization functions of numerical experiment CAE have been enhanced, the calculation time is longer than would be expected for the experimental precision, and specialized knowledge is required to use it. That is to say, it is the work of an analysis group in specialized division, and it is still too difficult for the design engineers to use by themselves. Also, experimental precision requires detailed models, which is to say, detailed information about the shape of the product. Accordingly, the sequence is still to do the design and then apply CAE. The fact that CAE supports the creative activities of design engineers, as stated at the beginning of this paper, simply means that a tool should be used prior to the confirmation of the drawings or even while the drawings are being created. This would be a CAE that can create a conceptual design proposal with good dynamic elements in the initial stages of development from planning to the conceptual design and then evaluate that proposal.

CAE that can play this role will be called "CAE for design engineers".

Please note that in **Fig. 11**, CAE for design engineers is positioned before drafting design. It is a tool for designing and drafting things, not for analyzing them after they have been made, like numerical experiment CAE. It is often the case that if the design engineer thinks products through carefully at the concept stage, the work will make good progress even in the detail stage.

4. 2 The role of CAE for design engineers

Now I would like to try to describe CAE for design engineers more concretely, based on the daily scene of the design department.

A freshman, Mr. A, is given a plan for a light-weight structure with a load capacity of one ton and put in charge of its design. The next day, he presents a design proposal, and he is asked about the reason for the shape. If every time he is asked, his answer is simply "This is the result produced by the optimum design tool (software name)," the person who is checking the drawing would probably feel uneasy. But if he were to say, "I calculated it using (software name), but in the end, I pulled out my textbooks and verified it", the checker could sign off on the drawing without concern. In other words, even if one uses the "optimum design tool", a process of once more verifying the results using basic equations, or of checking them in comparison to existing designs, is a necessary part of the design work in order to make the concept concrete.

Now if we ask what the role of the optimum design tool that Mr. A used is, one might answer that it compensates for his lack of experience, since he is a freshman, or that it allowed him to produce the drawings on time. In the design department, it is more important to have your colleagues and superiors look at the design early on than to brood over it alone. Unless the drawings are put into a form that anyone can see, none of the processes that follow the design stage can start. It is important to

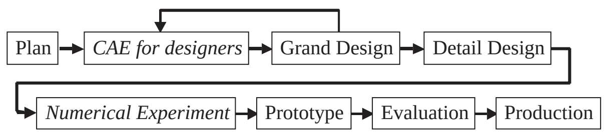


Fig. 11 CAE for desingers in the first stage of development procedure.

get together to examine the drawings by many stuffs, and for that to happen, it is important that drawings be produced quickly, at the beginning. The value of the optimum design tool is first and foremost that it allows the concept to be made concrete at an early stage.

The ideal form of CAE for design engineers must in essence be an interdependent relationship between a reverse analytical process called the optimum design method and a regular analytical process that considers the design by returning to the basics. Moreover, because the development of proposals one by one and making them concrete is the job of an individual, it is of vital importance that in the personal environment, CAE for designers allows the designer to do the job by himself. That is to say, CAE for designers should be operated in personal computers (**Fig. 12**).

4. 3 First order analysis

We have proposed the first order analysis (FOA) as a form of CAE for design engineers.[15] FOA is configured as described below.

4. 3. 1 The expression of the hierarchical structure of the design objective and its modeling

The design objective, exemplified by the body structure of an automobile in this case, is divided into different levels (**Fig. 13**). The configuration of FOA also conforms to this hierarchical structure. A single sheet becomes the responsibility of a single designer, while its reciprocal relationship with other sheets, which is to say, the relationship between parts, is maintained. This operation can be performed easily by using the spreadsheet of Microsoft Excel™.

For each sheet, the design objective can be replaced by a calculation model by means of a simple operation. The procedure is shown in **Fig. 14**.

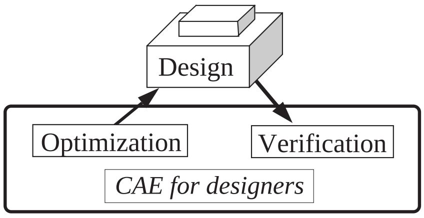


Fig. 12 Optical configuration of CAE for designers.

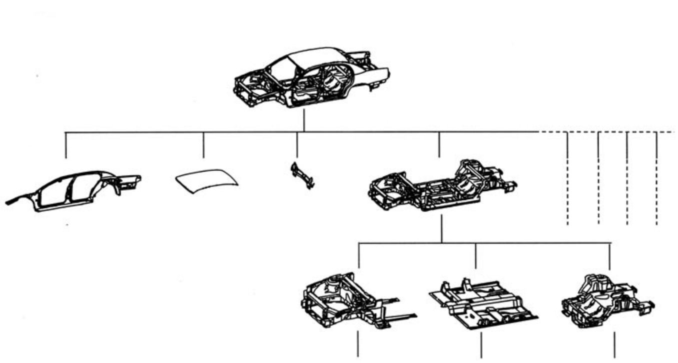
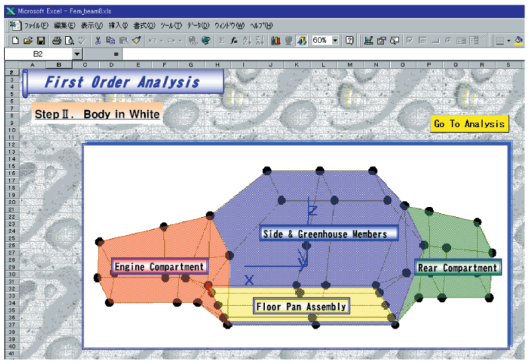
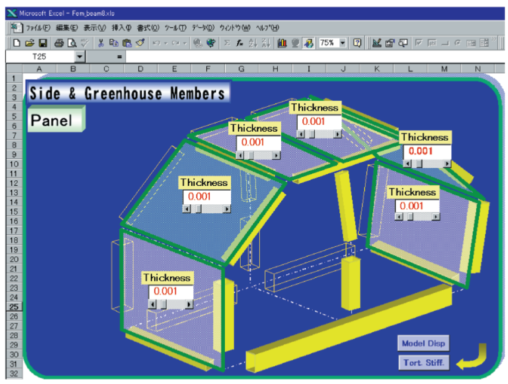


Fig. 13 Hierarchical data structure.



(a) Whole image of design objective.



(b) Designing part.

Fig. 14 Spread sheet describing hierarchical data configurations.

In Fig. 14(a), the entire body structure is expressed. Clicking on the cabin portion at this point causes that portion to appear on a separate sheet (Fig. 14(b)), where design changes can be made, such as the length of a part, the cross-sectional shape, the panel thickness, etc.

4. 3. 2 Analyzing the characteristics of the design objective

Once the shape of the design objective has been created using the procedure described above, the design engineer returns to the top page of the spreadsheet and clicks on the "Analyze" button. The system automatically creates a finite element model using beam and shear panel elements, then displays the results of the calculation. The boundary conditions, such as fixed positions, the loading positions and their values, etc., are set as necessary in the course of this process. **Figure 15** shows an example of the results. It shows the distribution of strain energy when the vibration characteristics (animation of the modes) and rigidity characteristics of the body structure are evaluated. By carrying out this analysis of characteristics nearly simultaneously and in parallel with the model creation (design changes) of the previous stage, the design engineer can, for example, adjust the dimensions and cross-sectional shape of the part for which he is responsible while observing in sequence the equalization of the stress distribution of the structure and the adjustment of the vibration mode.

4. 3. 3 Creating a structure by topology optimization

The need may arise to determine a new shape for the entire design objective or a portion of it. In these cases, the optimal structure can be created by using the topology optimization of a framework structure. **Figure 16** shows the results of a calculation of the portion at which the body front end is joined to the cabin. The calculation is based on the grand structure method. That is to say, after multiple nodes are created within the design region, the nodes are connected by beam elements, and the boundary conditions, etc., are input, the optimization calculation eliminates the unnecessary beams, leaving only the effective beams, then makes their diameters larger or smaller, according to the forces that act on them. The optimum beam structure is obtained as a result. If the design engineer sets the design region and boundary conditions at this point, the system automatically proceeds from the grand structure to displaying the results. The design engineer can also check his understanding of the characteristics of the optimum beam structure and their validity by once more applying the analysis

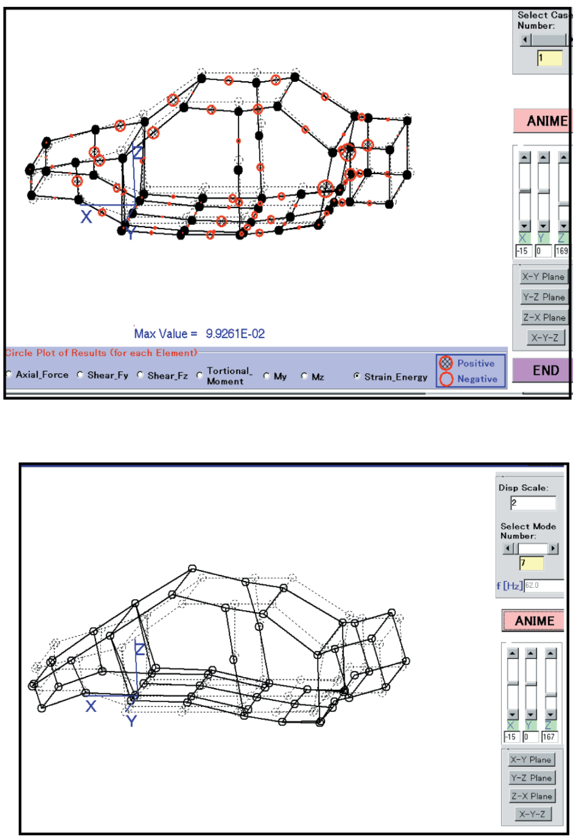


Fig. 15 Static and eigen-value analysis.

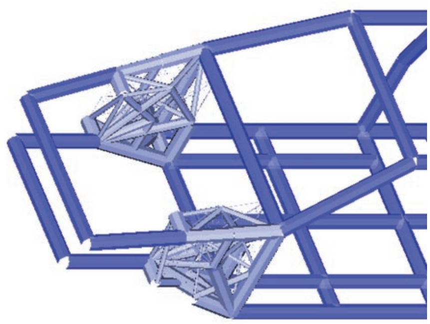


Fig. 16 Optimal design of front frames.

from the previous stage to the optimum beam structure.

4. 3. 4 What does FOA make possible?

The previous section described the basic configuration of FOA. FOA for the body structure is equipped with a user interface that builds knowledge of the mechanics of materials on the personal computer and that can provide the design engineer with calculation results for the parts and the entire product in a form that is suited to the design process (**Fig. 17**).

FOA is a form of CAE for design engineer that is intended for the initial stage of design that was not necessarily considered until now. It must be a system that the design engineers themselves can use, that drastically shortens the analysis time, and that is in a form that is suitable to the design process. When one compares design proposals A and B, it is important to determine immediately that A is better using one's knowledge and FOA. We also want to make FOA a system that can respond to the design engineer's motivation such as to determine the effects of the parts one is designing on the final performance of the product as well as the challenges of designing innovative structures and mechanisms. The most important thing for numerical experiment CAE is to approximate actual phenomena, besides the primary goal for FOA is to approximate the design engineer's thinking process.

Among the issues we are thinking of tackling in the future are crashworthiness and dynamic performance. We will probably have to begin by tracing the process of how the design engineer conceives of these points and incorporates them into a each mechanical product. The approach must also have an affinity for the existing design know-how that has been accumulated to date. This will probably take the form of a function that extracts the desired examples from a data base, processes them on the basis of know-how and logic, then presents them to the designer.

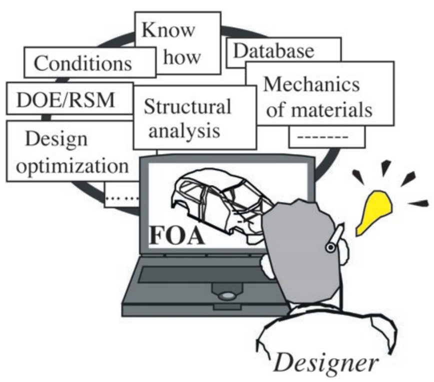


Fig. 17 FOA for automotive body structure design.

As was noted earlier in this paper, the progress of CAE is beginning to bring about changes in the manufacturing process, 'mono-tsukuri'. Looking at it from a different viewpoint, there is also the possibility that CAE might interfere with the normal succession of the traditional technologies to prototype and evaluate. If CAE with a new framework at least makes effective use of the technical know-how accumulated and becomes a common tool in the mechanical design, it may become possible for a wide range of people to make their own ideas concrete. Our dream is that a new business style might be born from this concept.

5. Conclusion

In this paper, I have considered the role that numerical experiment CAE has come to play in vehicle development. Also, CAE for design engineer has been considered as a tool that can be used further upstream in the design process, and the basic concept of first order analysis has been described as one example of this.

This paper is based on the advice of Prof. Noboru Kikuchi of the University of Michigan, a senior fellow of Toyota Central R&D Labs., Inc., as well as on discussions with the research staff of the Design Engineering Laboratory at Toyota Central R&D Labs., Inc.

Reference

1) Lemon, J. R., Tolani, S. K. and Klosterman, A. L. : "Integration and Implementation of Computer Aided Engineering and Related Manufacturing Capabilities into Mechanical Product Development Process" (1980), Gi-Jahrestagung
2) Toyota New Car's Manuals
3) Ministry of Transport : Notification, No.651 [2000-07-01]. Available from Internet : <URL:http://www.mlit.go.jp/jidosha/carinf/ast/00/ast_m_f_kok99.htm>

4) National Organization for Automotive Safety & Victims' Aid [2000-07-01] Available from Internet : <URL: http: //www.osa.go.jp>
5) Happee, R., et al. : "Body Modeling in Injury Biomechanics", Proc. of JSAE, No.60-99(1999)
6) Yoshimoto, et al. : Proc of JSAE, No.57-99(1999)
7) FHWA/NHTSA Nat. Crash Analysis Center [Cited July 1, 2000], Available from Internet : <URL: http://www.ncac.gwu.edu/ main.html >
8) Moeller, M. J., et al. : "NVH CAE Quality Metrics", SAE Tech. Pap. Ser., No.1999-01-1791(1999)
9) Freymann, R., et al. : "A New Optimization Approach in the Field of Structure-Acoustic", SAE Tech. Pap. Ser., No.2000-01-0729 (2000)
10) Sugiura, H., et al. : "Multibody Dynamic Analysis of Vehicle in Consideration of Body Stiffness Using Finite Element Model", Proc. of IPC-9, 1(1997), 151-156
11) Kobayashi, et al. : J. of SAE, Jpn., **52**-12(1998)
12) Lim, J., et al. : "Identification of Forces Transmitted onto Car Body through Rubber Bushings in Suspension System under Driving Conditions", SAE Tech. Pap. Ser., No.1999-01-1841(1999)
13) Suzuki, K., Kikuchi, N. : " A Homogenization Method for Shape and Topology Optimization", Comp. Methods Appl. Mech. Engrg., **93**(1991), 291-318
14) Nishiwaki, S., et al.:" Optimal Structural Design Considering Flexibility", Comp. Methods Appl. Mech. Eng. (to appear)
15) Nishigaki, H., Nishiwaki, S., Amago, T. and Kikuchi, N. : "First Order Analysis for Automotive Body Structure Design", ASME DETC 2000/ DAC-14533 (2000)

(Report received on Aug. 1, 2000)

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