## HPCI User Report

<table>
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<th>Project Number</th>
<th>Project Name</th>
<th>Project Representative</th>
<th>Affiliation</th>
<th>Country</th>
<th>Keywords</th>
<th>Software</th>
<th>Project Category</th>
<th>Periods of Use</th>
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</thead>
<tbody>
<tr>
<td>hp160033</td>
<td>Research for Next-generation Automotive Aerodynamics Evaluation Technology Simulated with Vehicle Dynamic Motion by Super-large-scale Transient Fluid Calculation</td>
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<td>マツダ株式会社／Mazda Motor Corporation</td>
<td>日本／Japan</td>
<td>非定常空力, CFD, 移動境界, BCM, IBM</td>
<td>CUBE</td>
<td>「京」産業利用(実証利用）／K Industrial Use</td>
<td>2016/4/1 - 2017/3/31</td>
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### Resource Information

<table>
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<tr>
<th>Institutions</th>
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<th>Allocated Resources</th>
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<tr>
<td>RIKEN AICS</td>
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<td>2,189,824</td>
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Research for Next-generation Automotive Aerodynamics Evaluation
Technology Simulated with Vehicle Dynamic Motion
by Super-large-scale Transient Fluid Calculation

Takashi Kamioka  Mazda Motor Corporation

1. Background and Objectives of the Research
The aerodynamic behavior which directly affects the driving stability and comfort of the car has been
investigated using an unsteady fluid dynamic analysis technology which is known as Japan's unique
large-scale CFD technology which can reproduce detailed vehicle geometry and complicated motion at the
same time. Building Cube Method (BCM) is adopted as a CFD technology, which has been verified in flow
field and aerodynamics characteristics repeatability around the commercial vehicle. By evaluating the
obtained results against the company's vehicle development process, it will be used for formulating design
guidelines for future automobile development.

2. Outline of Results
The three-dimensional fluid dynamic simulation of the actual driving test condition has been carried out to
get three-dimensional forces history by giving the translational position / attitude rotation of vehicle based
on the center of gravity of the body as input, as well as the translational position of each wheel, the tire
steering angle, and the tire rotation speed, and the change in the vehicle posture. From the obtained
calculation results, we examined the transient relationship between the flow field around the vehicle and
the fluid force applied to the vehicle during the vehicle motion.

自動車の走行安定性や快適性に直接影響を与える空気力学的挙動を、詳細な車両形状と複雑な運
動を同時に再現できる日本独自の大規模非定常流体解析技術を用いて、これまで知られていなか
った物理メカニズムの解明を目指すシミュレーションを実施する。得られた結果を自社の開発プ
ロセスと照らし合わせて評価し、将来の自動車開発の設計指針の策定に役立てる。

実走行テスト条件を模擬した車体重心基準の並進位置・姿勢回転、ならびに各輪タイヤの並進位
置・タイヤ舵角・タイヤ回転数を入力とし、時々刻々変化する車両姿勢と流体力の変化を 3 次元
解として出力することに成功した。得られた計算結果から、車両運動時の過渡的な車両周りの流
れ場と、車両へ付加される流体力の関係を考察した。
3. Calculation Model

Building Cube Method (BCM) developed by Nakahashi [1] is adopted in the present study. The computational domain used for the BCM configuration is initially filled with cubes [Fig. 1(a)] and then each cube is fed with the same number of uniform meshes [Fig. 1(b)]. When calculations are performed, the same number of cubes is assigned to each central processing unit (CPU).

![Fig.1 BCM configuration](image1)

In order to capture the motion of the body in the fluid calculation, the constraint immersed boundary method (IBM) [2] has been adopted in the incompressible Navier-Stokes equation. The detail information of the numerical scheme is tabled as follow.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Numerical method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time advancement</td>
<td>Implicit, 2nd Crank-Nicolson</td>
</tr>
<tr>
<td>Convective terms</td>
<td>Fractional step, QUICK</td>
</tr>
<tr>
<td>Viscous terms</td>
<td>2nd Central difference</td>
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</table>

To represent the complex geometry using uniform meshes in the BCM, a fast and easy implementation and robust interpolation for an incompressible IBM was developed by authors in [3].

The goal of this work is to investigate the flow physics encountered around a vehicle during the lane change maneuver. The computational grid (Cubes) used for the simulation and the lateral velocity profile of vehicle during lane change maneuver are shown in the Fig. 2. The equations of motion of the system are described below. The velocity of the vehicle including its linear and rotational component of the motion is given by

\[ \mathbf{u}_{\text{turn}} = [u_t, v_t, w_t] + [\omega_x, \omega_y, \omega_z][\tau_x, \tau_y, \tau_z]^T \]
The motion of the vehicle is split into two components namely, linear and rotational (as is shown in the equation above). The linear components of the vehicle are imposed as boundary condition to the computational domain; the rotational component of the motion is imposed through the immersed boundary method. As the linear velocity of the vehicle is unsteady, merely imposing it as boundary condition will not suffice. The acceleration due to the lane change maneuver has to be accounted in the momentum equation as shown below.

\[
\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho} \nabla p + \frac{\mu}{\rho} \nabla^2 \mathbf{u} + \mathbf{f}_{\text{turn}}, \quad \text{where} \quad \mathbf{f}_{\text{turn}} = \frac{\partial}{\partial t} [u_l, v_l, w_l]
\]

The corresponding boundary conditions on the computational domain boundaries are:

\[
\begin{align*}
X^- : & \quad \mathbf{u}_{in} = [u_l, v_l, w_l], \\
X^+ : & \quad \partial \mathbf{u} / \partial \mathbf{n} = 0 \\
Y^{+-} : & \quad \mathbf{u}_{Y^{+-}} = [\partial u / \partial y, \partial v / \partial y, 0] \\
Z^{+-} : & \quad \text{Slip, no penetration}
\end{align*}
\]

In the present simulations, Z component of the linear velocity of the vehicle is ignored, hence we use slip boundary condition in the Z direction. Lastly, the velocity condition for the immersed boundary method is imposed as follow.

\[
\mathbf{u}_{ib} = [\omega_x, \omega_y, \omega_z, [r_x, r_y, r_z]^T]
\]

4. Method and Effect (or Performance) of Parallel Computing

The load balancing technique has been adopted as shown in [3]. The runtime strong scaling test performance is shown in Fig. 3.

![Fig.3 Runtime per time-step and relative runtime for the full car model.](image)

5. Research Results

The calculation has been conducted on K computer using 1,024 nodes running around 73 hours per case to get the 4.2s physical duration time of vehicle maneuvering motion. The number of grid of coarse case was approximately 150 million cells with 6mm finest resolution around vehicle, and the fine case was approximately 1 billion cells with 1mm resolution. The fine case was difficult to conduct with given resources because of the limitation of time increment to get a long duration time. So, we have decided to examine the phenomena using coarse case results. However, since a thousand calculation nodes are also required in coarse case, this calculation can only be executed in K computer. In Fig. 4 visualization of the iso-surfaces of q-criterion is presented.
The sequence of images shows the vehicle in lane change maneuver.

In the lane change maneuver, the vehicle is in linear motion from $t=0$ to $t=2s$, the actual lane change maneuver begins at $t=2s$ and continues until $t=4.2s$ and then the vehicle continues in a linear motion. During the maneuver, the lateral velocity firstly increases in magnitude from 0 to 3 m/s up to $t=3.1s$, after which it decreases back down to 0. All other components of the vehicle’s velocity exhibit similar during the period of the maneuver.

In Fig. 5(a) the roll angle is plotted as function of time. Similar to lateral acceleration, roll angle also has an inflection point around $t=3.2s$. The force on the vehicle during the maneuver as plotted in Fig. 5(b). The forces are oriented with the vehicles longitudinal axis as the vehicle turns. The trend of the forces after the start of the turning maneuver is predicable up to the inflection point ($t=3.2s$). It is observable that the behavior of the lateral force is correlated with the trend of the roll angle.
6. Summary and Future Subjects
The three-dimensional forces history has been obtained together with three-dimensional flow field results by giving the translational position / attitude rotation of vehicle based on the center of gravity of the body as input, as well as the translational position of each wheel, the tire steering angle, and the tire rotation speed, and the change in the vehicle posture. From the obtained calculation results, we examined the transient relationship between the flow field around the vehicle and the fluid force applied to the vehicle during the vehicle motion.

References