Tuning Free CAE

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■ Position of CAE ■

CAD→CAE→Design→。。。

■ Property of FEM ■

	Arbitrary Shape	Inhomogenous material	Commercial Software	Parallel Computing	Mathematical Background
FEM	○	○	○ (Solid)	○	○
FDM	×	○	○ (Fluid)	○	×
BEM	◎	×	×	×	△

CAD→FEM software→Design。。。

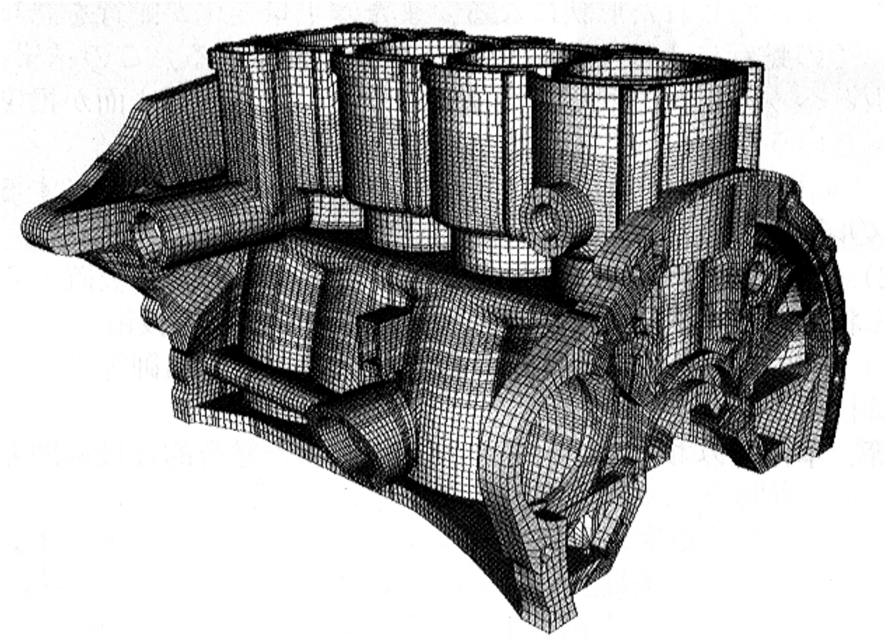
It is not so simple in reality!

■ Headache（1）：3D Mesh Generation ■

From CAD data

・Dilectly TETRA/HEXA mesh generation →Poor reliability？

・Interactively TETRA/HEXA mesh generation →Time consuming



Two-week task（although reduced to 1/3）
（Hitachi's mesher (JSME prize winner)）

Cause for time eating：Good quality mesh is required

→Accuracy dependent to mesh quality

Many researches as a detour

- Mesh free scheme

Only nodes are required. Bad time complexity.

Element-free Galerkin scheme
Partition of Unity scheme
hp-cloud scheme
Cells for integration are needed.
Free mesh scheme
Locally & temporarily generated elements around a node.
Voxecell mesh scheme
Large scale FEA with zigzag mesh

■ Headache(2):from FEM(Simulation) to Design(Control) ■

Interactive deign process by parameter changes on trial & errors
(Remeshing is required if shape is drastically changed.)

CAE replaces only experiments. The other is in old fashion.

■ Headache (3):**No good software for Fluid or Combustion** ■

■ Headache (4):**Time eating coding for parallel computation** ■

■ Tuning Free CAE ■

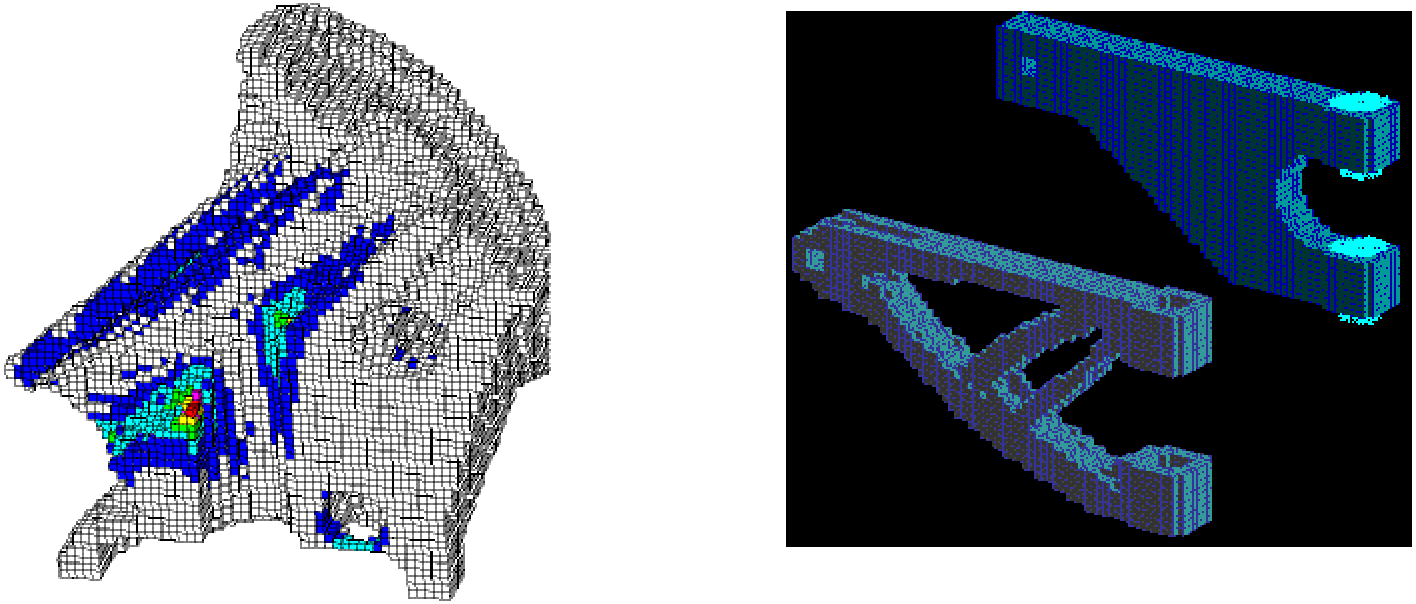
CAE without special technique and intuition

■ Two possible directions toward tuning free CAE ■

Massively large scale parallel computation →Quantity
Improvement numerical method →Quality

■ Seamless CAE from CAD to RP ■

Voxcell mesh scheme＋Optimal topology design
Tuning free based on Massively large scale parallel computation



No problems？ →Inaccurate compared with conventional CAE？

Tuning-free Computational Mechanics

(１)Tuning Free (from Intuition to Technology)

- Full Automatic Mesh Generator

Interactive process by user was omitted (from interactive to full-automatic)

- Adaptive Finite Element Method

Error control with a posteriori error estimation) (free from experience-based mesh generation)

- Optimal Parameter Design

Optimization under constraints(Sheet metal forming) (free from experience-based design)

- New FEM for Discontinuous HEXA Mesh

FEM with improved MLS for discontinuous mesh (Simplify interactive mesh generation)

- Common Platform on Parallel Computations (Free from coding for parallel computation.)

Common template for parallel FEM/FDM/FVM.

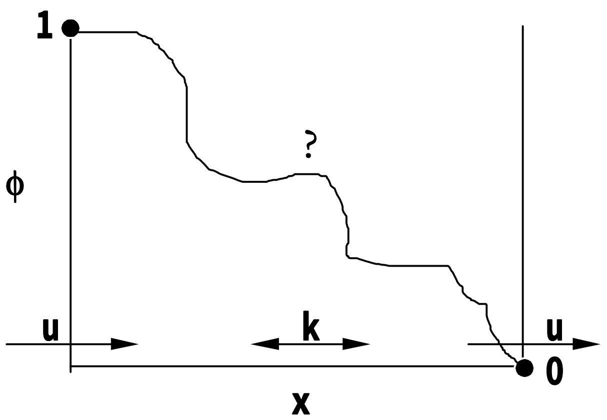
(2) Numerical Method ahead of Hardware’s Progress (hardware<software)

- Space-Time Stabilized Adaptive Fluid FEM

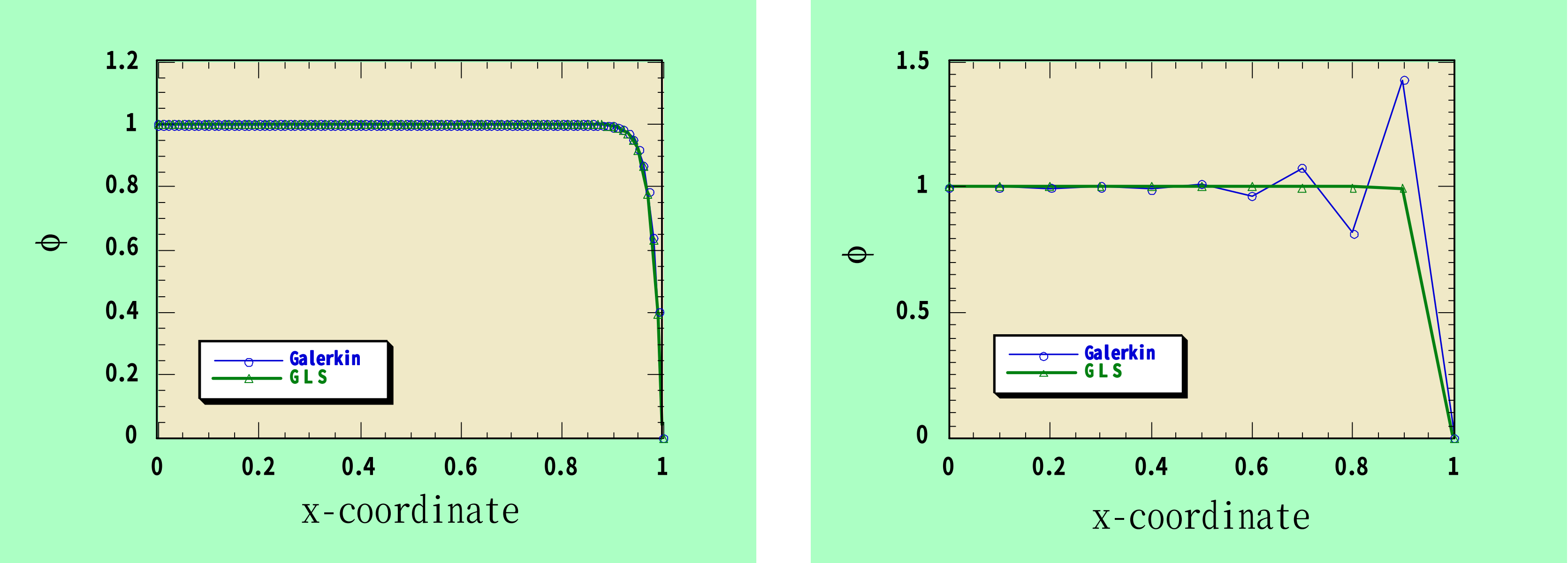
Exponential effects with adaptive mesh

■ Adaptive Space-time Stabilized FEM ■

Stabilized FEM : Numerically stable steady FEM even with coarse mesh（T.Hughes)



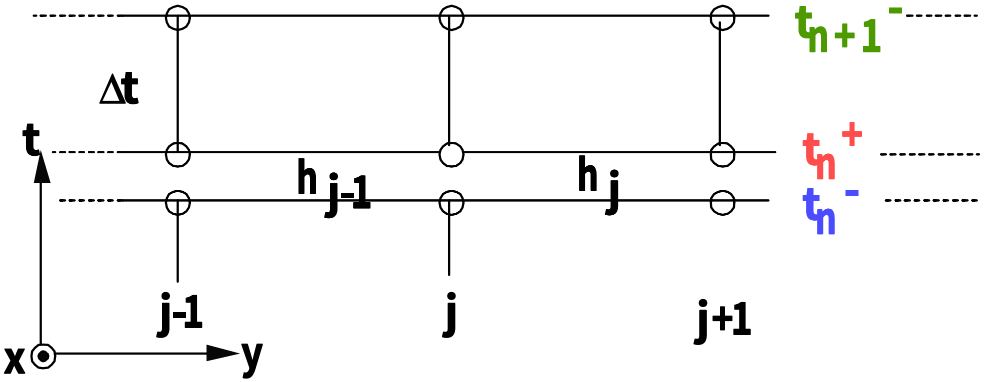
Advection-diffusion steady problem in 1D（u=50, k=1）



mesh with 100 elements

mesh with 10 elements

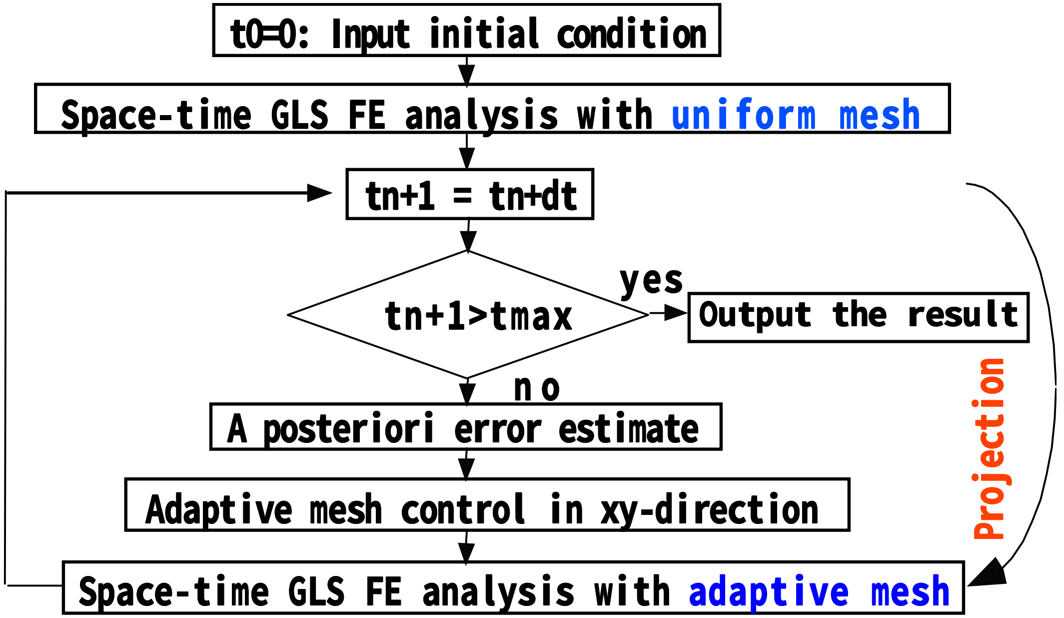
- **Space-time scheme** : Stable unsteady treatment with mesh in time-direction (T.Hughes)



h: mesh size in y-direction; Δt: mesh size in t-direction

Space-time mesh

- **Adaptive remeshing** : Mesh improvement with a posteriori error estimate (A.Tezuka, etc）


t0=0: Input initial condition

Space-time GLS FE analysis with uniform mesh

tn+1 = tn+dt

tn+1>tmax

yes

Output the result

no

A posteriori error estimate

Adaptive mesh control in xy-direction

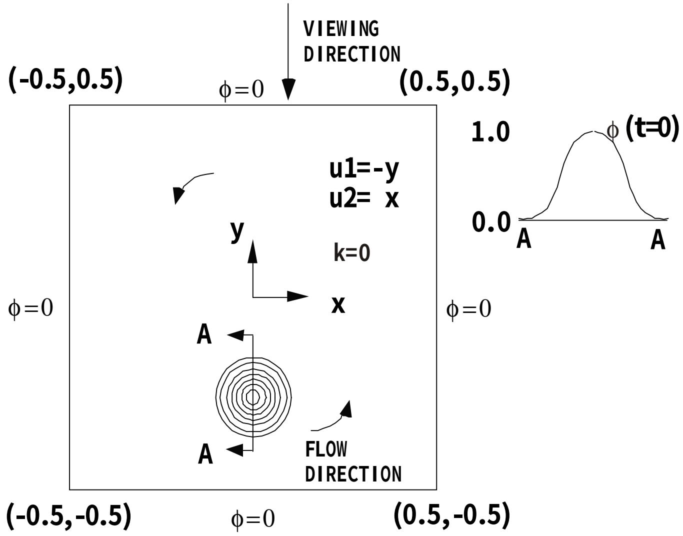
Space-time GLS FE analysis with adaptive mesh

Projection

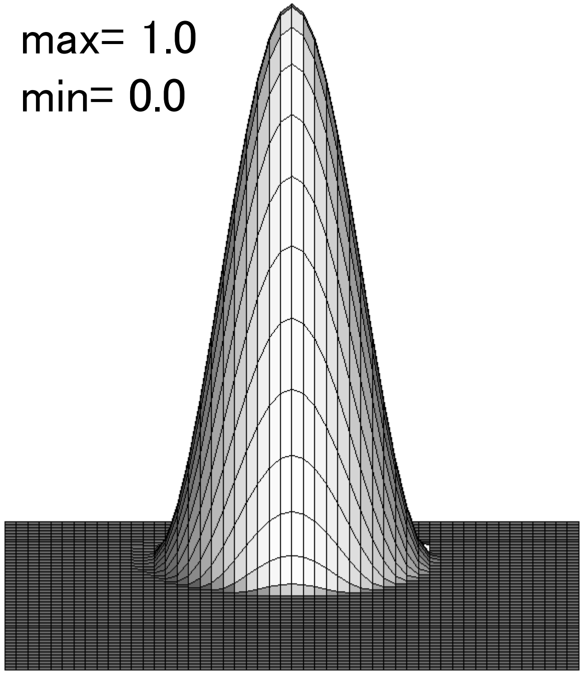
Algorithm

Application to Advection–Diffusion Problem (Direct mapping scheme)

(A.Tezuka)

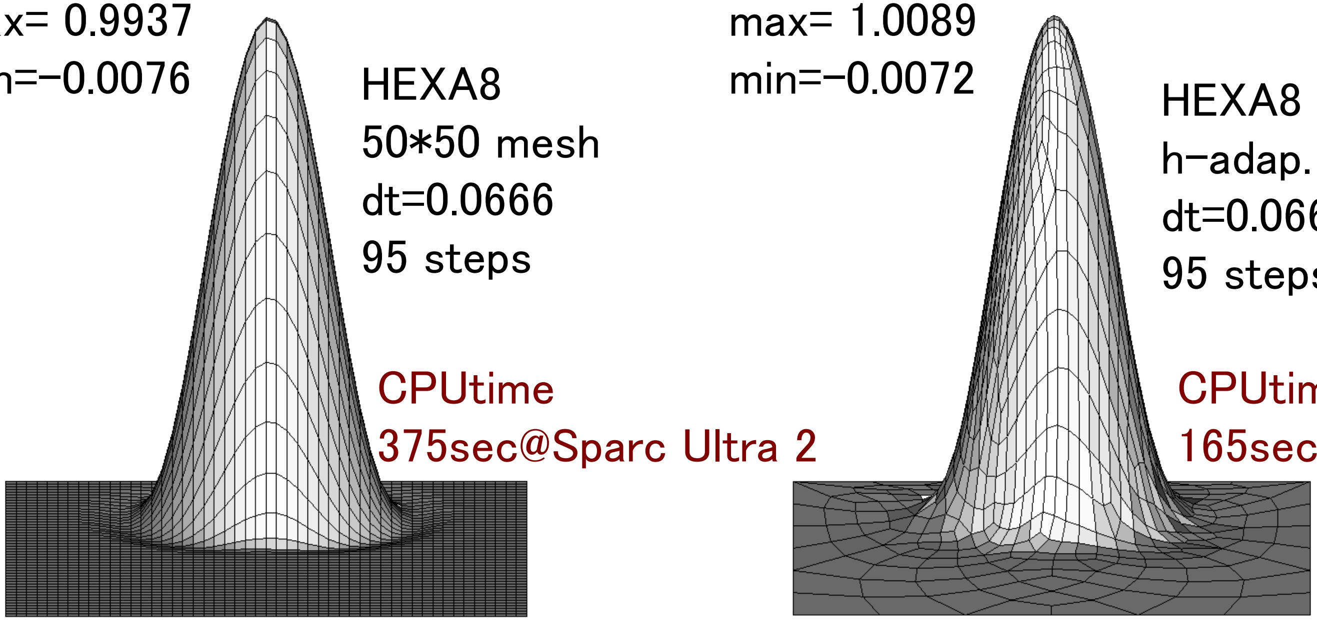


Lotating cone problem
(Benchmarch)



max= 1.0
min= 0.0

Initial condition on φ



max= 0.9937
min=−0.0076

HEXA8
50*50 mesh
dt=0.0666
95 steps

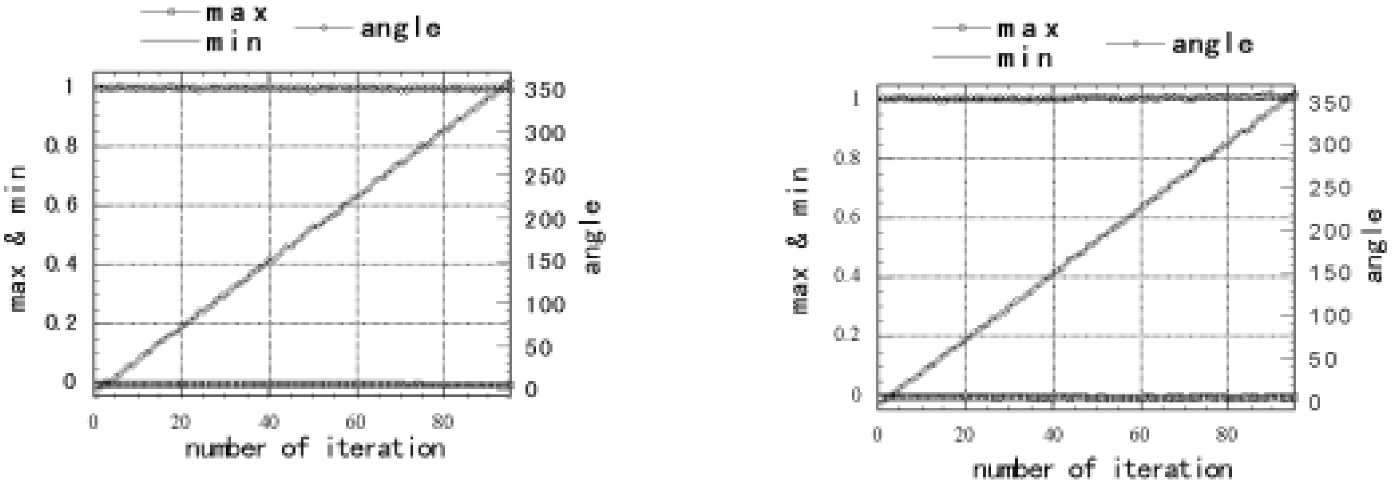
CPUtime
375sec@Sparc Ultra 2

max= 1.0089
min=−0.0072

HEXA8
h−adap.
dt=0.0666
95 steps

CPUtime
165sec@Sparc Ultra 2

Profile of ϕ after one rotation



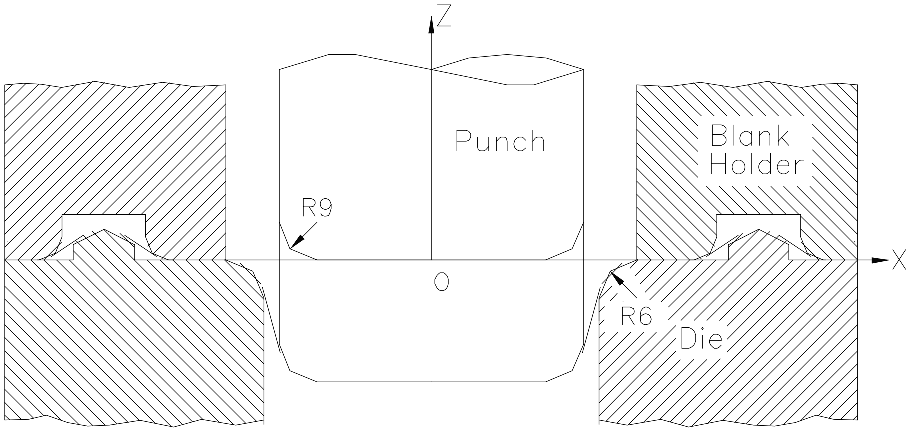
History of max & min of ϕ

■ Optimal Parameter Design ■

Sheet Metal Forming

- ･Used at consumer products, automobile
- ･To avoid tearing

Controlled by draw bead forces



(Unit ： mm)

Ordinary & Inverse Problem

- ･Ordinary Problem（FEA）
- ･Inverse Problem（Optimal Design）

Conventional Process

- ･By experiments based experience and intuition
- ･By trial and error with FEA

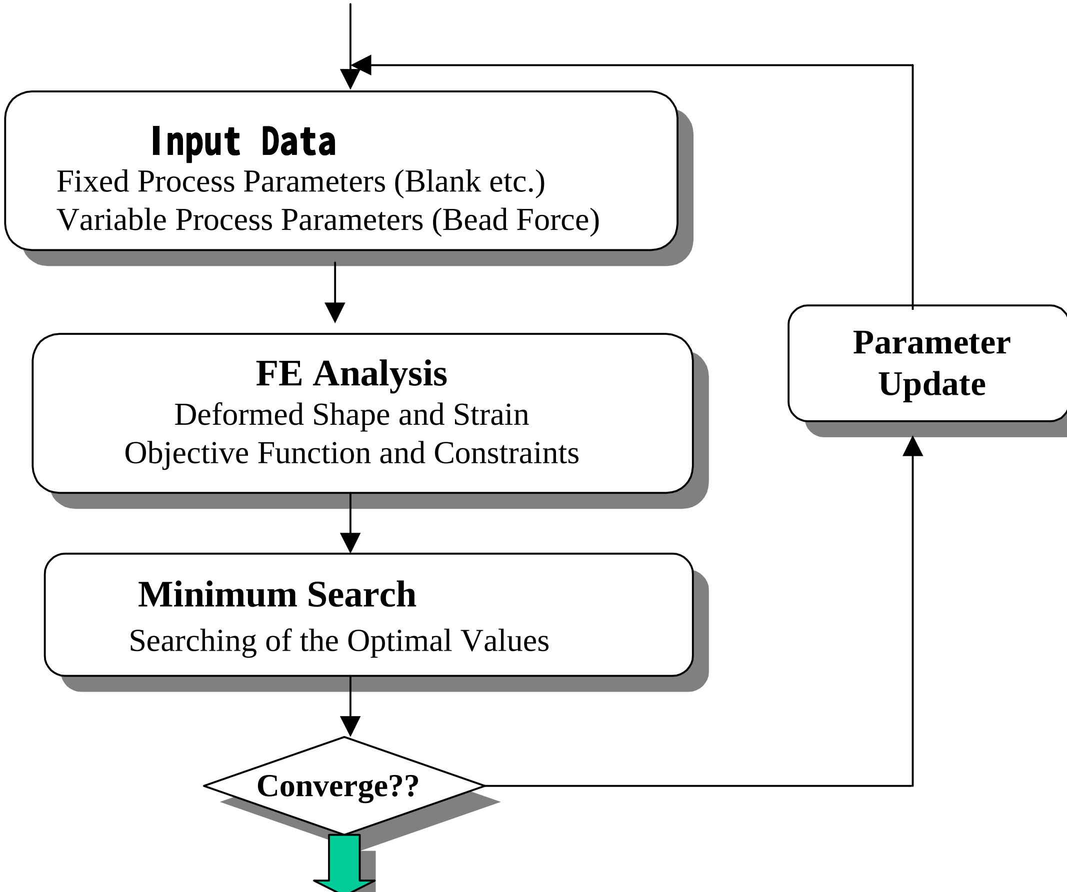
Optimal Parameter Design

Optimal choice of draw bead force

Rigid-plastic FEA with modified membrane element

Optimal search（Response Surface Method）

Evaluated at deep drawing



Input Data
Fixed Process Parameters (Blank etc.)
Variable Process Parameters (Bead Force)

FE Analysis
Deformed Shape and Strain
Objective Function and Constraints

Minimum Search
Searching of the Optimal Values

Converge??

Parameter Update

Optimal Search Engine

1. Based on sensitivity (SQP, BFGS,etc)

(1) By finite difference approximation

2n+1 times FEA for n design variables

$$\frac{\partial \phi}{\partial p_i} = \frac{\phi(\mathbf{p}+\Delta p_i)-\phi(\mathbf{p}-\Delta p_i)}{2\Delta p_i}$$

(2) By direct differentiation

$$\mathbf{R}=\mathbf{Q}^{\mathbf{m}}+\mathbf{Q}^{\mathbf{b}}-\mathbf{F}=0 \rightarrow \frac{\partial \mathbf{R}}{\partial \mathbf{p}}+\frac{\partial \mathbf{R}}{\partial \mathbf{U}}\frac{d\mathbf{U}}{d\mathbf{p}}+\frac{\partial \mathbf{R}}{\partial \mathbf{X}}\frac{d\mathbf{X}}{d\mathbf{p}}=0$$

• Problems on sensitivity

1) Possible local minimum convergence
2) Bad convergence w/ many design variables
3) Bad time complexity at FDA
4) Implementation needed at direct approach

2. Based on response of model

(1) By genetic algorithm (GA)

(2) By response surface

• Problems on GA

Disaster with large number of variables

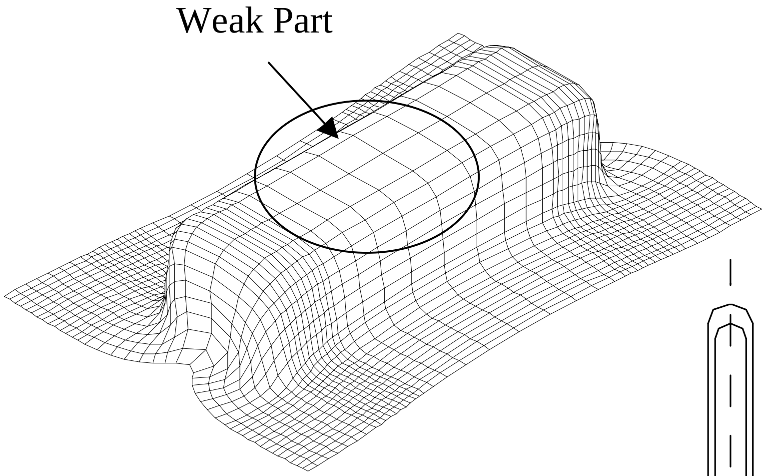
- Globally approximated quadratic function against real response
- Valid for discretized values
- Previous data can be added in database
- Less possibility for local minimum convergence
- Easy for implementation
- Approximated scheme, but sufficient in engineering

Bead Force Optimization (square cup drawing) (S.H.Kim & A.Tezuka)

- Assumption

Constant draw bead forces during the process

- Optimal target



Additional strain needed at weak part

stress-strain $\bar{\sigma} = 576(0.0009 + \bar{\varepsilon})^{0.274}$ Mpa

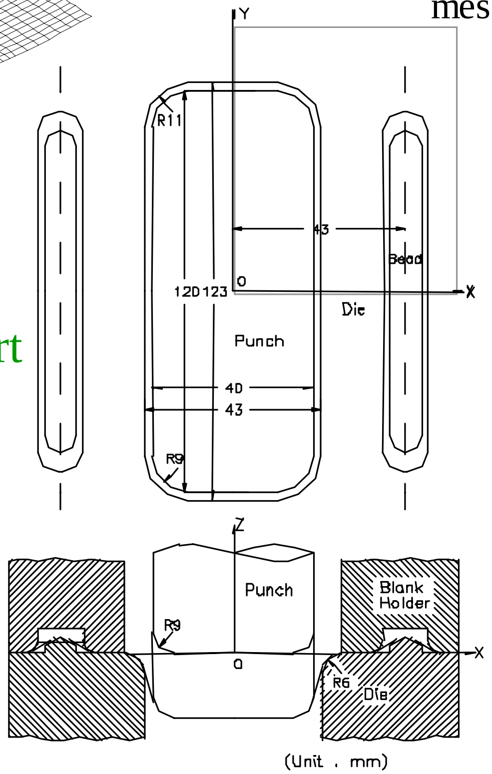
Lankford values $(r_0, r_{45}, r_{90}) = (1.833, 1.434, 2.016)$

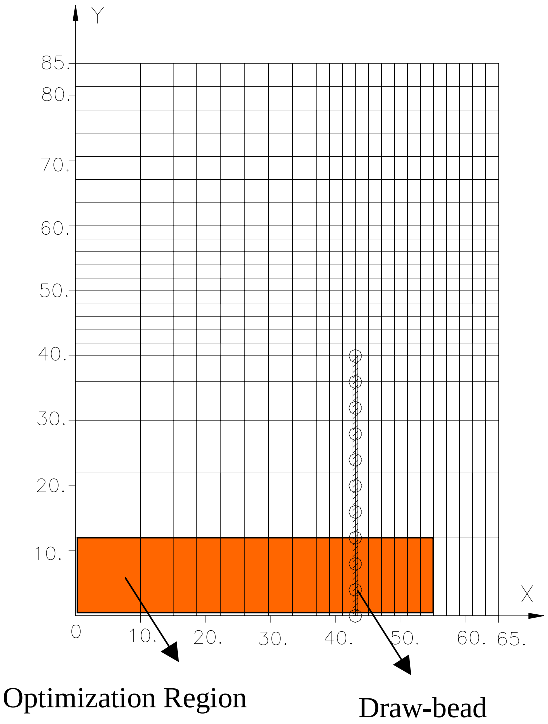
Thickness : t = 0.69 mm

Blank size: 130mm×170mm

Coulomb friction coeff. : 0.11

mesh





Model and mesh

Object Function

$$\min. \quad \Phi(E(\mathbf{U}(\mathbf{p}),\mathbf{X}(\mathbf{p}),\mathbf{p}),\mathbf{p}) = \int_{\Omega_{opt}} \left(E_1 - \tilde{E}_1\right)^2 d\Omega$$

Subject to $\mathbf{p} \geq \mathbf{0}$ （bead force must be positive）

$E_1 < \tilde{E}_C$ （to avoid tearing）

U: displacement、**X**: coordinates、**p**: process parameter（eq. draw bead force）

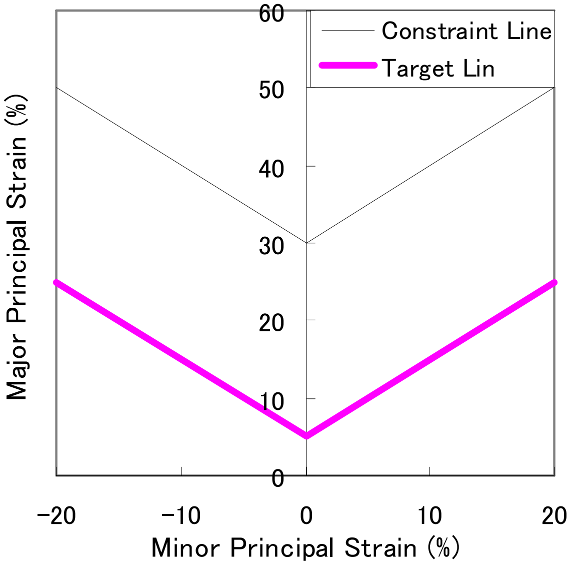
E_1 major principal strain

$\tilde{E}_1$:Target value

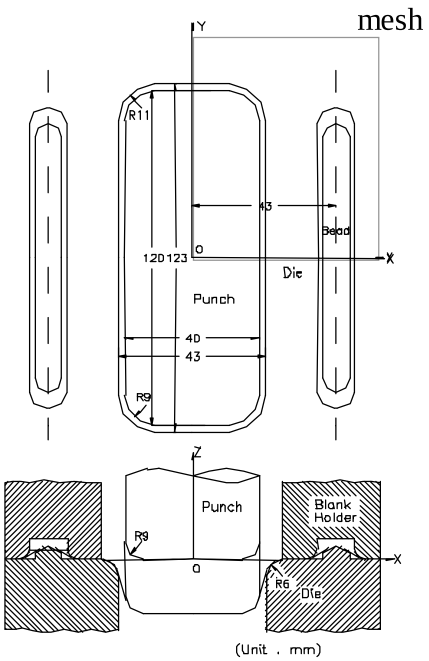
$$\tilde{\mathrm{E}}_1 = -\mathrm{E}_2 + \mathrm{E}_\mathrm{O} \text{ if } \mathrm{E}_2 \leq 0, \ \tilde{\mathrm{E}}_1 = \mathrm{E}_2 + \mathrm{E}_\mathrm{O} \text{ if } \mathrm{E}_2 > 0$$

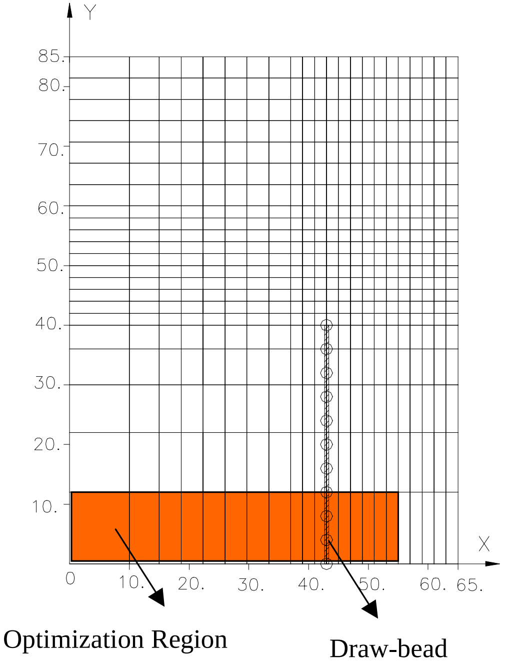
$\tilde{\mathrm{E}}_C$:boundary line for the fracture region

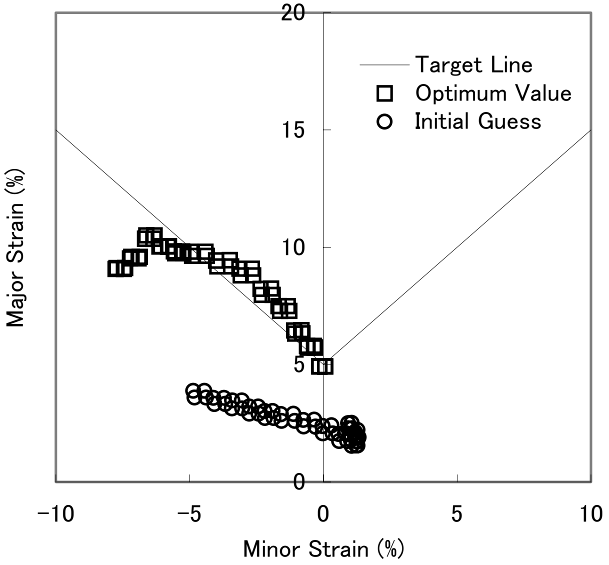
$$\tilde{\mathrm{E}}_\mathrm{c} = -\mathrm{E}_2 + \mathrm{E}_\mathrm{cO} \text{ if } \mathrm{E}_2 \leq 0, \tilde{\mathrm{E}}_\mathrm{c} = \mathrm{E}_2 + \mathrm{E}_\mathrm{cO} \text{ if } \mathrm{E}_2 > 0$$



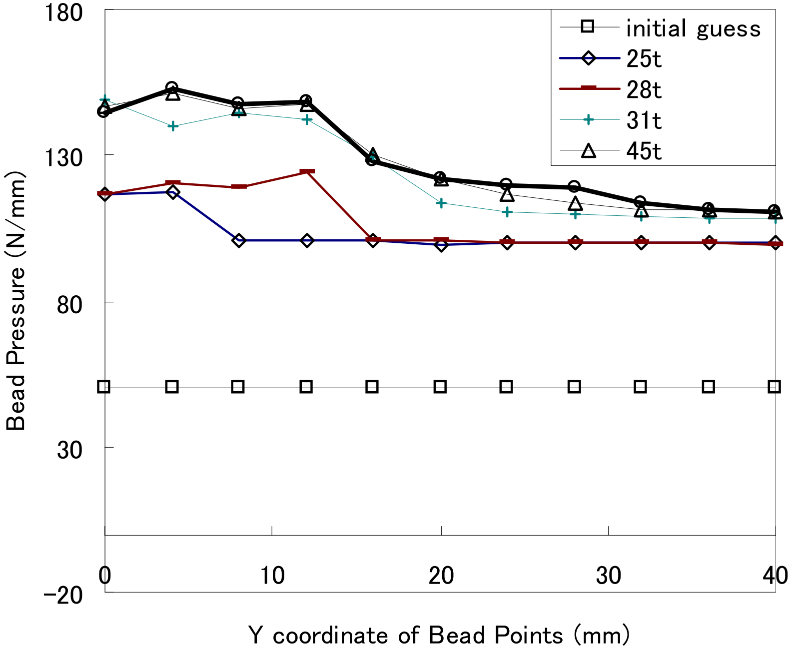
Target line and constraint line on the forming limit diagram







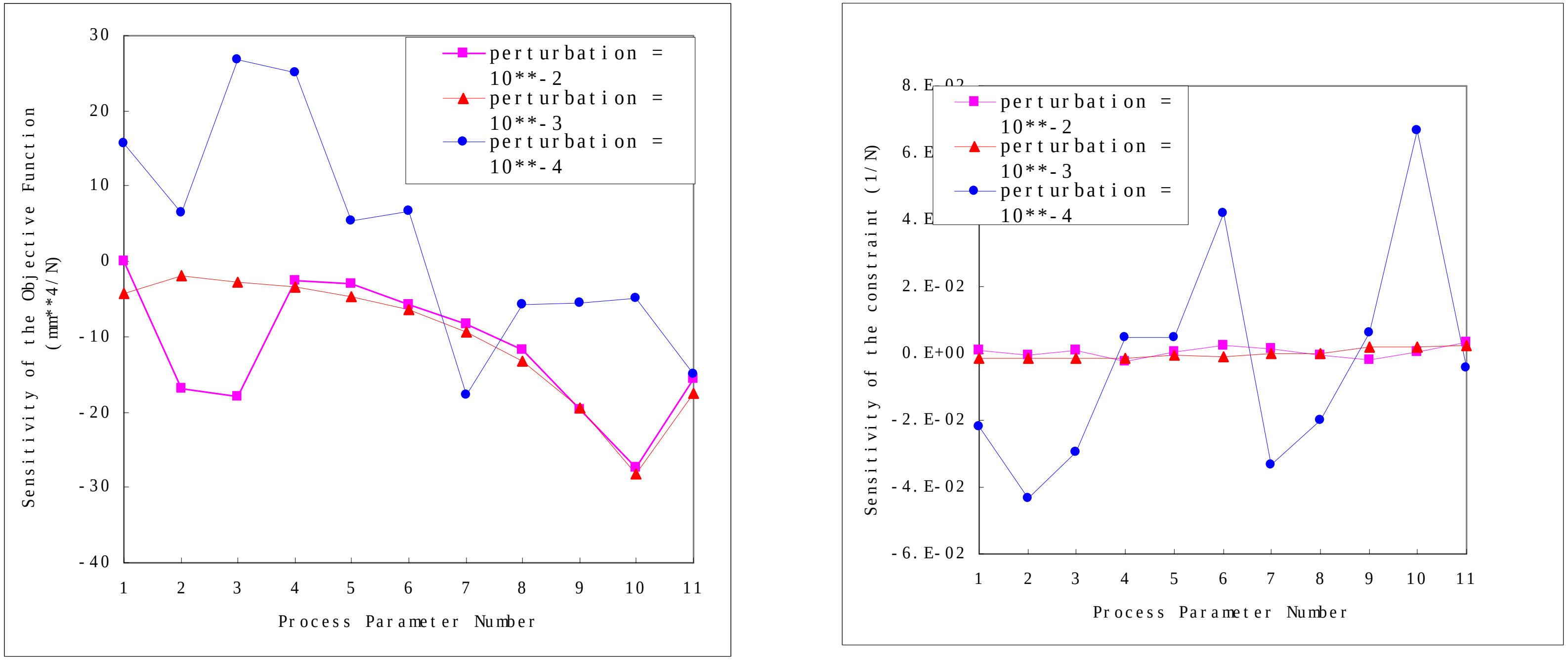
Principal strain distribution before/after optimization process



Equivalent bead forces during optimization

Response Surface Methodology

- 2n+1 FEA are needed to generate quadratic response surface
- Perturbation at each draw bead point around initial value,50 N/mm



Sensitivity on object function and constraints

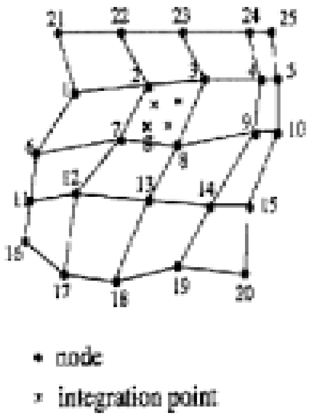
■ Discontinuous meshed mesh (DCMM) FEM ■

(C. Oishi, A.Tezuka & N. Asano)

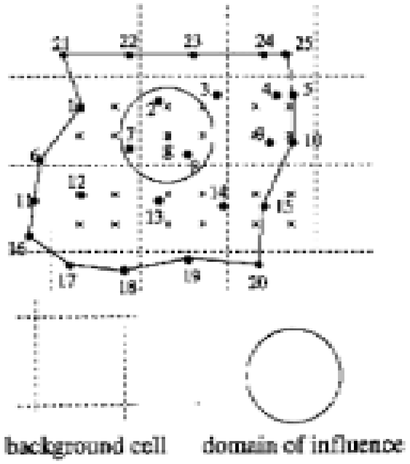
Element-Free Galerkin Method

(T. Belytschko)

- Integration unit in FEM and EFGM



(a) FEM



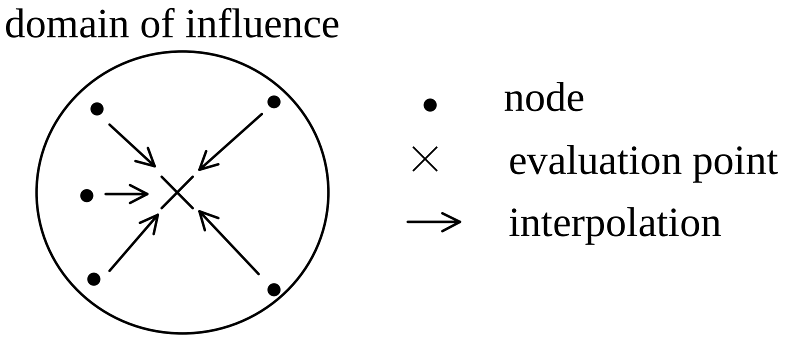
(b)EFGM

- Differences between FEM and EFGM

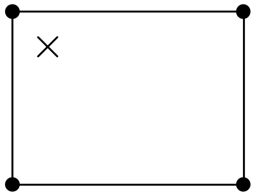
	FEM	EFGM
Weak form	Galerkin method	Galerkin method
Approximation function	Interpolation function defined in element	MLS function defined at integration point
Integration unit	Element	Background cell
Nodal value	$U^h{}_i(x_i)=U_i$	$U^h{}_i(x_i)\neq U_i$
Required information	Elements and nodes	Nodes only
Time complexity	Good	Bad

Moving Least Squares Method(MLSM)

Derived only with info. of nodes around an evaluation point



(a) EFGM



(b) FEM

Interpolation by nodes in support domain

$$J = \sum_{I}^{n} w_I(\mathbf{x}-\mathbf{x}_I)\left[\sum_{J=1}^{m} p_J(\mathbf{x})a_J(\mathbf{x})-u_I\right]^2$$

$$u^h(\mathbf{x}) = \sum_{J=1}^{m} p_J(\mathbf{x})a_J(\mathbf{x}) \equiv \sum_{I=1}^{n} \phi_I(\mathbf{x})u_I$$

m : number of basis in p_j, n : number of nodes in support domain

ϕ_I: approximation function in MLS

Coefficients a_J are decided in minimization of J

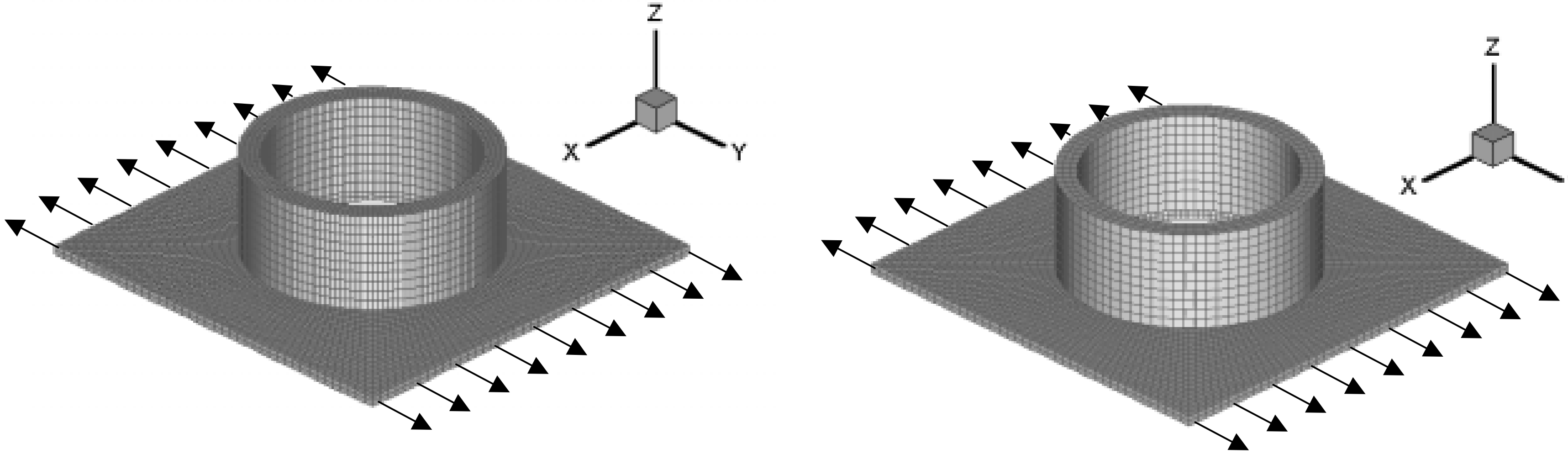
・Exponential weight function

$$w_I\left(d_I^2\right) = \begin{cases} \dfrac{e^{-(d_I/c)^2} - e^{-(d_{mI}/c)^2}}{\left(1-e^{-(d_{mI}/c)^2}\right)}, & d_I \leq d_{mI} \\ 0 & d_I > d_{mI} \end{cases} \qquad d_I = \| x - x_I \|$$

Example

Upper part fixed	Yong's modulus	2.1×10^5 MPa
Pulled plate	Poisson's ratio	0.3

5125 nodes	3955 nodes
3520 elements	2490 elements
	238 constraints

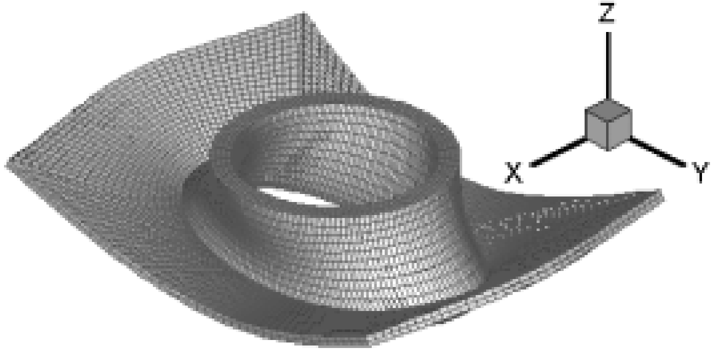


a)Continuous mesh b)Discontinuous mesh

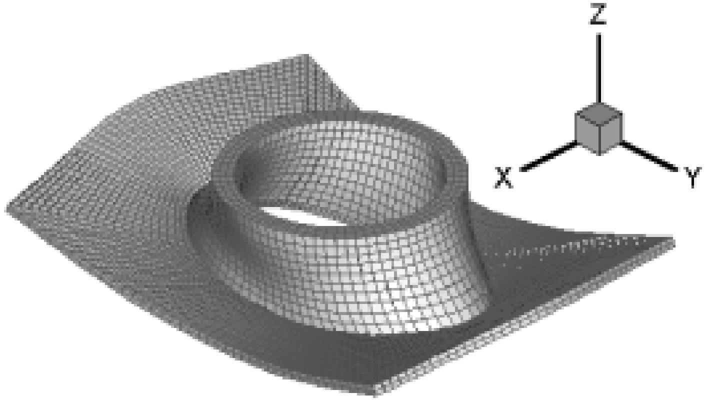
Pulled plate with pipe

Deformation

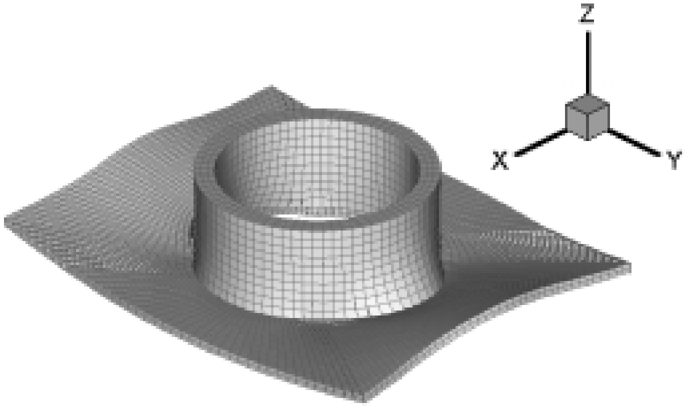
(scaled by 5,000)



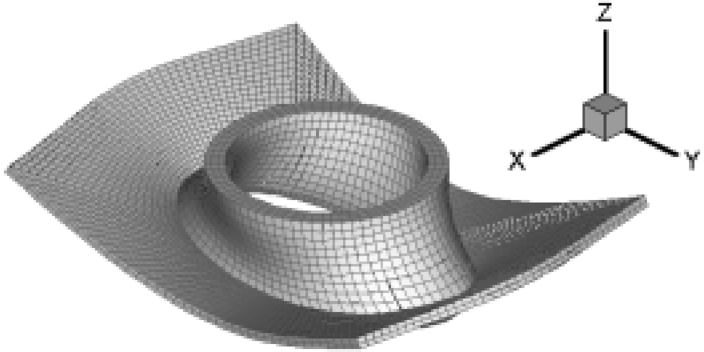
a) FEM



b) NLCM

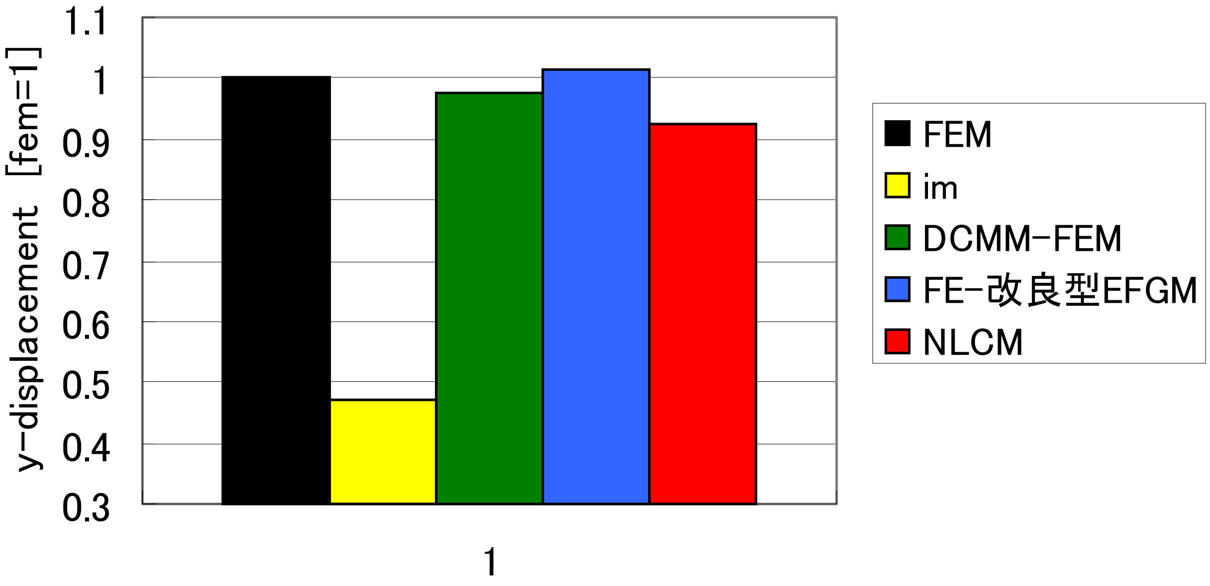


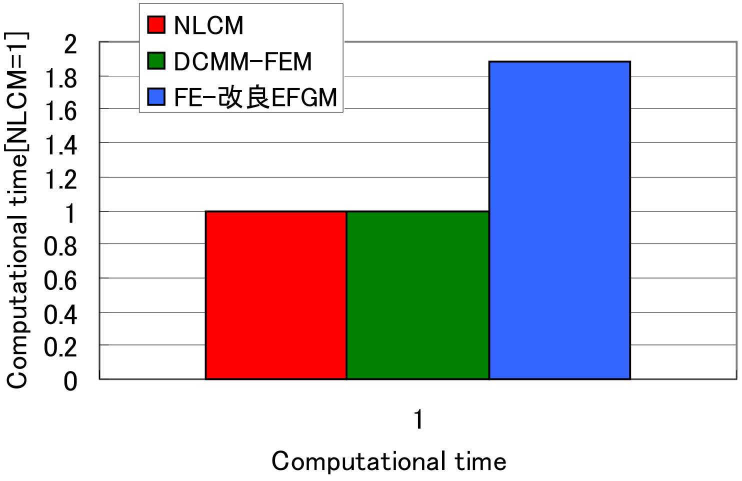
c) improved EFGM



d) DCMM-FEM

Evaluation


y-displacement [fem=1]
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1
FEM
im
DCMM-FEM
FE-改良型EFGM
NLCM


Computational time[NLCM=1]
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
Computational time
NLCM
DCMM-FEM
FE-改良EFGM

■ Common Platform for Parallel Computations ■

(Collaboration with Fuji Research Institute)

Target：Researchers on computational mechanics

→Limited with FEM/FDM/FVM

Purpose：Easy shift to parallel computations

→Simple procedure on modification with MPI

Point：Flexible for modification

→Common for FEM/FDM/FVM

Method： General purpose reliable schemes

→Domain de composition. Interface with free software

Motivations

For fast computation

- I’d like to replace with fast matrix solver
- I’d like to generate stiffness matrix more fast

For large scale computation

- I‘d like to save memory at matrix solver
- I‘d like to save memory at generating stiffness matrix

Problems

- Time consuming task to modify a program with MPI for parallel computations
- Parallel matrix solver such as PETSc, Aztec, and GEOFEM are for professional researchers on parallel computations
- FEM/FDM/FVM are individually developed.

Requirements on parallel platform

１．Required data

・Nodal info（num. of element，ndf，coordinates）

・Element info（num. of element，connectivity）

・Boundary condition（fix，slide，constraint）

・Load condition

・Subroutine to construct stiffness matrix

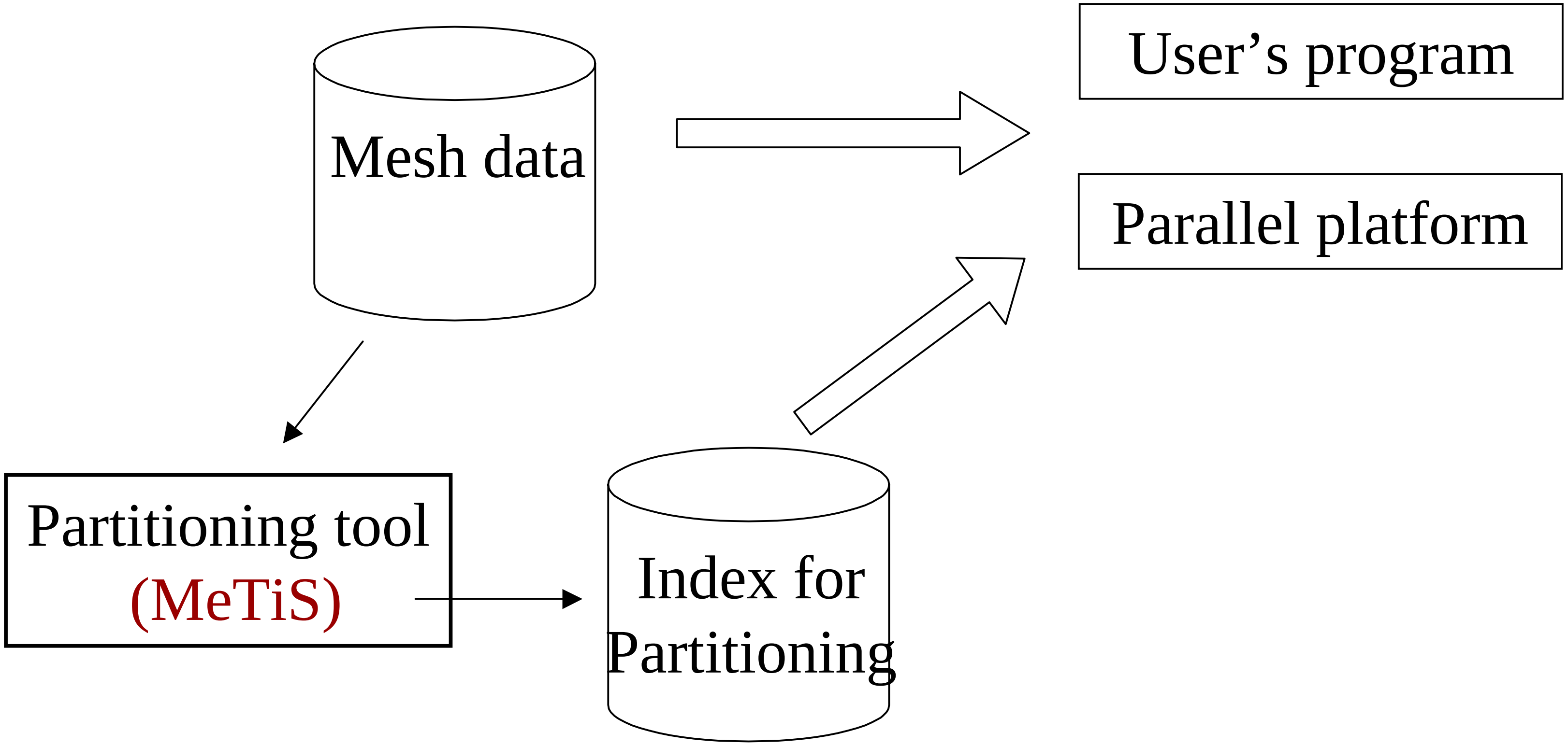
２．GMRES and BiCGSTAB are equipped

３．Partitioning by MeTiS

４．Parallel efficiency more than 70% at SR8000@32 nodes

Use of Partitioning Tool

- Interface for partitioning tool(MeTiS)



Mesh data

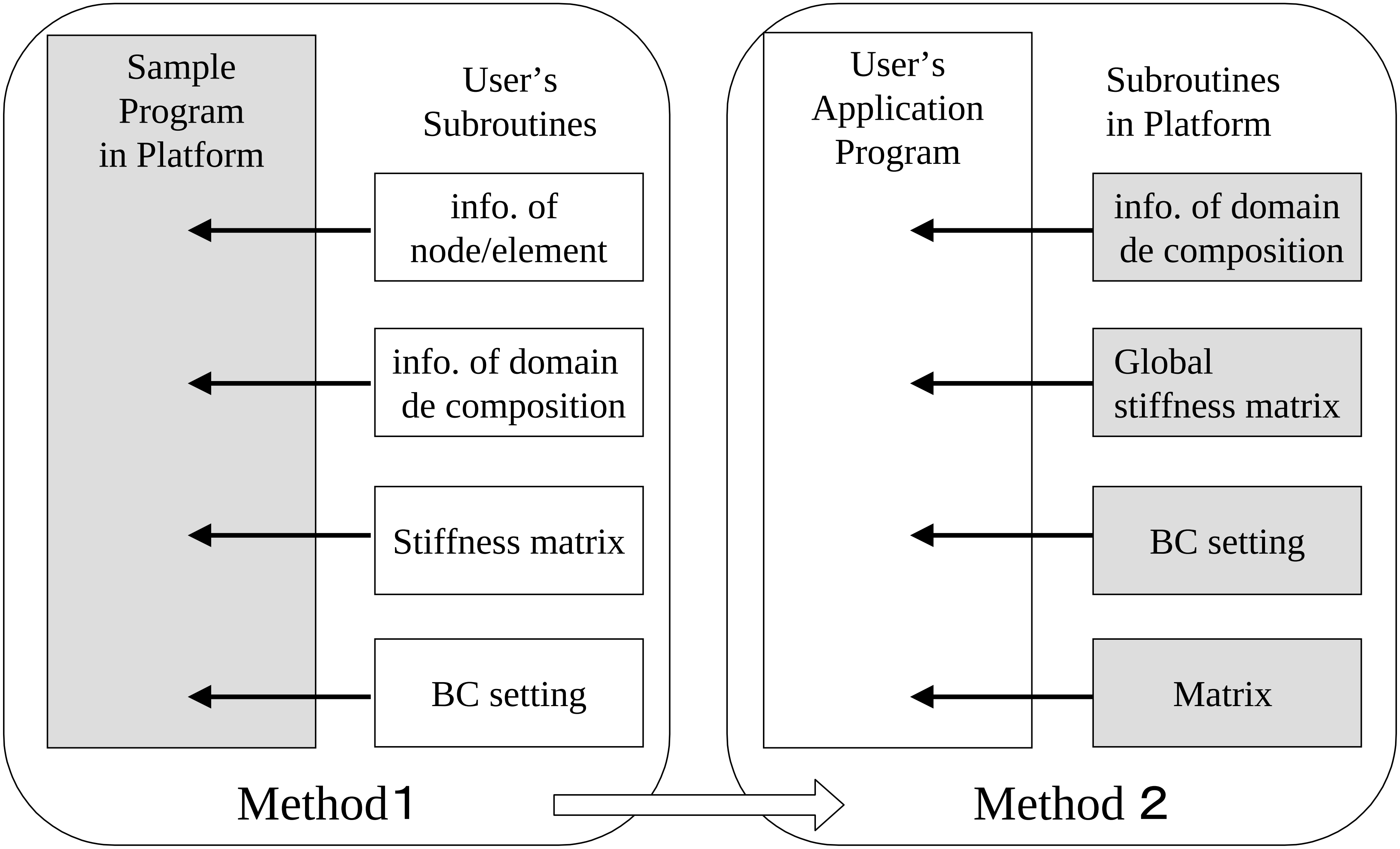
User's program

Parallel platform

Partitioning tool (MeTiS)

Index for Partitioning

How to use Parallel Platform



Sample Program in Platform

User's Subroutines

info. of node/element

info. of domain de composition

Stiffness matrix

BC setting

Method1

User's Application Program

Subroutines in Platform

info. of domain de composition

Global stiffness matrix

BC setting

Matrix

Method 2

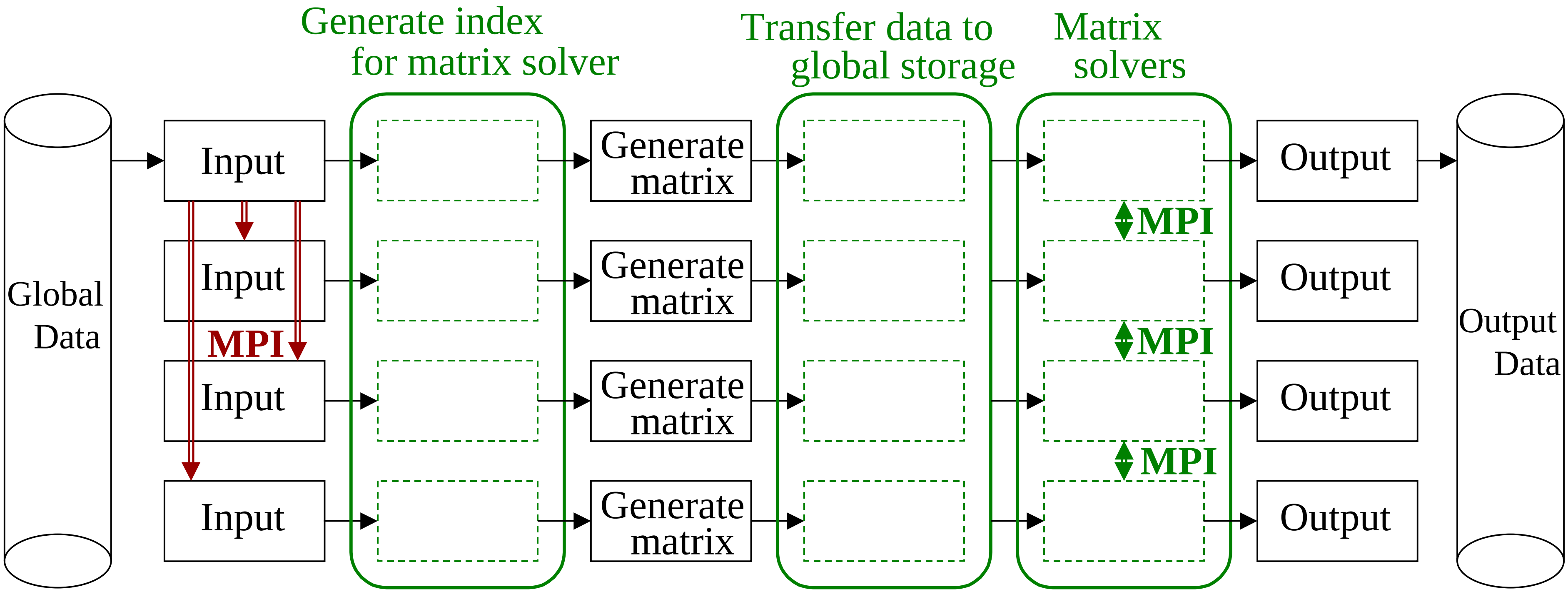
Modification method for FEM program

- Pattern1
  - Stiffness matrix generated at master PE, then solver called
- Pattern2
  - Stiffness matrix generated at each PE, then solver called.

```
DIMENSION  Aij(□), WORK(□), Bi(□)
CALL MPI_INIT(...)                    ;MPI initialized

IF(MYRANK.EQ.0)  THEN                 ;at Master PE
DO I=1, 要素数                        ; Stiff. Matrix
・・・・・
Aij(□)=□
END DO
END IF

CALL GM2_SOLVE(Aij,Bi,....,WORK)      ;Solver

CALL MPI_FINALIZE(...)                ;MPI terminated
STOP
END
```

```
DIMENSION  Aij(□), WORK(□), Bi(□), IDOMAIN(□)
CALL MPI  INIT(...)                           ;MPI initialized

set IDOMAIN(I)                                ;Partition info.

DO I=1, 要素数                                ; Stiff. Matrix
IF(IDOMAIN(I).EQ.MYRANK)  THEN                ; at Each PE
・・・・・
Aij(□)=□
END IF
END DO

CALL GM3_SOLVE(Aij,Bi,IDOMAIN,....,WORK)      ;Solver

CALL MPI  FINALIZE(...)                       ;MPI terminated
STOP
END
```

Flow at Platform



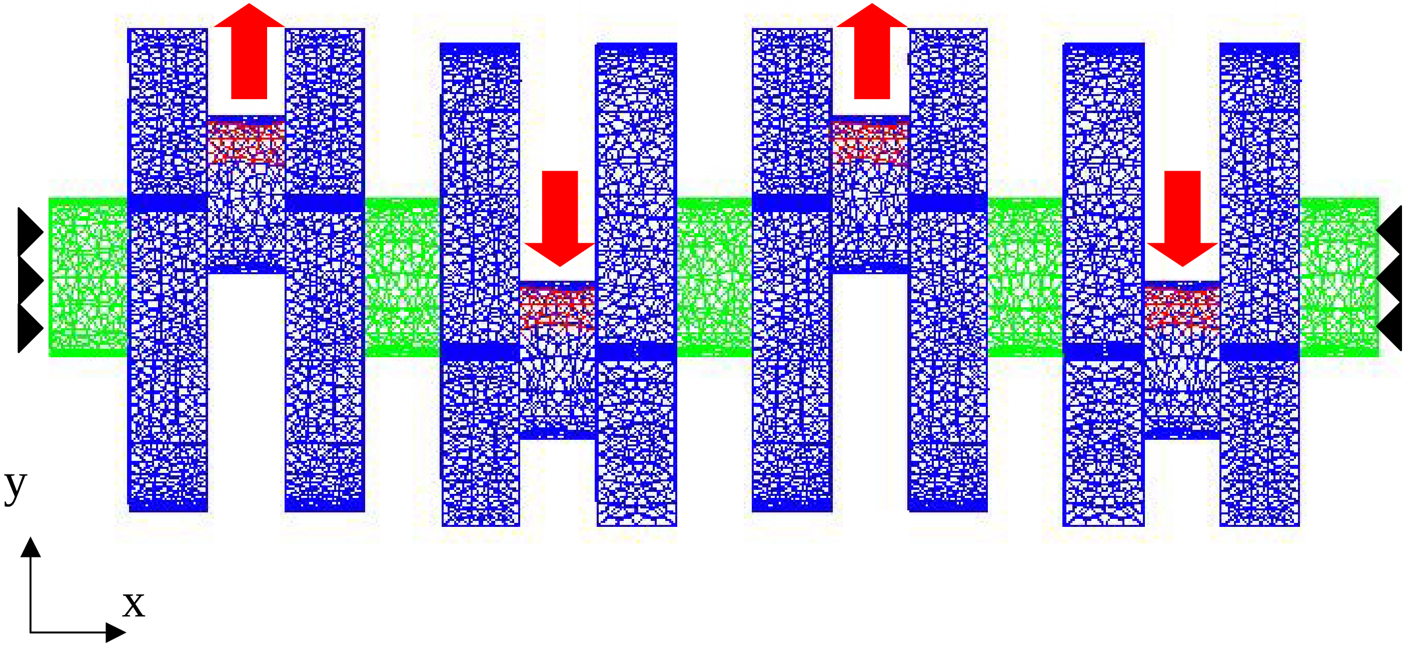
- Mesh Data

  nodes/elements, coordinates, element connectivity, partitioning index（by MeTis)
- Control Data

  boundary conditions, material values, time step, etc

■ Example：3D Crankshaft ■

（by graduate student at Yokohama national Univ. ）



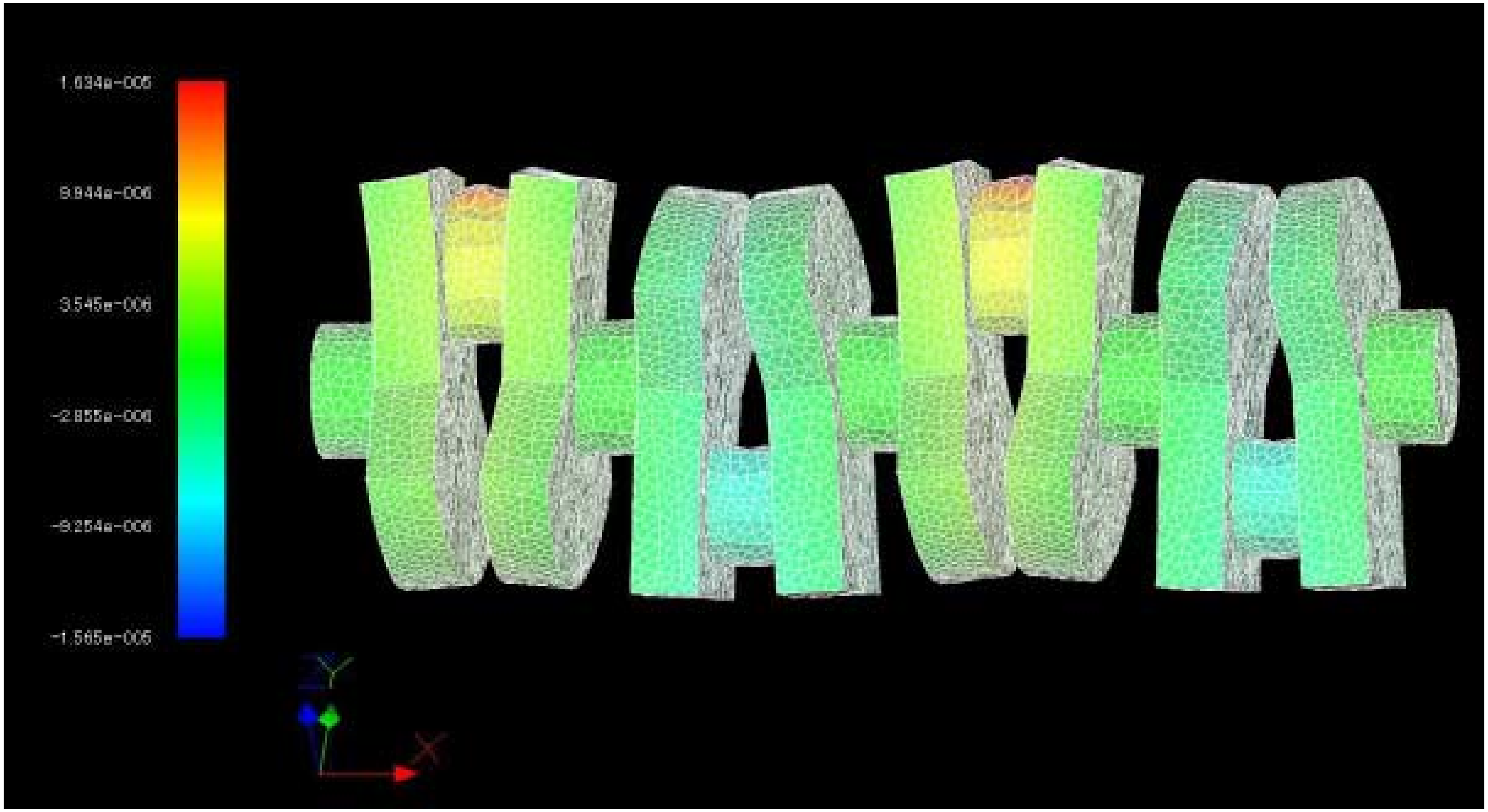
3D elastic FEM model with boundary/load conditions

Elastic model, 79,043 nodes, 62,968 HEXA elements

Partitioning by MeTiS for 8 CPU

One hour modification

Elapsed time 541 sec , 8 CPUs in Hitachi SR8000



Deformation

Big projects on computational mechanics in Japan

1. Earth Simulator Project

Whole earth is modeled and analyzed with CAE
Prediction of the global warming phenomenon with 1 km mesh
Parallel computer with 30TFLOPS will be developed
Amount of project money is $0.4 billion for 5 years

・GeoFEM (http://geofem.tokyo.rist.or.jp/index.html) (1997-2001)
Multi-Purpose Parallel FEM System for Solid Earth
Free source code download available
http://geofem.tokyo.rist.or.jp/new_en/index.html

2. Adventure project (http://adventure.q.t.u-tokyo.ac.jp/)

ADVanced ENgineering analysis Tool for Ultra large REal world.
Free source code download available
http://adventure.q.t.u-tokyo.ac.jp/software/download.html

Free FEM software for reference

1. for single processor

(1) http://phase.etl.go.jp/mirrors/netlib/ (free code department store)

Recommendations

http://phase.etl.go.jp/mirrors/netlib/slap/index.html
(GMRES, BCG Matrix Solver. by Lawrence Livermore National Lab.)
http://phase.etl.go.jp/mirrors/netlib/linalg/spooles/index.html
(sparse real and complex direct matrix solver)
http://phase.etl.go.jp/mirrors/netlib/voronoi/index.html
(2D mesh generation, triangulation, and mesh display at X-Window)
http://phase.etl.go.jp/mirrors/netlib/f2c/index.html
(Convert Fortran 77 to C or C++)

1. for single processor (cont.)

(2) Information on FEM

http://www.engr.usask.ca/~macphed/finite/fe_resources/node10.html(Various information of FEM)

(My name is listed at http://www-users.informatik.rwthaachen.de/%7Eroberts/peoplelist.html :-)

(3) Etc

http://www.mech.port.ac.uk/sdalby/mbm/CTFRProg.htm

(Binary source listed in Prof. Ross's book)

http://www.quint.co.jp/Japanese/pro/vox/voxdemo/license.htm

(VOXELCON developed by Prof. N. Kikuchi at U of Michigan)

2. for parallel computation

http://www.cs.sandia.gov/CRF/aztec1.html
(AZTEC)
http://www-fp.mcs.anl.gov/petsc/
(PETSc)
http://geofem.tokyo.rist.or.jp/new_en/index.html
(GEOFEM)
http://adventure.q.t.u-tokyo.ac.jp/software/download.html
(ADVENTURE)
http://www-users.cs.umn.edu/~karypis/metis/
(Partitioning software)

IT related companies

1. **INCS** (http://www.incs.co.jp/)
3D die for cellular phone. Internet driven factory.
Averaged age is 24.5. Half are part-time employees.

Intuition & experience→3D CAD+Database
(for experts) (not for experts)

2. **TOYOTA motors**
Small wagon “bB” was developed only for 12 months
Trial units were not tested. CAE predicted everything.
CAE’s result database decides the design

■ Conclusions ■

As examples of tuning free CAE,
Adaptive space–time stabilized FEM
Optimal process parameter design
Discontinuous mapped mesh FEM
Parallel platform for FEM/FDM/FVM
are discussed.

We'd like to extend our research to
Multi–physics FEA
Massively parallel computations
Optimal design with complicated constraints
Inverse problem with large variables
in near future