Interim Report on the Joint Study of Earth Simulator Center and Japan Automobile Manufacturers Association

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The present study named ES-CAR Project (earth simulator + car) is being carried out jointly by the Earth Simulator Center (hereafter "ESC") and the Japan Automobile Manufacturers Association ("JAMA") for the period from June 2004 to March 2006. With the help of ESC's massively parallel supercomputer system, the ES-CAR Project is aimed at outlining a next-generation vehicle performance simulation that can be put to good use from around 2010 or 3 to 5 years after the project's 2006 completion. Introduced in this interim report are the history, FY 2004 activities, and scheduled FY 2005 activities of the ES-CAR Project.

Keywords: Vehicle, crash, collision, aerodynamics, engine combustion, improving simulation accuracy improving simulation speed

1. History Leading to the ES-CAR Project

In September 2003, ESC brought a proposal to JAMA concerning a joint project to develop an all-inclusive vehicle simulation using the Earth Simulator. JAMA responded by initiating a working group to evaluate the proposal, and decided to accept the proposal despite the fact that no vehicle manufacturer in the JAMA membership had ever used an earth simulator before. The reasons for JAMA's decision were: a) simulation had been an important vehicle development tool for all the JAMA member companies and b) the Earth Simulator offered a good prospect of realizing the types of simulation that had been out of the reach of JAMA member companies due to hardware limitations.

Thus, a nearly two-year long ES-CAR Project was launched in June 2004. In view of the ESC proposal, the target was set on "studying all-inclusive, accurate and realtime simulation using the Earth Simulator". For preparation, the ES-CAR working group was formed within JAMA. The working group's members were enlisted from each of the 14 JAMA member vehicle manufacturing companies and from ESC, with NEC Corporation representatives also participating in their secretariat capacity. The 9 software houses that developed the software programs for ESC – namely, LSTC, ESI, Mecalog, Ricardo, CDADAPCO, IGENIE, CHD, Altair Engineering and JRI – were invited to help operate and improve software efficiency. More software houses will likely be invited as the ES-CAR Project advances into its second year.

To realize all-inclusive, accurate and realtime vehicle simulation, it was decided to first formulate the super-scale counterparts (over 10 times greater in elements) of the existing finite element models for collision, aerodynamic force, and engine combustion in order to elevate the simulation accuracy and speed. Since no vehicle manufacturer anywhere in the world had used finite element models of this vast scale, the activities in FY 2004 centered on examining the operation of new large models and the possibility of improving their simulation accuracy and speed. Explanations on these activities are given in section 3 of this interim report.

2. Current Status of Vehicle Simulation

Effort for leveraging computer simulation in vehicle development has been undertaken in full scale since the spread of super computers manufactured by CRAY in the late 1980s. The use of computer simulation thereafter accelerated with the availability to higher-performing and lower-priced supercomputers capable of handling more calculation items. Around the year 2000 the simulation scale was remarkably expanded by parallel computing technology. Expansion of scope of simulation provided more detailed simulation model and phenomena we tried to solve, and enabled us to conduct simulation closer to real behavior.

In today's collision simulation, large-scale calculation models on order of one million elements are employed to perform finite element analysis. In such large-scale models, one element covers a 5 to 10 mm square so that a deformation of the vehicle, for example, can be expressed within 1 cm of resolution. Engine combustion simulation, aerodynamic performance simulation around vehicle body and other simulations have also benefited from the increase of resolution and have achieved higher accuracy in reproducing real-world phenomena. In addition to increased resolution, software improvements such as improvements in theoretical physical expression models are also assisting in the enhancement of simulation accuracy, making simulation more reliable and useful in the development of new vehicles.

It goes without saying that improvements in supercomputer performance have shortened the calculation time to greatly benefit the vehicle development sites. In the past, many said that physical testing is faster than computer simulation as they struggled with using simulation in their vehicle development activities. This was mainly due to low level of precision and accuracy as well as considerable time required for simulation.

Today, even a collision simulation of a one million element scale can be finished in less than 2 days, enabling frequent body design modification and trial. This is a drastic change from a while ago when it took a full week to complete 10,000-element scale simulation. Thanks mainly to the quickened availability of simulation results, simulation has become a daily-use tool of vehicle development teams under the ever mounting pressure from the management to shorten the development period for each new vehicle.

Nevertheless it is true that the application of simulation is still limited only to certain aspects of the vehicle. To be more specific, over a half of the evaluation and check items required for the development of a new vehicle are still being evaluated or checked by physical testing or traditional methods because it remains technically difficult to apply simulation to these items. In the mean time, the vehicle developing teams are being confronted by the growing demands to incorporate new technologies, meet stricter regulations, deal with environmental issues, and further shorten the development period. The result is the mounting expectations for next-generation simulation to be more accurate, speedier, and applicable to a wider range of automotive aspects.

The ES-CAR Project was motivated by these expectations, years ahead of the simulation advancement schedules drawn by most vehicle manufacturers. The practical aim of this project was set on investigating the maximum limit of simulation accuracy in relation to model scale for the three most commonly used types of simulations – collision, engine combustion, and aerodynamic performance simulations.

3. Current Activity and Future Plan

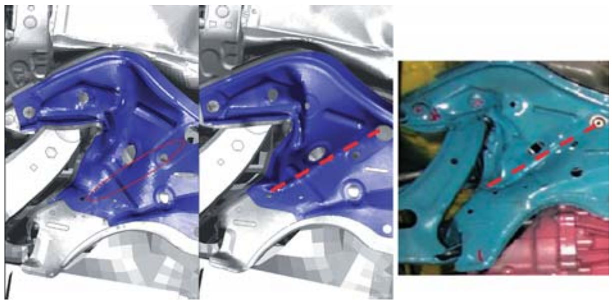
3.1. Collision Analysis

3.1.1. FY 2004 Activities

A collision analysis program, which is common in vehicle development, was ported on ESC's earth simulator (the Earth Simulator), and feasibility studies including operation check and various performance evaluations were completed. Then, an finite element model capable of accurately reproducing the body shape of a vehicle was completed and operated. The following results were obtained:

Recently a typical finite element model for collision analysis is made by around a million elements and it requires 38 hours to simulate a collision phenomenon of a 100 millisecond duration by using 16 CPUs. In the ES-CAR Project, the model accuracy has been elevated to 5 million and 10 million elements but the calculation time has been shortened to 12 and 35 hours, respectively, by using 512 CPUs on the Earth Simulator . This new higher-accuracy collision models has reproduced the deformations of the parts that are not reproducible by the existing one million element models (see the figures below).

Further, the new higher-accuracy collision model could get a better acceleration-time graph, which is comparable to that of experiment. In addition, while the existing finite element models require a vast number of manhours for model corrections to obtain an intended reproducibility, much of the formulation of the new higher-accuracy model can be automated due to its ability to reproduce shapes accurately. Thus, new finite element model may be created in a much shorter period.



1-million-element model simulation   10-million-element model simulation   Experiment (photo image)

3.1.2. FY 2005 Activities

In FY 2005, three major activities will be launched. First, individual element technologies will be further advanced to achieve accurate and realtime analysis. Analytical collision configurations will be diversified from the last fiscal year's full-lap frontal collision to other configurations such as offset frontal collision and side impact with a deformable barrier . Second, the accuracy of finite element models will be further raised to obtained (obtain) an acceleration-time graph that will even more closely resemble the measured acceleration-time graph. Third, a tuning will be conducted to improve the parallel, vectorization and analytical efficiency of 10 million element models so as to shorten the simulation time from the current 35 hours to a dozen hours which will permit body design modification and trial on an overnight schedule.

3.2. Engine Combustion

3.2.1. Current State of Engine Combustion Simulation

Engine combustion simulation can be grouped into three types: 1) air flow formation, 2) fuel spray and air-fuel mixing, and 3) ignition and combustion. In the first-type simulation, variations from the average flow speed in relation to time are formulated into a turbulence model capable of predicting the effective opening area and the swirl flow inside the cylinder.

In the second-type simulation, while air flow is treated with the Euler equation, fuel spray is generally treated with the Lagrange equation which considers sprayed fluid as particles. Models for the separation, collision and evaporation of sprayed fluid have been formulated on the basis of measured results, and a satisfactory prediction accuracy for the distribution of air-fuel mixture inside the combustion chamber has been confirmed by LIF or other visualization methods.

In the third-type simulation, a variety of calculation models have been proposed to suit different combustion modes. For diffusion combustion characteristic of diesel engines, a calculation method using a probability density function of air-fuel ratios is applied in order to determine the air-fuel ratio distribution at a high resolution level. For flame propagation combustion characteristic of spark ignition gasoline engines, a coherent flamelet model is employed to solve flame surface density transport equations for estimating the size of wrinkle-shaped flame that correlates with propagation speed, assuming flame to be an aggregation of stratified pieces of flame. Researchers are studying another model which will assume the flame surface to be the dividing surface of burned and unburned areas and will determine the displacement of flame surface by transport equations.

Overall, varied engine combustion models are formulated to suit different combustion modes so as to reduce the calculation load and to predict the combustion pressure, exhaust gas composition and other combustion characteristics within a reasonably short period of time. For more detailed analysis of transient characteristics including multi-cylinder combustion behavior, it is necessary to further advance the calculation capability of the supercomputer.

3.2.2. Achievements of the ES-CAR Project

(1) Software Adaptation to the Earth Simulator

The sizes of pointer variables were adjusted, the routine codes were modified, and vectorization was promoted for large calculation scale.

Performance evaluation results (30 million elements)

CPU bit	32	64	128	248
Operation time	16408s	9413s	5676s	4038s
Performance ratio	1.0	1.7	2.9	4.1
Vectorization rate	99.0%	98.9%	98.6%	98.3%

(2) Formulation of Large-Scale Calculation Models

Simulation programs were modified to enable data processing for mesh formulation and calculation domain division in large-scale calculation models of tens of millions of elements, which is a scale considered unapproachable until recently due to the limited calculation capacities of supercomputers. Thus, preparations to formulate large-scale models by ESC's earth simulator have been completed in the first year of the ES-CAR Project.

3.2.3. Remaining Task of the ES-CAR Project

The remaining task of the ES-CAR Project for its second year is to conduct engine simulation including the intake manifold, exhaust manifold and other components of the intake and exhaust systems in order to determine, for example, the effects of manifold shape on the flow, fuel distribution and turbulences in each cylinder. This will enable the analysis of engine combustion in greater detail by analyzing the phenomena in each cylinder from a multi-cylinder engine perspective, while the existing simulation techniques have only permitted analysis on a single cylinder basis.

3.3. Aerodynamic Simulation

3.3.1. History and Activities

A hexahedron computational mesh, tetrahedron computational mesh or their hybrid mesh is generally used in aerodynamic force analysis today. While providing a higher calculation accuracy, the hexahedron mesh has difficulties in reproducing complex shapes. Inversely, the tetrahedron mesh can reproduce complex shapes with greater ease but its calculation accuracy is low. To examine a possible coexistence of calculation accuracy and shape reproducibility, large-scale calculation was performed using tetrahedron elements offering impressive shape reproducibility, and attempts were made to improve the calculation accuracy through element division.

Aerodynamic Simulation around the vehicle was performed by a large-scale calculation model, and the whole series of operations including mesh generation, domain division, calculation and results file unification were completed. Effects of element division on calculation accuracy were studied by changing the number of calculation elements of the large-scale model. Un-steady calculation was performed for three calculation models of 10 million, 25 million and 90 million meshes, respectively, using incompressible ROE solvers. In the aerodynamic simulation, the elements were merely divided without optimizing the element division for each mesh. An earth simulator of a 64 CPU was employed.

3.3.2. Simulation Results

As shown in Table 1, the 64 CPU earth simulator was able to complete aerodynamic simulation in 120 hours using a 90 million mesh model. The calculation results were compared with the experimental results, and it was confirmed that due to element division the simulation accuracy had improved with regard to the boundary layer separation areas of the vehicle body and the vortex generated by the door mirrors and front pillars. For example, the simulation indicated the generation of two vortices, one behind the door mirror and the other behind the front pillar as a result of element division. It was suggested that the complex air flow around the vehicle could be analyzed with greater accuracy through optimization of element division.

3.3.3. Scheduled Activities

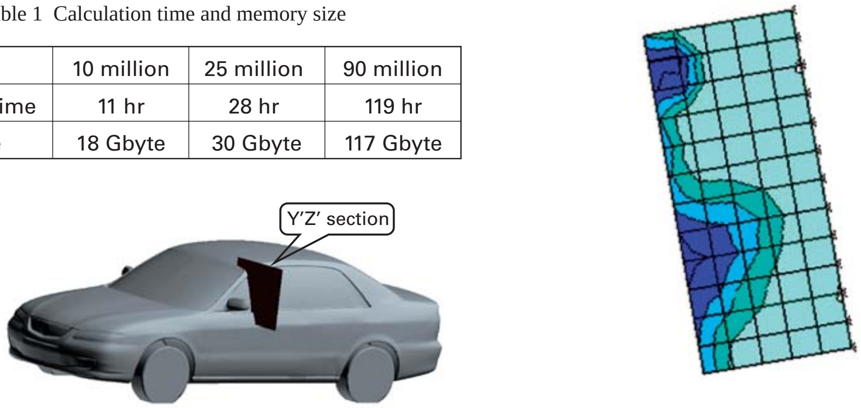
In FY 2005, a calculation model reproducing in detail the engine room, underfloor and suspensions will be formulated, and element division will be carried out and optimized to perform the un-steady calculation of air flow around the vehicle. The simulation results will be compared with the experimental results to determine the calculation model's accuracy with respect to the air flow and pressure fluctuation around the vehicle.

4. Conclusion

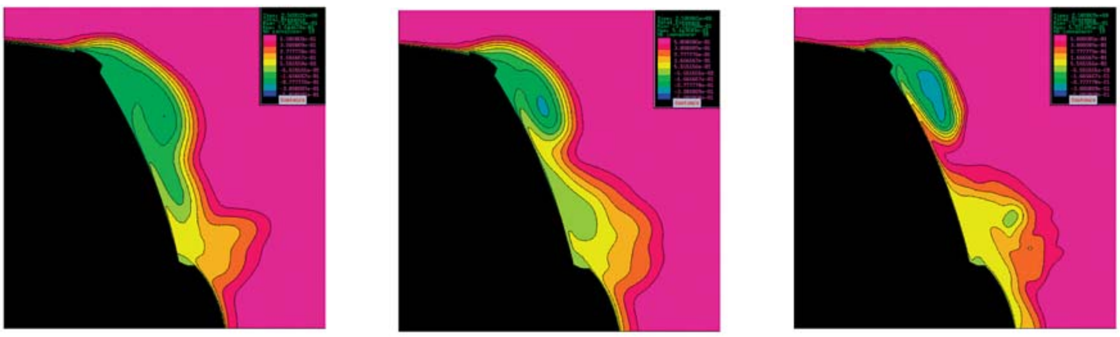
The FY 2004 activities of the ES-CAR Project indicated that the simulation of vehicle performance using an efficient supercomputer like ESC's earth simulator (the Earth Simulator) would be possible 3 to 5 years later, provided that necessary data would be produced and the simulation results would be properly evaluated. Efforts will be exerted in FY 2005 to bring accurate and realtime simulation closer into reality. Finally, the authors thank the members of the companies involved in the ES-CAR Project for their unsparing support.

Table 1 Calculation time and memory size

	10 million	25 million	90 million
Calculation time	11 hr	28 hr	119 hr
Memory size	18 Gbyte	30 Gbyte	117 Gbyte



(a) Y-Z section　　(b) Experimental results



(c) 10 million mesh model　　(d) 25 million mesh model　　(e) 90 million mesh model

Fig. 1 Pressure distribution on Y-Z section (600 mm behind door mirror)

地球シミュレータセンターと自動車工業会による共同研究の中間報告

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1. 共同研究に至った経緯

‘03年9月地球シミュレータセンター（以下ESC）より、(社)日本自動車工業（以下自工会）に「車まるごとシミュレーションの地球シミュレータを使った検討」という共同研究の申し入れがあり検討の結果、約2年にわたる共同研究を開始した。共同研究のテーマはESCからの申し入れと、自動車開発を取り巻く環境、ニーズを考慮し、「地球シミュレータを活用した自動車まるごと、高精度、リアルタイムシミュレーションの検討」とした。

共同研究の具体的な内容は自動車まるごとシミュレーション実現にむけ、まずは、車両の衝突・空力・エンジン燃焼等各シミュレーションの高精度化、リアルタイム化の検討を従来のシミュレーションモデルの10倍以上という超大規模な高精度シミュレーションモデルを使って実施することとした。これだけ超大規模なシミュレーションモデルは、世界の自動車会社でも実施の実績がなく、‘04年度は、動作検証と、超大規模モデルによりシミュレーション精度がどれくらい向上するかを中心に研究を実施した。

2. 自動車シミュレーションの現状（テーマ選定の背景）

自動車を開発する上で評価・確認すべき項目はシミュレーションが可能な項目より多い。一方、自動車開発においては、新技術、新法規、環境問題、更なる期間短縮など新たに取り組むべき課題が今後ますます増えてくる。そしてそれらはシミュレーションへの期待となる。そんな期待に答えるためには、更に精密性と時間短縮を追及し広範囲に適用できるシミュレーションを目指した更なる技術開発が必要となる。

今回の研究は、その技術開発の一環であり、数年先の検討と思われてきた課題を今実施しようとするものである。自動車のシミュレーションでは代表例となる“衝突シミュレーション”、“エンジン燃焼シミュレーション”、“車体周りの空力シミュレーション”について、解析モデル規模の面から精密性の限界を調査することとした。

3. まとめ

‘04年度の活動を通じて、地球シミュレータを活用し、3から5年後の自動車性能シミュレーションの研究が可能であることがわかった。また、このような活動には、地球シミュレータのような高性能なスーパーコンピュータが必要であるばかりでなく、データ作成、結果評価の環境を整備することが必要であること。また、本活動を通じて、このような研究活動は世界でも例がないことを実感できた。‘04年度の活動を通じて、高精度化、リアルタイム化を実現するための方向性がわかったので、‘05年度は、具体的な成果をだすべく、活動を続けていく予定である。最後に、共同研究をサポートいただいている協力会社の方々にお礼を申し上げ、結びとする。

キーワード：車両，衝突，空力，エンジン燃焼，シミュレーション精度の改善，シミュレーション速度の改善