Web-based integrated cloud CAE platform for large-scale finite element analysis

Yu IHARA*, Gaku HASHIMOTO* and Hiroshi OKUDA*
* Department of Human and Engineered Environmental Studies, Graduate School of Frontier Sciences, The University of Tokyo
5-1-5, Kashiwanoha, Kashiwa, Chiba, 277-8562, Japan
E-mail: ihara@multi.k.u-tokyo.ac.jp

Received: 5 October 2017; Revised: 3 November 2017; Accepted: 5 December 2017

Abstract
The cost of preparing analysis and data handling is remarkable compared with the speedup from parallelization. Several studies have reported for a problem solving environment (PSE) or a cloud computer aided engineering (CAE) service. However, few studies have covered part of CAE process. This paper proposes design of cloud CAE platform and development of a web-based all-in-one CAE system. The platform design takes account of applying to large-scale analyses by imaging methods and data structures. Assembling them, we provide cloud CAE services. As numerical examples, we apply the system to some finite element analysis models. We confirmed that this system has ability for CAE work which has a hundred million degrees of freedom.

Keywords: Cloud computing, CAE, Finite element analysis, Parallel computing

1. Introduction

In the past decade, computational science has dramatically enhanced. Therefore computer aided design (CAD) and cloud computer aided engineering (CAE) have been widely spread in manufacturing processes of various products. It might be difficult to execute commercial CAE software, e.g. ANSYS, Nastran or Abaqus, with good parallel performance for large-scale analyses on massively parallel machines. The first reason is that introduction cost increases according to the number of cores. The second reason is that commercial software is provided as executable binary files and is not applicable to supercomputers which has special computer architectures, such as Fujitsu SPARC64.

Open-source software optimized to show good parallel performance is receiving a lot of attention from CAE users. However the CAE users have two issues for introducing open-source CAE software into product development. First, data handling frequently takes much time because large-scale computational data have different formats at each process such as preprocess (i.e. mesh generation and domain decomposition), solver and postprocess (i.e. visualization and graphing). Although supercomputer performance has been rapidly increasing, the cost of data handling time is remarkable in comparison with decrease of execution time of computational fluid dynamics (CFD) or computational solid mechanics (CSM) solver. Second, open-source CAE software requires various computer skills generally. For example, some of CAE users have enough experience in writing programs, compiling programs, writing shell scripts and submitting jobs to supercomputers’ job schedulers. If CAE users implement parallel computing, considerable skills are needed in large-scale data handling. Therefore, it is necessary to develop an all-in-one system including preprocess, solver and postprocess and every operation should be performed with a unified graphical user interface (GUI).

Cloud computing services in CAE field have been recently offered, such as ‘Fujitsu Technical Computing Solution TC cloud’ service. As this kind of service, computer resources including CFD or CSM solver licenses are offered to users. Such service is often provided by a Remote Desktop application on Windows workstation. Therefore, users need to install some client software. The computer resource is not available for assignment to some users simultaneously. Even if hardware virtualization is adopted for multiple user, virtualization overhead is not negligible. Considering this situation, those services might not effectively use strengths such as ‘broad network access’, ‘resource pooling’ and ‘rapid elasticity’
of cloud computing. Therefore by utilizing open-source software, which has features that users can customize and use many case at same time without license charge, and developing appropriate application for using CAE on cloud, cloud CAE will be able to provide in adopted the above three cloud service definition strictly.

As researches on cloud computing services, Georgescu and Chow constructed a GPU-accelerated CAE system using open-source solvers and cloud computing services (Georgescu, 2011). However they only adopted an Infrastructure as a Service (IaaS) cloud service as computational nodes. Cho constructed a simulation service platform based on cloud computing (Cho, 2012). However the Cho’s platform needs to install client software and supported only Windows OS. Cloud CAE systems were proposed in Okuda et al. and Wada. Okuda et al. constructed a cloud CAE system consisting of large-scale structural analysis open-source software ‘FrontISTR’ and an engineering-data handling system ‘ASNARO’ (Okuda, 2013). Despite adoption of structural analysis open-source software, the data-handling system is commercial software. Moreover, preprocess is not contained by the constructed system. Wada constructed a web-based CAE system consisting of structural analysis open-source software ‘ADVENTURE Solid’ (Wada, 2003). The system had some problems such as poor interactivity caused from heavy server processes and poor flexibility. Thus it is difficult to handle large-scale analysis models.

Furthermore, in the point of view of problem solving environments for CAE, Shioya et al. proposed a client-server type CAE system based on a back-end PC cluster and a Java3D-based front-end web interface (Shioya, 2007). Cheng and Fen developed a web-based distributed problem solving environment (PSE) for engineering applications (Cheng, 2006). In these researches, the constructed systems express analysis models as 3D models on web-browsers. However their works have a limit for further large-scale model because of rendering surface point to client’s browser. Additionally they no longer universal because of using Java applet. Chrome browser is not supports Java applets now. Safari browser on iOS and Android’s browser has not supported it from the beginning. Wei et al. presented object-oriented implementation of PSE and its modules to optimize engineering systems (Wei, 2004). Their work is also is not universal because of only supporting Windows.

In this study, a cloud CAE platform is proposed to facilitate development of all-in-one system with GUI and the platform is applied to some case studies including large-scale structural analysis. This paper is based upon Ihara et al. (Ihara, 2015), and includes the following additional research: improvement of CAE platform concepts, adding numerical examples which are more large-scale stress analysis and eigenvalue analysis.

This paper is structured as follows: In section 2, we show outline of cloud CAE platform for web-based CAE work. In section 3, we develop some elements for application of cloud CAE platform to structural analysis. In section 4, we confirm that our CAE platform has ability for interactive CAE work including large-scale analysis by some numerical examples. In section 5, we present concluding remarks and describe our work’s social meaning.

2. Outline of cloud CAE platform

The cloud CAE platform is software which runs on a cloud server and can construct a web-based CAE system from a cloud server and client computer (see Figure 1). This platform consists of Data Manager (DM), Job Manager (JM) and User Manager (UM). And the platform provides Platform as a Service (PaaS) cloud services for users. DM, JM and UM are platform equipment. The users customize Application Plug-in (AP) and add AP to the platform in order to construct a web-based CAE system (see Figure 2). Some functions for each platform equipment are described below. DM converts data formats at each process such as preprocess, solver and postprocess. The information of data-conversion from original data to derived data is saved as SQL database relations. Therefore it secures derived data’s reproducibility (see Figure 3). Furthermore, it records that who owns data. DM hierarchically manages the relations as some tree-structures. It is easy to search original data from derived data. UM manages user’s account. UM handles user registration, authentication and log-in. JM manages batch jobs. JM supervises current job’s status and system load.

AP consists of two elements (see Figure 4). One is background processing program for data converter. Considering parallelization and fast execution, AP is mainly written in general-purpose programming languages, such as C, C++, FORTRAN and Java. The background processing program is executed by submitting a batch job. The job is queued after that and put into running state according to current running job’s status monitored by JM. Another is web-script for displaying the converted data on a web-browser. Considering convenience of Common Gateway Interface (CGI), it is mainly written in script language such as PHP, Perl and Ruby. APs need to be developed for several CSM/CFD solver and mesh generator. For example, APs of mesh generator is realized by combination of a mesh generation program and a web-script for visualizing CAD data and analysis mesh.
3. Application of cloud CAE platform to structural analysis

In the present study, we develop APs named Geometry-load, Geometry-mesher, Mesh-load, Mesh-setup, Model-load, Solver-run and Result-load in order to apply the proposed cloud CAE platform to large-scale finite element analysis. As open-source software, we use parallel finite element analysis program ‘FrontISTR’ and two tetrahedral mesh generation programs, ‘ADVENTURE TetMesh’ and ‘Netgen’. DM’s data structures are classified into four categories: geometry model, finite element mesh, analysis model including boundary conditions or material parameters and computational results such as displacement, stress and strain. A cloud CAE system is constructed by the cloud CAE platform and the developed APs and provides Software as a Service (SaaS) cloud services.

3.1. 360-degree image capturing method

360-degree image capturing method is proposed to reduce CPU load for displaying large-scale 3D models on a web browser. In 360-degree image capturing method, 3D geometric shapes of a body are expressed as 2D screen images shot from every angle by using OpenGL on a cloud server with high performance GPU. Rotation of 3D models is expressed as screen images copied from screen buffer and these screen images are converted from the bitmap image to compressed Portable Network Graphics (PNG) image (see Figure 5). Because these images are only shown on a client computer, CPU loading is not high for displaying large-scale model and a particular graphic device is not necessary.

3.2. APs functions

Operating procedure of the system and functions of APs are shown below (see Figure 6). APs are written in C++ language, launch by JM. APs’ interface is provides web page by php script.

3.2.1. Geometry-load plug-in

Geometry-load plug-in can display a geometry model such as CAD model by 360-degree image capturing method. The AP reads geometry data by REVOCAP mesh library and Open CASCADE. The AP supports geometry data in IGES, STEP and STL formats. Then the AP draws surface polygons from geometry data by
360-degree image capturing method. Furthermore, The AP offers an input interface of Geometry-Mesher plug-in. The input interface is web page which generated php script including the AP. The interface can assign meshing parameters (e.g. mesh fineness, order of finite elements) and select one from auto tetrahedral mesh generation programs, ‘ADVENTURE TetMesh’ and ‘Netgen’.

3.2.2. Geometry-Mesher plug-in In accordance with the assigned meshing parameters, Geometry-Mesher plug-in executes a selected tetrahedral mesh generator by JM. If mesh generation is successful, it registers tetrahedral mesh with DM. The AP creates new finite element mesh data from the geometry data.

3.2.3. Mesh-load plug-in Mesh-load plug-in can display finite element mesh by 360-degree image capturing method. The AP reads mesh data by REVOCAP mesh library. The AP supports finite element mesh data in Netgen (.vol), ADVENTURE TetMesh (.tmsh) and HECMW mesh (.msh) formats.

The AP generates surface groups of the analysis mesh and different colors are given to the surface groups for identification. After that, the AP sets a boundary condition for the surface group (see Figure 7).
The AP offers an input interface of Mesh-setup plug-in. Through the input interface, parameters of boundary conditions and material properties are assigned.

3.2.4. Mesh-setup plug-in  In accordance with the assigned parameters, Mesh-setup plug-in creates new finite element analysis model data from the finite element mesh data. Specifically, the AP reads the mesh data by REVOCAP mesh library and read the assigned parameters, then the AP converts the mesh data and assigned boundary conditions into FrontISTR analysis model data (HECMW mesh data (.msh) and FrontISTR control data (.cnt)). After that the AP the registers analysis model data with DM.

3.2.5. Model-load plug-in  Model-load plug-in reads FEA model data by REVOCAP mesh library, then the AP draws its image by 360-degree image capturing method. The AP supports finite element analysis data in HECMW mesh data (.msh) and FrontISTR control data (.cnt) formats. The AP offers an input interface of Solver-run plug-in. Through the input interface, an appropriate linear solver is selected from direct and iterative methods is selected and parameters, such as convergence tolerance and preconditioner for iterative solver is assigned.

3.2.6. Solver-run plug-in  In accordance with the selected linear solver and the assigned parameters, Solver-run plug-in creates batch job which executes FEA by FrontISTR and send the batch job to computational servers by JM. Before parallel execution of FrontISTR, the analysis model is decomposed into some domains with a partitioning tool based on METIS. The AP creates new numerical result data from the finite element analysis model data.

3.2.7. Result-load plug-in  Result-load plug-in reads displays numerical results of finite element analysis by REVOCAP mesh library. Then the AP draws its image such as deformed shapes of the analysis model, color contour of displacement and stress by 360-degree image capturing method. The AP supports numerical result data in HECMW result (.res) and AVS UCD (.inp) formats.

4. Numerical examples

In this section, effectiveness of the proposed CAE platform is demonstrated. As numerical examples, we prepared a connecting-rod model in Figure 8 and drill model in Figure 9 as geometry data in STL format. The cloud CAE platform software and some APs run on Cloud CAE server (see Table 1).

4.1. Static stress analysis of connecting-rod model

Static stress analysis of the connecting-rod model is executed. Analysis meshes are created from geometry data as shown in Figure 8. The coarse quadratic tetrahedral mesh (5,993 nodes and 25,262 elements) is created by Netgen program; the fine quadratic tetrahedral mesh (53,237,284 nodes and 39,503,057 elements) is created by ADVENTURE TetMesh program. Figure 10 shows the coarse and fine finite element analysis meshes. Appropriate boundary conditions
were assigned to them as shown in Figure 11. The fixed boundary conditions are given on the inside of the small end and normal traction vectors are given on the upper boundary of the large end. The coarse and fine finite element meshes are divided into 8 and 512 domains respectively. For fine finite element analysis mesh, parallel computing of static stress analysis is executed by 512 message passing interface (MPI) processes (16 MPI processes/node) on Oakleaf-FX (see Table 1) and Preconditioned CG method with 3×3 block diagonal scaling is used as the iterative linear solver. For coarse finite element analysis mesh, parallel computing is executed by 8 MPI processes on PC cluster (see Table 1) and MUMPS is used as the direct solver. Figure 12 shows deformation of the connecting-rod. Table 2 shows execution time for each CAE process. We hereby confirmed that this system have ability for interactive CAE works including large-scale analysis.

Fig. 10 Analysis meshes of connecting-rod model. The left figure is the coarse mesh and the right figure is the fine mesh.

Fig. 11 Analysis mesh and boundary conditions of connecting-rod model.

Fig. 12 Deformation of the connecting-rod model.

4.2. Eigenvalue analysis of drill model

Eigenvalue analysis of the drill model is executed. Analysis meshes are created from geometry data as shown in Figure 9. The fine quadratic tetrahedral mesh (1,925,371 nodes and 1,350,595 elements) is created by ADVENTURE TetMesh. Figure 13 shows the fine finite element analysis meshes. The fixed boundary conditions are given on the bottom boundary (see Figure 13). The fine finite element mesh is divided into 64 domains. Parallel computing of eigenvalue analysis is executed by 64 MPI processes (16 MPI processes/node) on Oakleaf-FX (see Table 1) and Preconditioned
Table 1 Specifications of computational servers.

<table>
<thead>
<tr>
<th>Nodes</th>
<th>Cores/ nodes</th>
<th>CPU</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC cluster</td>
<td>12</td>
<td>8</td>
<td>Intel Xeon X5550 @2.67GHz×2</td>
</tr>
<tr>
<td>Cloud CAE server</td>
<td>1</td>
<td>20</td>
<td>Intel Xeon E5-2650v3 @2.30GHz×2</td>
</tr>
<tr>
<td>Oakleaf-FX</td>
<td>4,800</td>
<td>16</td>
<td>SPARC64 IXfx @1.85GHz</td>
</tr>
</tbody>
</table>

Table 2 Elapsed time of each process in the static stress analyses.

<table>
<thead>
<tr>
<th>Process</th>
<th>Fine model</th>
<th>Coarse model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Show geometry model</td>
<td>7s</td>
<td>7s</td>
</tr>
<tr>
<td>Running auto tetrahedral mesher</td>
<td>1h 3m 16s</td>
<td>7s</td>
</tr>
<tr>
<td>Show finite element mesh</td>
<td>11m 39s</td>
<td>14s</td>
</tr>
<tr>
<td>Assigning boundary conditions</td>
<td>14m 10s</td>
<td>3s</td>
</tr>
<tr>
<td>Show finite elemental analysis model</td>
<td>11m 01s</td>
<td>3s</td>
</tr>
<tr>
<td>Domain decomposition</td>
<td>14m 15s</td>
<td>1s</td>
</tr>
<tr>
<td>Finite element analysis</td>
<td>38m 52s</td>
<td>3s</td>
</tr>
<tr>
<td>Visualization of FEA result</td>
<td>45m 52s</td>
<td>6s</td>
</tr>
</tbody>
</table>

conjugate gradient (CG) method with 3×3 block diagonal scaling is used as the iterative linear solver. Figure 14 shows deformation of the drill model which are from 1st mode to 3th mode shown.

5. Conclusion

In the present study, as one of applications constructed by the platform, numerical examples of large-scale finite element analysis were shown. The application system constructed by the platform and APs can be used through any device which has a web browser. The proposed cloud CAE platform is expected to solve technical issues for introducing open source software to CAE and lead more efficient product design. Additionally this system is able to be provided as inexpensive service (i.e. IaaS cloud service’s computational charge and a little extra). Therefore this system can help to introduce CAE into small firm and personal use more.

Fig. 13 Analysis mesh and boundary conditions of drill model.
(a) 1st mode (451 Hz)  (b) 2nd mode (491 Hz)  (c) 3rd mode (2111 Hz)

Fig. 14 Three lowest eigenmodes of the drill model.

<table>
<thead>
<tr>
<th>Process</th>
<th>Elapsed time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Show geometry model</td>
<td>25s</td>
</tr>
<tr>
<td>Running auto tetrahedral mesher</td>
<td>3m 40s</td>
</tr>
<tr>
<td>Show finite element mesh</td>
<td>43s</td>
</tr>
<tr>
<td>Assigning boundary conditions</td>
<td>32s</td>
</tr>
<tr>
<td>Show FE model</td>
<td>1m 6s</td>
</tr>
<tr>
<td>Domain decomposition</td>
<td>31s</td>
</tr>
<tr>
<td>Finite element analysis</td>
<td>2h 55m 30s</td>
</tr>
<tr>
<td>Visualization of FEA result</td>
<td>6m 59s</td>
</tr>
</tbody>
</table>

Table 3 Elapsed time of each process in the eigenvalue analysis.

References


