ADVENTURE_Magnetic

Electromagnetic Field Analysis with HDDM

Version 1.9.0

User's Manual

March 15, 2018

ADVENTURE Project

Contents

1. Introduction

The current document contains information on the ADVENTURE_Magnetic finite element analysis solver designed in ADVENTURE Project [1] for analysis of the electromagnetic fields using Hierarchical Domain Decomposition Method with parallel data processing techniques.

1.1. Program Features

ADVENTURE_Magnetic has the following features.

- ADVENTURE_Magnetic supports non-linear magnetostatic analysis, time-harmonic eddy current analysis and non-steady eddy current analysis.
- ADVENTURE_Magnetic supports the dynamic load distribution of CPUs in parallel computing environments using the Hierarchical Domain Decomposition method (HDDM)[2][3][4][5].
- ADVENTURE_Magnetic supports the single mode where all computations are performed as a single process.
- ADVENTURE_Magnetic supports the shared-memory parallel mode with OpenMP, and the hybrid parallel mode with OpenMP and MPI
- ADVENTURE_Magnetic can analyze 2 billion DOF models for non-linear magnetostatic problems and 3.5 billion complex DOF models for time-harmonic eddy current problems.

1.2. Operational Environments

The ADVENTURE_Magnetic operates in the following operational environments.

Operating system	: UNIX, Linux
Data processing library	: MPI
Others	: C compiler, ADVENTURE_IO

MPICH [7] or OpenMPI [8] can be used as a free MPI library [6]. The MPICH can be obtained on the Web site “http://www-unix.mcs.anl.gov/mpi/mpich/”, and the OpenMPI on the Web site “http://www.open-mpi.org/”.

In addition, the ADVENTURE_IO can be obtained on the Web site “http://adventure.sys.t.u-tokyo.ac.jp/”. Please refer to ADVENTURE_IO’s manual for the installation of the ADVENTURE_IO.

1.3. Program Compilation and Installation

To compile the ADVENTURE_Magnetic module, you need properly installed MPI environment and ADVENTURE_IO liblaries on your computer. The following procedure should be followed to compile the ADVENTURE_Mangetic module.

(1) File Extraction from Archive

The necessary data are contained in AdvMagnetic-1.9.0.tar.gz.

```
% gunzip -c AdvMagnetic-1.9.0.tar.gz | tar xvf -
```

After decompressing the AdvMagnetic-1.9.0.tar.gz archive file, the directory AdvMagnetic-1.9.0 will be created. The contents of AdvMagnetic-1.9.0 are as follows.

HDDM	: Source file of ADVENTURE_Magnetic
doc	: Documents
tools	: Tools
lib	: Libraries
common	: Common source codes
sample_data	: Sample data

(2) Edit “Makefile.in”.

Move to a top directory “AdvMagnetic-1.9.0” and edit “Makefile.in”.

```
# ************************************************************************
#  Copyright (C) 2000, 2001, 2002 Shinobu Yoshimura,
#  The University of Tokyo,
#  the Japan Society for the Promotion of Science (JSPS)
#  Copyright (C) 2003, 2005, 2007, 2014, 2015, 2016, 2017 ADVENTURE Project,
#  All Rights Reserved
# ************************************************************************

# Include file for each Makefile
# Please modify for your own environment

# path for ADVENTURE_IO system
ADVSYSD        =       $(HOME)/ADVENTURE/bin        ← (A)

# path for install directory
INSTALL_DIR        =       $(HOME)/ADVENTURE        ← (B)
INSTALL_BINDIR     =       $(INSTALL_DIR)/bin
INSTALL_DOCDIR     =       $(INSTALL_DIR)/doc
INSTALL_DOCMAGDIR =       $(INSTALL_DOCDIR)/AdvMag

# C compiler & linker
CC       =       gcc               ← (C)
LINKER   =       $(CC)
AR       =       ar
ARFLAGS =       cr

# parallel C compiler & linker
MPI_CC      =     mpicc            ← (D)
MPI_LINKER =     $(MPI_CC)


# Compiler options
CFLAGS   = -O2                     ← (E)
OMPFLAGS = -fopenmp -lgomp
```

(A) Change this part according to the directory in which you installed `advsis-config` that is the file of ADVENTURE_IO.

```
# path for ADVENTURE_IO system
ADVSYSD        =      $(HOME)/ADVENTURE/bin
```

(B) Change this part according to the directory in which you want to install ADVENTURE_Mangtic.

```
# path for install directory
INSTALL_DIR       =       $(HOME)/ADVENTURE
```

(C) Change the red part according to your C compiler environment.

```
# C compiler & linker
CC      =       gcc
LINKER  =       $(CC)
```

(D) Change the red part according to your MPI environment.

```
# parallel C compiler & linker
MPI_CC      =     mpicc
MPI_LINKER =     $(MPI_CC)
```

(E) Change the red part according to your compile option.

```
# Compiler options
CFLAGS   = -O2
OMPFLAGS = -fopenmp -lgomp
```

(3) Compile by the following command.

```
% make
```

(4) Install by the following command

```
% make install
```

The following files will be installed.

Executable modules for Non-Linear Magnetostatic Analysis

- bin/advmag_static-s : Single mode
- bin/advmag_static-s_omp : Shared-memory parallel mode
- bin/advmag_static-p : Parallel mode with static load distribution
- bin/advmag_static-p_omp : Hybrid parallel mode
- bin/advmag_static-h : Parallel mode with dynamic load distribution

Executable modules for Time-harmonic Eddy Current Analysis

- bin/advmag_th_eddy-s : Single mode
- bin/advmag_th_eddy-s_omp : Shared-memory parallel mode
- bin/advmag_th_eddy-p : Parallel mode with static load distribution
- bin/advmag_th_eddy-p_omp : Hybrid parallel mode
- bin/advmag_th_eddy-h : Parallel mode with dynamic load distribution

Executable modules for Non-steady Eddy Current Analysis

- `bin/advmag_ns_eddy-s` : Single mode
- `bin/advmag_ns_eddy-s_omp` : Shared-memory parallel mode
- `bin/advmag_ns_eddy-p` : Parallel mode with static load distribution
- `bin/advmag_ns_eddy-p_omp` : Hybrid parallel mode
- `bin/advmag_ns_eddy-h` : Parallel mode with dynamic load distribution

Tools

- `bin/advmag_makefem` : Tool for entire FEA model data
- `bin/advmag_makeUCD` : Tool for make AVS format file
- `bin/advmag_nodalforce` : Tool for computing distribution of electromagnetic force
- `bin/advmag_graphCurrentDensity` : Tool for computing time change of current density
- `bin/advmag_dd_data-(s/p)` : Tool for domain decomposition of physical quantities data

Manuals

- `doc/AdvMag/manual-jp.pdf` : User's Manual in Japanese
- `doc/AdvMag/manual-eg.pdf` : User's Manual in English

1.4. Program Execution

The ADVENTURE_Magnetic module can be executed in 5 versions. You do not need MPI to execute the single mode and the shared-memory parallel mode of ADVENTURE_Magnetic. The command of execution of 5 versions is described below.

- Single mode

% advmag_static-s [*options*] *data_dir*
% advmag_th_eddy-s [*options*] *data_dir*
% advmag_ns_eddy-s [*options*] *data_dir*

- Shared-memory parallel mode

% advmag_static-s_omp [*options*] *data_dir*
% advmag_th_eddy-s_omp [*options*] *data_dir*
% advmag_ns_eddy-s_omp [*options*] *data_dir*

- Parallel mode with static load distribution using MPI

% mpirun [*options for mpirun*] advmag_static-p [*options*] *data_dir*
% mpirun [*options for mpirun*] advmag_th_eddy-p [*options*] *data_dir*
% mpirun [*options for mpirun*] advmag_ns_eddy-p [*options*] *data_dir*

- Hybrid parallel mode

% mpirun [*options for mpirun*] advmag_static-p_omp [*options*] *data_dir*
% mpirun [*options for mpirun*] advmag_th_eddy-p_omp [*options*] *data_dir*
% mpirun [*options for mpirun*] advmag_ns_eddy-p_omp [*options*] *data_dir*

- Parallel mode with dynamic load distribution using MPI

% mpirun [*options for mpirun*] advmag_static-h [*options*] *data_dir*
% mpirun [*options for mpirun*] advmag_th_eddy-h [*options*] *data_dir*
% mpirun [*options for mpirun*] advmag_ns_eddy-h [*options*] *data_dir*

When you use the single mode and the hybrid mode, the number of threads are set as an environmental variable.

- sh

  `% OMP_NUM_THREADS=`*n*
- csh or tcsh

  `% setenv OMP_NUM_THREADS` *n*
- bash

  `% export OMP_NUM_THREADS=`*n*

The options [*options for mpirun*] are specified for the `mpirun`.

- `-np` *n*

  The number of machines (corresponding to the number of parts).
- `-machinefile` *machine_file*

  The files contain the name of network machines.

The options [*options*] are specified for the ADVENTURE_Magnetic executable (see Section 5.3 of the current manual for details). The option *data_dir* should contain a name of the top directory with data files for analysis (input/output directory).

2. Parallel Processing and Analysis Solver

2. 1. Parallel Processing

ADVENTURE_Magnetic uses the Hierarchical Domain Decomposition method[2][3][4][5] to provide parallel processing of analysis data. An entire-type model is decomposed in two steps (Fig. 1) by the ADVENTURE_Metis module prior to execution of ADVENTURE_Magnetic. A large decomposed unit of the first hierarchy level is called Part, and smaller units of the decomposed Part (second hierarchy level) are called Subdoamins. The details are given in the User's Manual of the ADVENUTRE_Metis module.

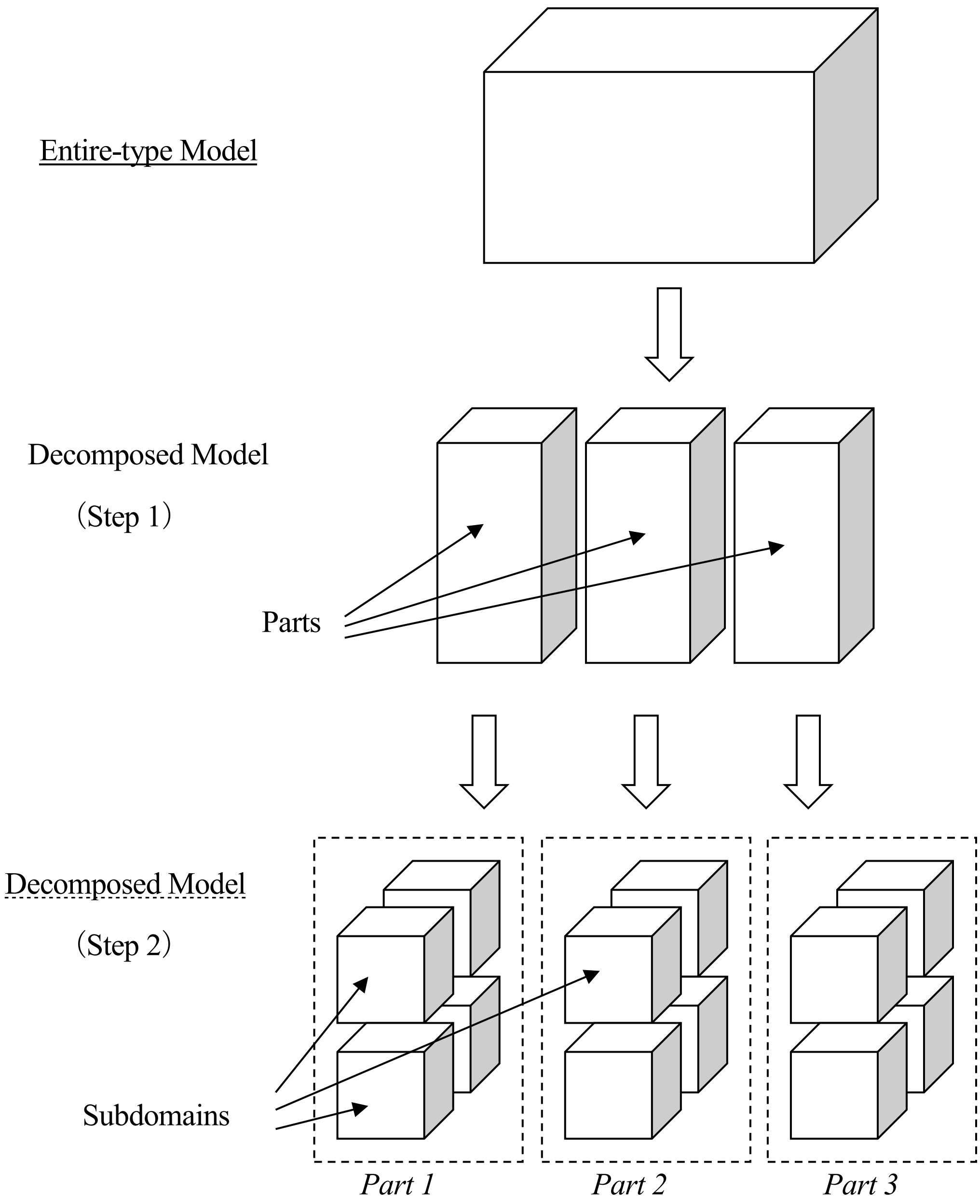


Fig. 1. Hierarchical Domain Decomposition

ADVENTURE_Magnetic supports several methods of load distribution to use CPUs in the most efficient way. The Message Passing Interface (MPI) library is used for parallel data processing. The number of processes depends on user-defined environment.

The distributed package contains 5 modes of ADVERNTURE_Magnetic.

(1) Single mode

advmag_static-s, advmag_th_eddy-s, advmag_ns_eddy-s

A single CPU does all computations without parallel data processing. The program can be compiled and executed without MPI. There are no limitations on numbers of “Subdomains” and “Parts”. The model prepared for parallel computation can be used for the single processor without adjustment (Fig. 2). In the single processor, the computational and data reprocessing procedure for each “Part” occurs in the same order as it would be occurred in the parallel computing system. If the parallel computation is not performed well the single mode of the program can be used as a checker.

(2) Shared-memory parallel mode

advmag_static-s_omp, advmag_th_eddy-s_omp, advmag_ns_eddy-s_omp

A single CPU does all computations without parallel data processing. The program can be compiled and executed without MPI. There are no limitations on numbers of “Subdomains” and “Parts”, just like the single mode.

(3) Static load distribution mode

advmag_static-p, advmag_th_eddy-p, advmag_ns_eddy-p

One CPU treats one “Part” and the processes are statically distributed between CPUs as shown in Fig. 3. The number of CPUs should correspond to the number of “Parts”. This mode works efficiently if all nodes have the same performance (uniform system).

(4) Hybrid parallel mode

advmag_static-p, advmag_th_eddy-p, advmag_ns_eddy-p

The static load distribution mode is shared-memory parallelized with OpneMP (Fig. 4). One MPI process treats one “Part”. The number of MPI processes should correspond to the number of “Parts”.

(5) Dynamic load distribution mode

advmag_static-h, advmag_th_eddy-h, advmag_ns_eddy-h

The processes are dynamically distributed between CPUs. All CPUs are subdivided into Parent CPUs and Child CPUs. The Child CPUs compute for “Subdomains” and the Parent CPUs collect the computed information. The number of available CPUs should be more than the number of “Parts”. Each “Part” will be assigned to one CPU, and the other CPUs will be used for computations of “Subdomains” (Fig. 5).

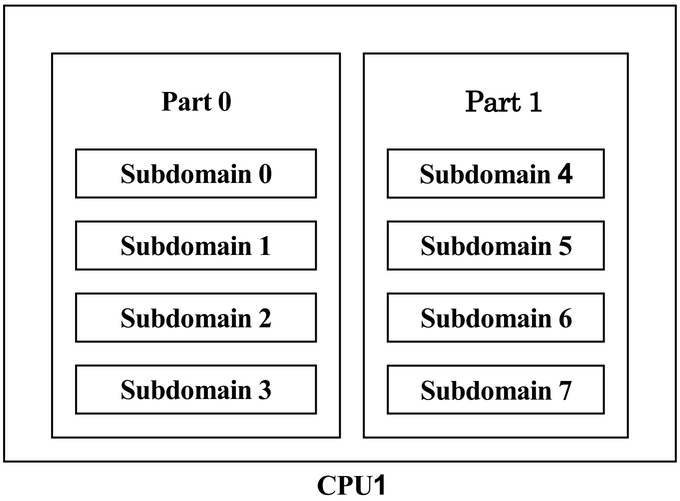


Fig. 2. Adjustment of Domain to CPUs (Single mode)

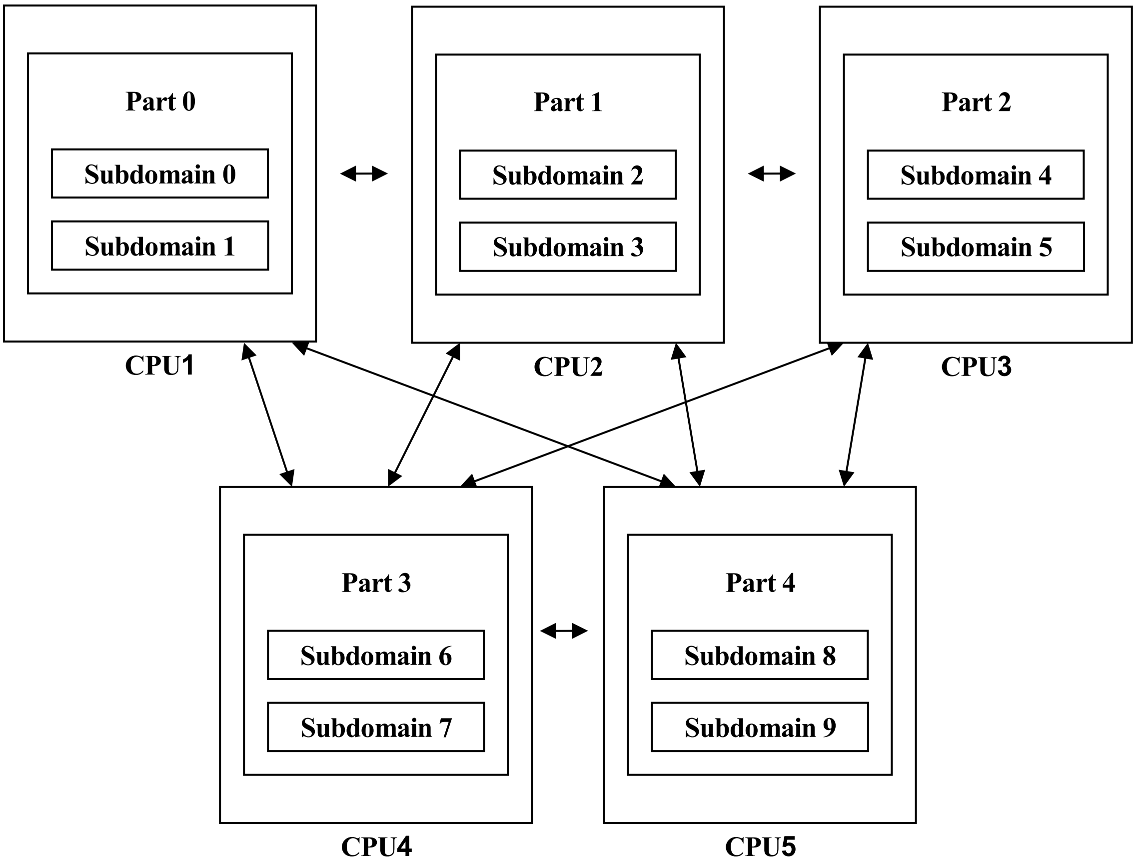


Fig. 3. Adjustment of Domains to CPUs (Static load distribution mode)

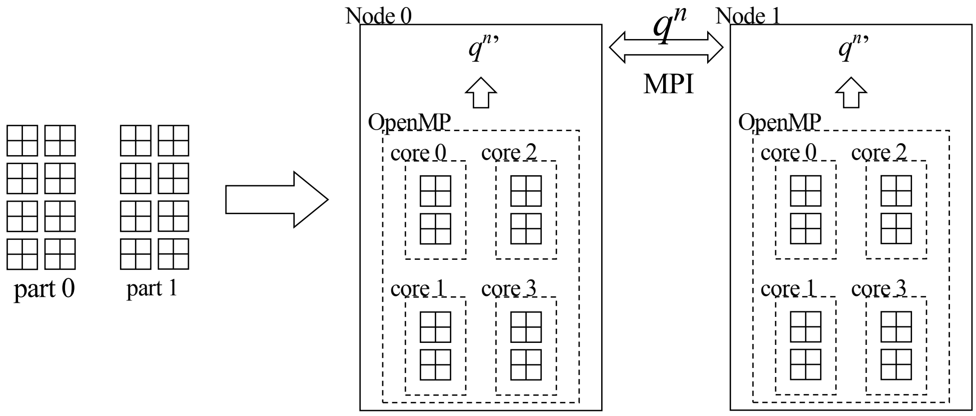


Fig. 4. Hybrid parallel mode

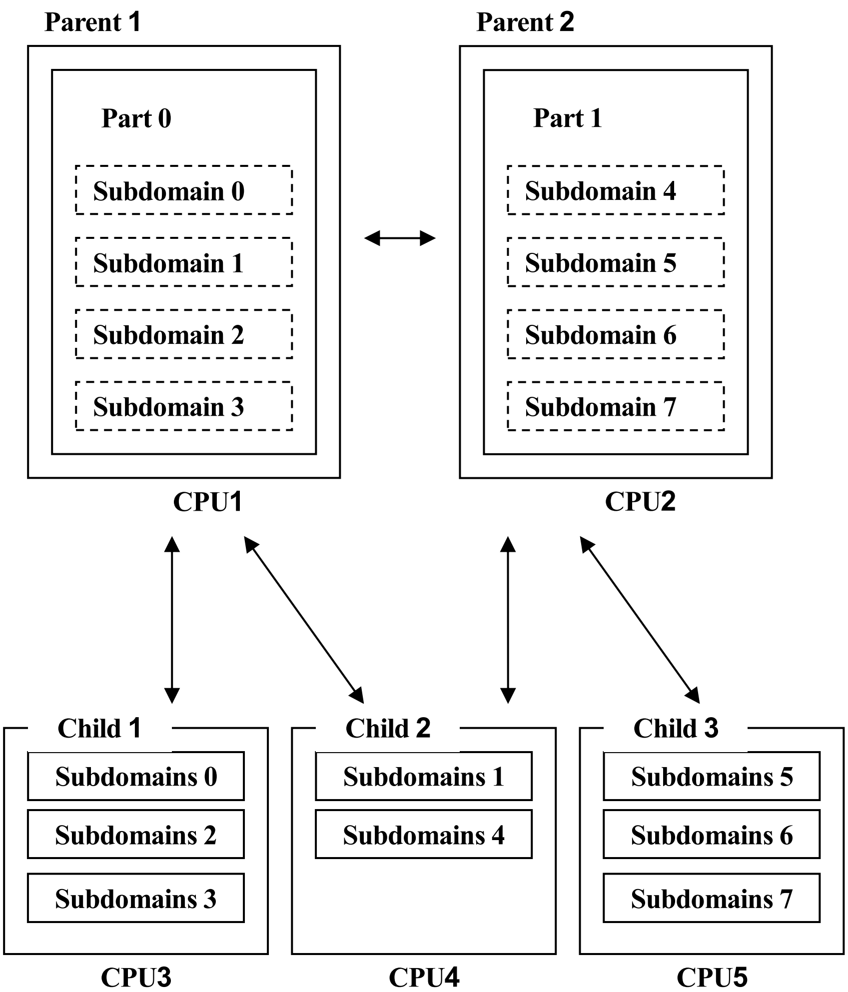


Fig. 5. Adjustment of Domains to CPUs (Dynamic load distribution mode)

2. 2. ADVENTURE_Metis

The computational performance of ADVENTURE_Magnetic module depends on the proper domain decomposition using the ADVENTURE_Metis. To execute the ADVENTURE_Metis, the number of parts and number of subdomains should be determined before. Basically, the number of "Parts" should be decided based on the method used for parallel processing, the number of nodes used in network, and the computing environments. Then number of "Subdomains" should be decided based on the memory used of computational processes. Good performance can be achieved if the number of elements in one subdomain lies in about 100 [9].

The number of elements in "Subdomains" that should be created by ADVENTURE_Metis module can be calculated using the following equation.

$$n = \frac{N_{element}}{N_{part} \times N_{subdomain}}$$

where

n	: the number of elements in the considered "Subdomains"
$N_{element}$	: the total number of elements
N_{part}	: the total number of "Parts"
$N_{subdomain}$	: the number of "Subdomains" in one "Part"

Compared with the static load distribution method, much data transfer accomplished between the "Parent" and the "Child" in case of dynamic load distribution method. The static load distribution method results in better performance for uniform computer environments.

3. Analysis Algorithm

3. 1. Flow of analysis

The algorithm of analysis using the ADVENTURE_Magnetic module is shown in Fig. 6.

(1) Creation of mesh data.

Mesh of the entire-type model data is prepared by ADVENTURE_TetMesh.

(2) Setting of boundary conditions.

Boundary conditions are set to mesh using the pre-processor module ADVENTURE_BCtool. The data of the extracted mesh surface groups are converted into GUI input binary format by using the **msh2pch** command. Then the boundary conditions are set up by the **bcGUI** command. For more details, see the manual of ADVENTURE_BCtool and Appendix A.1.

(3) Creation of the entire-type FEA model file.

The boundary conditions and material properties attached to mesh can be saved in an entire-type FEA model of the ADVENTURE binary format. In order to perform this operation, **advmag_makefem** tool is used. See Appendix A.1 for details of this tool. This tool is distributed with the current version of ADVENTURE_Magnetic.

(4) Domain decomposition.

Domain decomposition of the entire-type analysis model is done by ADVENTURE_Metis.

`% mpirun` [*options for mpirun*] `adventure_metis -HDDM -difn 1` [*options*]
model_filename directory_name div_num

The degree-of-freedom used for nodal displacements in static analysis of solids is 3. However, the degree-of-freedom used in ADVENTURE_Magnetic should be 1. The necessary option `-difn 1` is used to set the degree-of-freedom for inner boundary nodes to 1.

(5) Electromagnetic field analysis

The HDDM-type model data are analyzed by finite element analysis solver ADVENTURE_Magnetic.

(6) Visualization of analysis results

The analysis results can be visualized using AVS / Express, Micro AVS or ParaView. In order to make visualization files, **advmag_makeUCD** tool is used. See Appendix A.2 for details of this tool. Moreover, visualization files of distribution of electromagnetic force can be made by **advmag_nodalforce** tool. See Appendix A.3.

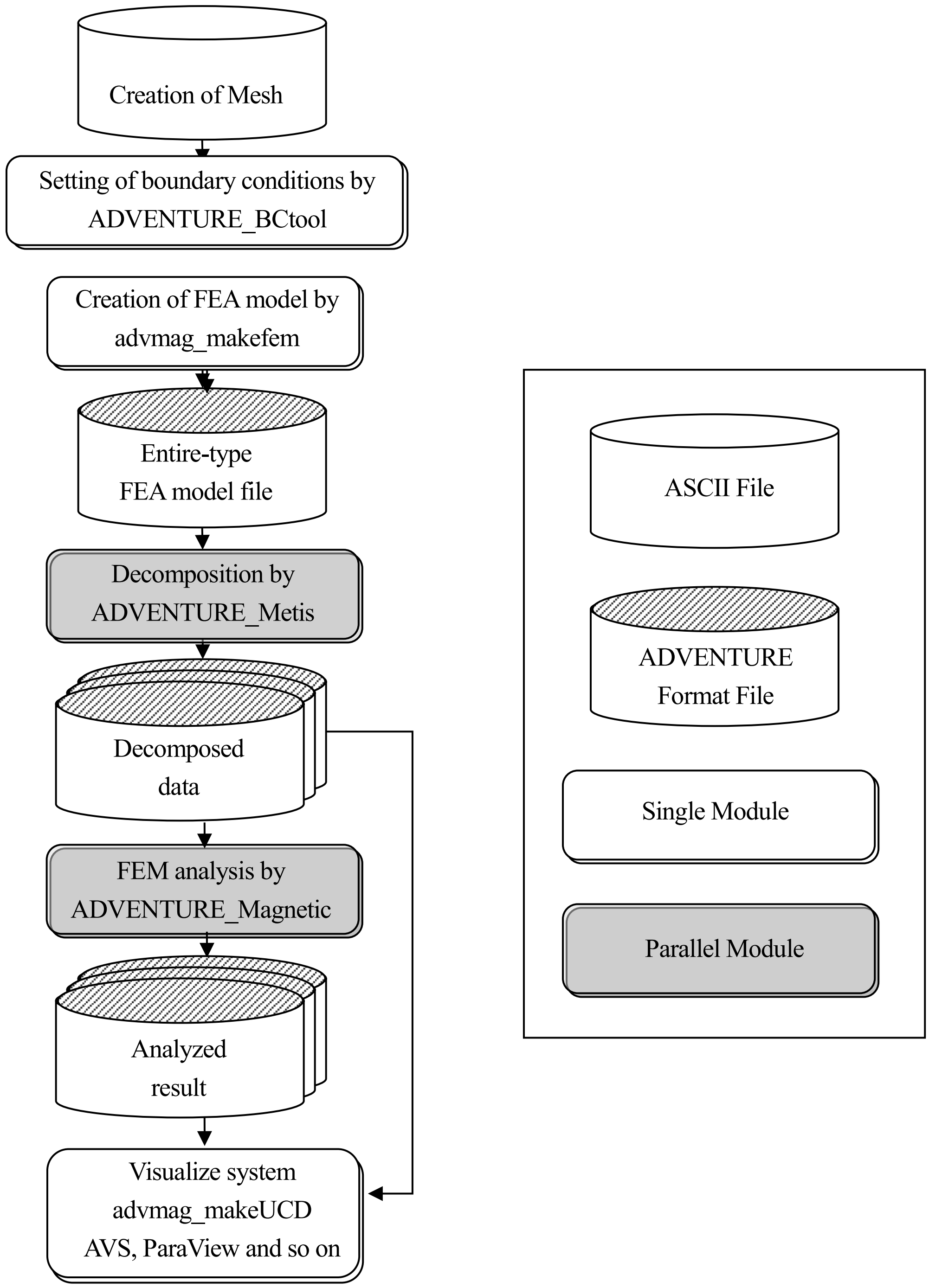


Fig. 6. Algorithm of Analysis Using ADVENTURE_Magnetic Module.

4. Program Compilation and Installation

To compile the ADVENTURE_Magnetic module, you need properly installed MPI environment and ADVENTURE_IO libraries on your computer. The following procedure should be followed to compile the ADVENTURE_Mangetic module.

(1) Edit "Makefile.in".
Move to a top directory "AdvMagnetic-1.9.0" and edit "Makefile.in".

```
# ***************************************************************************
#  Copyright (C) 2000, 2001, 2002 Shinobu Yoshimura,
#  The University of Tokyo,
#  the Japan Society for the Promotion of Science (JSPS)
#  Copyright (C) 2003, 2005, 2007, 2014, 2015, 2016, 2017 ADVENTURE Project,
#  All Rights Reserved
# ***************************************************************************

# Include file for each Makefile
# Please modify for your own environment

# path for ADVENTURE_IO system
ADVSYSD         =      $(HOME)/ADVENTURE/bin          ← (A)

# path for install directory
INSTALL_DIR        =      $(HOME)/ADVENTURE           ← (B)
INSTALL_BINDIR     =      $(INSTALL_DIR)/bin
INSTALL_DOCDIR     =      $(INSTALL_DIR)/doc
INSTALL_DOCMAGDIR =       $(INSTALL_DOCDIR)/AdvMag

# C compiler & linker
CC       =       gcc                      ← (C)
LINKER   =       $(CC)
AR       =       ar
ARFLAGS =        cr

# parallel C compiler & linker
MPI_CC      =     mpicc                   ← (D)
MPI_LINKER =      $(MPI_CC)


# Compiler options
CFLAGS   = -O2                            ← (E)
OMPFLAGS = -fopenmp -lgomp
```

(A) Change this part according to the directory in which you installed `advsis-config` that is the file of ADVENTURE_IO.

```
# path for ADVENTURE_IO system
ADVSYSD       =     $(HOME)/ADVENTURE/bin
```

(B) Change this part according to the directory in which you want to install ADVENTURE_Mangtic.

```
# path for install directory
INSTALL_DIR       =     $(HOME)/ADVENTURE
```

(C) Change the red part according to your C compiler environment.

```
# C compiler & linker
CC       =       gcc
LINKER   =       $(CC)
```

(D) Change the red part according to your MPI environment.

```
# parallel C compiler & linker
MPI_CC      =    mpicc
MPI_LINKER =    $(MPI_CC)
```

(E) Change the red part according to your compile option.

```
# Compiler options
CFLAGS   = -O2
OMPFLAGS = -fopenmp -lgomp
```

(2) Compile by the following command.

```
% make
```

(3) Install by the following command

```
% make install
```

The following files will be installed.

Executable modules for Non-linear Magnetostatic Analysis

- `bin/advmag_static-s` : Single mode
- `bin/advmag_static-s_omp` : Shared-memory parallel mode
- `bin/advmag_static-p` : Parallel mode with static load distribution
- `bin/advmag_static-p_omp` : Hybrid parallel mode
- `bin/advmag_static-h` : Parallel mode with dynamic load distribution

Executable modules for Time-harmonic Eddy Current Analysis

- `bin/advmag_th_eddy-s` : Single mode
- `bin/advmag_th_eddy-s_omp` : Shared-memory parallel mode
- `bin/advmag_th_eddy-p` : Parallel mode with static load distribution

- bin/advmag_th_eddy-p_omp : Hybrid parallel mode
- bin/advmag_th_eddy-h : Parallel mode with dynamic load distribution

Executable modules for Non-steady Eddy Current Analysis

- bin/advmag_ns_eddy-s : Single mode
- bin/advmag_ns_eddy-s_omp : Shared-memory parallel mode
- bin/advmag_ns_eddy-p : Parallel mode with static load distribution
- bin/advmag_ns_eddy-p_omp : Hybrid parallel mode
- bin/advmag_ns_eddy-h : Parallel mode with dynamic load distribution

Tools

- bin/advmag_makefem : Tool for entire FEA model data
- bin/advmag_makeUCD : Tool for make AVS format file
- bin/advmag_nodalforce : Tool for computing distribution of electromagnetic force
- bin/advmag_graphCurrentDensity : Tool for computing time change of current density
- bin/advmag_dd_data-(s/p) : Tool for domain decomposition of physical quantities data

Manuals

- doc/AdvMag/manual-jp.pdf : User's Manual in Japanese
- doc/AdvMag/manual-eg.pdf : User's Manual in English

5. Program Execution

The ADVENTURE_Magnetic module can be executed in 3 modes. To execute ADVENTURE_Magnetic with mpirun, use the following commands.

- Single mode

  % advmag_static-s [*options*] *data_dir*
  % advmag_th_eddy-s [*options*] *data_dir*
  % advmag_ns_eddy-s [*options*] *data_dir*

- Shared-memory parallel mode

  % advmag_static-s_omp [*options*] *data_dir*
  % advmag_th_eddy-s_omp [*options*] *data_dir*
  % advmag_ns_eddy-s_omp [*options*] *data_dir*

- Parallel mode with static load distribution using MPI

  % mpirun [*options for mpirun*] advmag_static-p [*options*] *data_dir*
  % mpirun [*options for mpirun*] advmag_th_eddy-p [*options*] *data_dir*
  % mpirun [*options for mpirun*] advmag_ns_eddy-p [*options*] *data_dir*

- Hybrid parallel mode

  % mpirun [*options for mpirun*] advmag_static-p_omp [*options*] *data_dir*
  % mpirun [*options for mpirun*] advmag_th_eddy-p_omp [*options*] *data_dir*
  % mpirun [*options for mpirun*] advmag_ns_eddy-p_omp [*options*] *data_dir*

- Parallel mode with dynamic load distribution using MPI

  % mpirun [*options for mpirun*] advmag_static-h [*options*] *data_dir*
  % mpirun [*options for mpirun*] advmag_th_eddy-h [*options*] *data_dir*
  % mpirun [*options for mpirun*] advmag_ns_eddy-h [*options*] *data_dir*

When you use the single mode and the hybrid mode, the number of threads are set as an environmental variable.

- sh

  % OMP_NUM_THREADS=*n*
- csh or tcsh

  % setenv OMP_NUM_THREADS *n*
- bash

  % export OMP_NUM_THREADS=*n*

The options [*options for mpirun*] are specified for the mpirun. The options [*options*] are specified for the ADVENTURE_Magnetic executable (see Section 5.3 of the current manual for details). The option *data_dir* should contain a name of the top directory with data files for analysis (input/output directory).

5.1. Names of Input / Output Files

5.1.1. Names of files

The default names of input and output files are presented below. The files are located under the top directory defined by *data_dir*. Moreover, these names can be changed with options (see Section 5.3.5 of current manual for details). Here, ***P*** indicates the Part number.

- FEA model file : *data_dir*/**model_one/input.adv**
- HDDM-type analysis model file : *data_dir*/**model/advhddm_in_*P*.adv**
- HDDM-type physical quantities data file :
  data_dir/ **dd_data/advhddm_in_dd_data_time_*T*_*P*.adv**
- Condition of analysis file : *data_dir*/**result/advhddm_out.adv**
- Analysis results : *data_dir*/**result/advhddm_out_*P*.adv**
- Analysis results of non-steady analysis : *data_dir*/**result/advhddm_out_*T*_*P*.adv**
- Condition of initial value file : *data_dir*/**initial/advhddm_out.adv**
- Initial values : *data_dir*/**initial/advhddm_out_*P*.adv**
- Material data file : *data_dir*/**mtrl.dat**

Furthermore, there are some input files which names are declared in material data file. These names are specified by relative path from *data_dir*.

- Excitation current density data
- Magnetization vector data
- Definition of shape
- *B-H* curve data

See Appendix "B. Format of Input / Output files" for details of these files.

5.1.2. Files used by each module

Input / Output files used by each module are as follows.

- Module of Non-Linear Magnetostatic Analysis :
  advmag_static-s, advmag_static-s_omp, advmag_static-p, advmag_static-p_omp, advmag_static-h
  - Input
    - HDDM-type analysis model file
    - Material data file
    - Excitation current density data
    - Magnetization vector data
    - Definition of shape
    - *B-H* curve data
  - Output
    - Condition of analysis file
    - Analysis results

- Module of Time-Harmonic Eddy Current Analysis :
  advmag_th_eddy-s, advmag_th_eddy-s_omp, advmag_th_eddy-p, advmag_th_eddy-p_omp, advmag_th_eddy-h
  - Input
    - HDDM-type analysis model file
    - Material data file
    - Excitation current density data
    - Definition of shape
  - Output
    - Condition of analysis file

- ✧ Analysis results

- Module of Non-steady Eddy Current Analysis :
  advmag_ns_eddy-s, advmag_ns_eddy-s_omp, advmag_ns_eddy-p,
  advmag_ns_eddy-p_omp, advmag_ns_eddy-h
  - ➢ Input
    - ✧ HDDM-type analysis model file
    - ✧ Material data file
    - ✧ Excitation current density data
    - ✧ Definition of shape
    - ✧ Condition of initial value file
    - ✧ Initial values
    - ✧ *B-H* curve data
    - ✧ HDDM-type Physical quantities data file
  - ➢ Output
    - ✧ Condition of analysis file
    - ✧ Analysis results of non-steady analysis

5.2. About the Unit System

Conversion functions of data unit systems are not implemented in the current version of the program; the unit system of the input data should be consistent.

In this manual, the International System of Units (SI) is used.

5.3. Command Options

The following command options can be used. Here, *n* indicates the integer number, *x* the floating point number, *s* the characters. Data in () are the default numbers or characters.

5.3.1. Common Options to All Modules

- `-memlimit` *n* (`1000`)

  The option specifies the upper limit of memory *n* [in Mbytes], which can be used for one process. If this limit is exceeded, the process will be terminated.

- `-help` or `-h`

  These options are used to display the help information.

- `-version` or `-v`

  These options are used to display the version of the code.

5.3.2. Options for the HDDM

ADVENTURE_Magnetic use the HDDM solver to solve the linear equations of stiffness matrix. The following options can be used to control the HDDM solver.

- `-hddm-solver` *s* (`CR or COCR`)

  This option specifies which HDDM solver will be used. The default characters and the character string that can be specified differ depending on the analysis function.

  For non-linear magnetostatic analysis (default `CG`), or non-steady eddy current analysis (default: `CR`)

- `CG` : Conjugate Gradient (CG) method
- `CR` : Conjugate Residual (CR) method
- `MINRES` : Minimal Residual (MINRES) method
- `QMR` : Quasi-Minimal Residual (QMR) method

For time-harmonic eddy current analysis (default: `COCR`)

- `COCG` : Conjugate Orthogonal Conjugate Gradient (COCG) method
- `COCR` : Conjugate Orthogonal Conjugate Residual (COCR) method
- `MINRES-like_CS`: Modified MINRES method for complex symmetric matrices
- `QMR` : Quasi-Minimal Residual (QMR) method

- `-hddm-pc` *s* (`diag`)

  This option specifies which preconditioner will be used.

  - `none` : Any preconditiner won't be used.
  - `diag` : A simplified block diagonal scaling will be used as a preconditioner.

- `-hddm-conv` *x* (Non-Linear Magnetostatic Analysis: `1.0e-05`, Time-Harmonic Eddy Current Analysis: `1.0e-03`)

  The option specifies the tolerance for convergence of iterations. The iterations stop when the relative error becomes smaller than the tolerance *x*.

- `-hddm-div` *x* (`1.0e+10`)

  The option specifies the tolerance for divergence of iterations. The iterations stop when the relative error becomes larger than the tolerance *x*.

- `-hddm-max-loop` *n* (`4000`)

  The option specifies the maximum number of HDDM iterations.

- `-hddm-log` or `-hddm-no-log`

  These options specify whether the history of iterations will be output to file or not. Usually, the history of iterations will be output to following files.

  Non-liner Magnetostatic analysis

  data_dir/**calc_log/log_g_HDDM_Static**

  Time-Harmonic Eddy Current analysis

  data_dir/**calc_log/log_g_HDDM_TH_Eddy**

  Non-steady Eddy Current analysis

  data_dir/**calc_log/log_g_HDDM_NS_Eddy_*T***

- `-output-at-a-time` *n* (`0`)

  The option limits the number of simultaneous output of Analysis results to *n*. When it is set to 0, it is not limited.

- `-output-compressing`

  The option specifies the Analysis results will be compressed using gzip after output.

5.3.3. Options for the Linear Solver of Subdomains

ADVENTURE_Magnetic uses the iterative method to solve the linear equations of subdomains. The following options can be used to control the iterative method in subdomains.

- `-solver` *s* (`CG or COCG`)

  This option specifies which solver in subdomains will be used. The default characters and the character string that can be specified differ depending on the analysis function. Also, this option is invalidated when the *A* method with the Lagrange multiplier is used in Non-Linear Magnetostatic

Analysis.

For non-linear magnetostatic analysis, or non-steady eddy current analysis (default: `CG`)

- `CG` : Conjugate Gradient (CG) method
- `CR` : Conjugate Residual (CR) method

For time-harmonic eddy current analysis (default: `COCR`)

- `COCG` : Conjugate Orthogonal Conjugate Gradient (COCG) method
- `COCR` : Conjugate Orthogonal Conjugate Residual (COCR) method

- `-solver-pc` *s* (`ICC`)

  This option specifies which preconditioner will be used.

  - `none` : Any preconditiner won't be used.
  - `diag` : A diagonal scaling will be used as a preconditioner.
  - `ICC` : A shifted incomplete Cholesky factorization will be used as a preconditioner.

- `-solver-pc-param` *x* (`1.2`)

  This option specifies a parameter of the preconditioner.

  - `none` : -
  - `diag` : -
  - `ICC` : The accelerative parameter

- `-solver-conv` *x* (`1.0e-09`)

  The option specifies the tolerance for convergence of iterations. The iterations stop when the relative error becomes smaller than the tolerance *x*.

- `-solver-div` *x* (`1.0e+10`)

  The option specifies the tolerance for divergence of iterations. The iterations stop when the relative error becomes larger than the tolerance *x*.

- `-solver-log` or `-solver-no-log`

  These options specify whether the history of iterations will be output to file or not. Usually, the history of iterations won't be output.

5.3.4. Options for the Module of Non-Linear Magnetostatic Analysis

The following options can be used to control the module of Non-Linear Magnetostatic Analysis.

- `-formulation` *s* (`A`)

  The option specifies the formulation of the time-harmonic eddy current problem.

  - `A` : A method
  - `A-p` : A method with the Lagrange multiplier [11]

- `-nl-method` *s* (`Newton`)

  The option specifies the method to solve the simultaneous non-linear equations for the magnetic reluctivity.

  - `None` : Not consider non-linearity
  - `Newton` : Newton method
  - `Picard` : Picard iteration

- `-nl-max-loop` *n* (`30`)

  The option specifies the maximum number of non-linear iterations.

- `-nl-eps` *x* (`1.0e-03`)

  The option specifies the tolerance for convergence of iterations. The iterations stop when the error becomes smaller than the tolerance *x*.

- `-nl-div` *x* (1.0e+10)

  The option specifies the tolerance for divergence of iterations. The iterations stop when the error becomes larger than the tolerance *x*.
- `-nl-curve` *s* (nuB)

  The option specifies the characteristic curve for Newton method.
  - `nuB` : ν-B curve
  - nuB2 : ν-B^2 curve
- `-nl-curve-ip` *n* (1)

  The option specifies the interpolation method for characteristic curves.
  - 1 : the first-order interpolation
  - 3 : the third-order interpolation
- `-nl-picard-weight` *x* (0.112)

  The option specifies the weight for Picard iteration.

5.3.5. Option for the Module of Time-Harmonic Eddy Current Analysis

The following option can be used to control the module of Time-Harmonic Eddy Current Analysis.

- `-formulation` *s* (APhi)

  The option specifies the formulation of the time-harmonic eddy current problem.
  - `APhi` : A-ϕ method
  - `A` : A method

5.3.6. Option for the Module of Non-steady Eddy Current Analysis

The following option can be used to control the module of Time-Harmonic Eddy Current Analysis.

- `-delta-t` *x* (0.01)

  The option specifies the time step Δt.
- `-time-step` *n* (20)

  The option specifies the number of time step.
- `-start-step` *n* (1)

  The option specifies the number of re-start time step.
- `-inivalue-type` *s* (zero)

  The option specifies the initial value of non-steady analysis.
  - `zero` : Use zero as initial values
  - `static` : Use the result of non-linear magnetostatic analysis
  - `real` : Use the real part of result of time-harmonic eddy current analysis
  - `imaginary` : Use the imaginary part of result of time-harmonic eddy current analysis
- `-formulation` *s* (APhi)

  The option specifies the formulation of the non-steady eddy current problem.
  - `APhi` : A-ϕ method
  - `A` : A method
- `-nl-method` *s* (None)

  The option specifies the method to consider the non-linearity for the magnetic reluctivity.
  - `None` : Not consider non-linearity
  - `Explicit` : Explicit non-linearity
- `-hetero-conductivity`

  The option for input the conductivity in each element.

5.3.7. Options for Input / Output Filename Speification

Usually, the user should set only the name of the directory for analysis data. However, the filenames, other than the default filenames, can be specified adding the following options to the command line. Here, ***P*** indicates the Part number.

- `-onedata-dir` *dir* (model_one)

  The option specifies the name of directory with FEA model file.
- `-onedata-file` *file* (input)

  The option specifies the name of FEA model. The characters **.adv** will be added to the filename set by *file*.
- `-model-dir` *dir* (model)

  The option specifies the name of directory with HDDM-type analysis model file.
- `-model-file` *file* (advhddm_in)

  The option specifies the name of HDDM-type analysis model. The characters **_*P*.adv** will be added to the filename set by *file*.
- `-Inivalue-dir` *dir* (initial)

  The option specifies the name of directory with Condition of initial value file and Initial values.
- `-Inivalue-file` *file* (advhddm_out)

  The option specifies the name of Condition of initial value file and Initial values. The characters **.adv** will be added to the filename of Condition of analysis set by *file*. The characters **_*P*.adv** will be added to the filename of Analysis results set by *file*.
- `-result-dir` *dir* (result)

  The option specifies the name of directory with Condition of analysis file and Analysis results.
- `-result-file` *file* (advhddm_out)

  The option specifies the name of Condition of analysis file and Analysis results. The characters **.adv** will be added to the filename of Condition of analysis set by *file*. The characters **_*P*.adv** will be added and the characters **_*T*_*P*.adv** will be added for non-steady analysis to the filename of Analysis results set by *file*.
- `-mtrldat-dir` *dir* (There are no default.)

  The option specifies the name of directory with Material data file.
- `-mtrldat-file` *file* (mtrl.dat)

  The option specifies the name of Material data file.

Appendix

A. Tools

ADVENTURE_Magnetic has the following tools in addition to the modules for analysis.

A.1. Tool for making FEA model file: `advmag_makefem`

The boundary conditions attached to mesh can be saved in an entire-type FEA model file of ADVENTURE binary format by using the `advmag_makefem` tool.

`% advmag_makefem` *mshFILE fgrFILE cndFILE matFILE advFILE* [*options*]

Input

mshFILE	: Mesh data file (extension is msh)
fgrFILE	: Mesh surface data file (extension is fgr)
cndFILE	: File with boundary conditions (extension is cnd)
matFILE	: Material properties data file (extension is dat)

Output

advFILE	: Entire-type FEA model file (extension is adv)

The above *cndFILE* is created by `bcGUI` command of ADVENTURE_Bctool. After startup of `bcGUI`, a defualtwindow will appear on the screen. Then the boundary conditions are attached to a surface group as follows.

(1) Select the surface group.
(2) Select the menu **Add Displacement** from the main menu **BC**.
(3) Check the **[X]** box and set the values to 0 in the test box on the right.

Refer to subsection 5.3.1 about options.

A.2. Tool for making visualization file advmag_makeUCD

The UCD file or VTK file can be made by using the `advmag_makeUCD` tool. Give option –avsfile (AVS / Explress), -avsfile-micro (Micro AVS) or –vtkfile (ParaView).

`% advmag_makeUCD` [*options*] *data_dir*

Input

FEA model file
HDDM-type analysis model file
Condition of analysis file
Analysis results

Output

UCD file

The following options specify can be used to control this tool.

- `-avsfile`

  The option specifies the output of UCD file formatted for AVS / Express.

- `-avsfile-micro`

The option specifies the output of UCD file formatted for Micro AVS.

- `-avsfile-dir` *dir* (result)

  The option specifies the name of directory with UCD file.

- `-avsfile-file` *file* (avs)

  The option specifies the name of UCD file. The characters `_*.inp` will be added to the filename set by *file*.

VTK file

The following options specify can be used to control this tool.

- `-vtkfile`

  The option specifies the output of VTK file.

- `-vtkfile-dir` *dir* (result)

  The option specifies the name of directory with VTK file.

- `-vtkfile-file` *file* (res)

  The option specifies the name of VTK file. The characters `.vtu` will be added to the filename set by *file*.

Refer to subsection 5.3.1 about options, too.

A.3. Tool for computing distribution of electromagnetic force advmag_nodalforce

The UCD file or VTK file of distribution of electromagnetic force can be made by using the `advmag_nodalforce` tool. Give option –avsfile (AVS / Explress), -avsfile-micro (Micro AVS) or –vtkfile (ParaView).

% `advmag_nodalforce` [*options*] *data_dir*

Input

FEA model file

HDDM-type analysis model file

Condition of analysis file

Analysis results

Output

UCD file

The following options specify can be used to control this tool.

- `-avsfile`

  The option specifies the output of UCD file formatted for AVS / Express.

- `-avsfile-micro`

  The option specifies the output of UCD file formatted for Micro AVS.

- `-avsfile-dir` *dir* (result)

  The option specifies the name of directory with UCD file.

- `-avsfile-file` *file* (avs)

  The option specifies the name of UCD file. The characters `_NF.inp` will be added to the filename set by *file*.

VTK file

The following options specify can be used to control this tool.

- `-vtkfile`

  The option specifies the output of VTK file.

- `-vtkfile-dir` *dir* (result)

The option specifies the name of directory with VTK file.

- `-vtkfile-file` *file* (res)

  The option specifies the name of VTK file. The characters `_NF.vtu` will be added to the filename set by *file*.

Refer to 5.3.1 about options, too.

A. 4. Tool for computing time change of current density

The time change of current density in coils for non-steady eddy current analysis can be made by using the `advmag_graphCurrentDensity` tool.

`% advmag_graphCurrentDensity` *input x y z output* [*options*]

Input

Definition of shape (*input*)

Output

Time change of current density (*output*)

The X-, Y-, and Z-components are written to *output* _x, *output* _y and *output* _z, respectively.

```
0      0          <- Time[s]    Current density[A/m^2](x, y or z)
0.01   0.7
0.02   1.4
   ::
   :
```

The following options specify can be used to control this tool.

- `-delta-t` *x* (0.01)

  The option specifies the time step Δt.

- `-time-step` *n* (20)

  The option specifies the number of time step.

Refer to subsection 5.3.1 about options, too.

Graphs can be written by gnuplot or by import to spread sheet software (LibreOffice Calc, Microsoft Excel, etc.). Follows are example of sequence.

```
% advmag_graphCurrentDensity coil_ns.dat 0.16 0.01 0.0 Jo –delta-t 8.33333e--04 –time-step 100
% gnuplot
gnuplot> plot “Jo_x” w lines, “Jo_y” w lines, “Jo_z” w lines
```

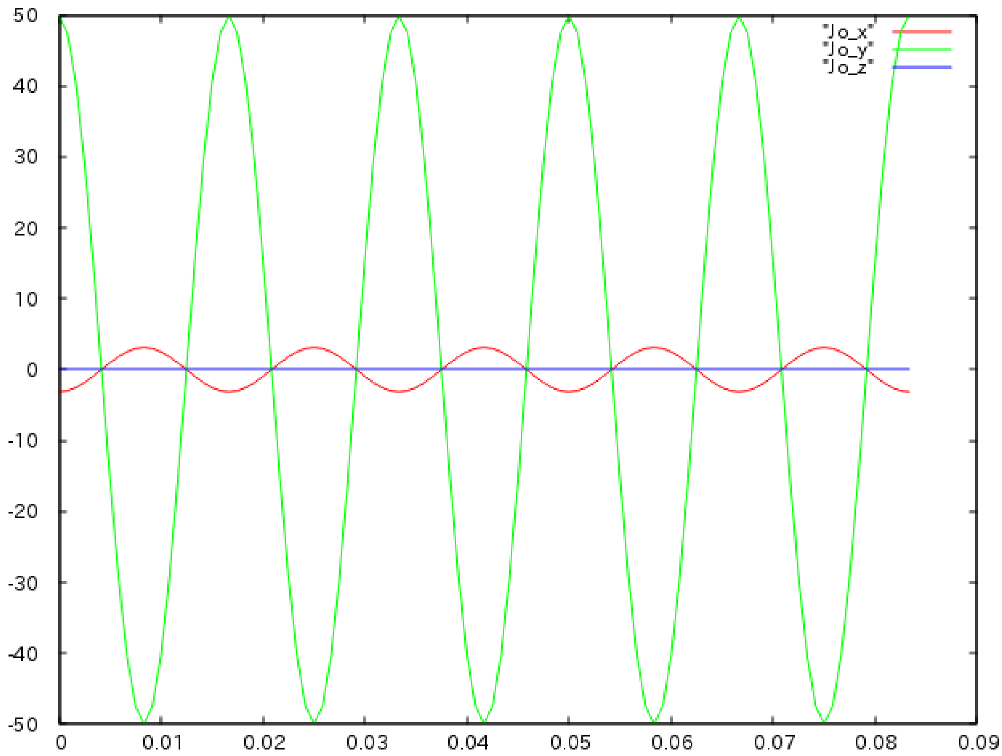


Fig. 7 Time change of current density (Horizontal: Time [s], Vertical: Current density [A/m^2])

A. 5. Tool for domain decomposition of physical quantities data

Physical quantity file can be decomposed by using the `advmag_dd_data-(s/p)` tool.

% `advmag_dd_data-s` *num* (*label* *type* *dim* *file* ...) [*options*] *data_dir*

% `mpirun` [*options for mpirun*] `advmag_dd_data-p` *num* (*label* *type* *dim* *file* ...) [*options*]

Option

num : Numbers of physical quantities

label : Label in HDDM-type physical quantities data file

type : elem or node

dim : Dimension of the physical quantity

file : Physical quantity file (*file*_1, *file*_2 …)

Input

FEA model file

HDDM-type analysis model file

Physical quantity file

Output

HDDM-type physical quantities data file

Refer to subsection 5.3.1 about options.

B. Format of Input / Output files

ADVENTURE_Magnetic uses the following files.

- FEA model file
- HDDM-type analysis model file
- Condition of analysis file
- Analysis results
- Material data file
- Excitation current density data
- Magnetization vector data
- Definition of shape
- *B-H* curve data

The format of these files are as follows.

B. 1. FEA model file

This file is ADVENTURE binary format file made by `advmag_makefem`. Properties of this files are shown below.

```
########################################################
  Connectivity of element
########################################################
[Properties]
  1: content_type=Element
  2: num_items=(number of elements)
  3: num_nodes_per_element=10
  4: dimension=3
  5: element_type=3DQuadraticTetrahedron
  6: format=i4i4i4i4i4i4i4i4i4i4

########################################################
  Coordinates of nodes
########################################################
[Properties]
  1: content_type=Node
  2: num_items=(number of nodes)
  3: dimension=3
  4: format=f8f8f8

########################################################
  Boundary conditions
########################################################
[Properties]
  1: content_type=FEGenericAttribute
  2: num_items=(number of nodes attached boundary condition)
  3: fega_type=NodeVariable
```

```
  4: label=DirichletBCs_Axn0
  5: format=
  6: index_byte=4

#########################################################
  Material numbers
#########################################################
[Properties]
  1: content_type=FEGenericAttribute
  2: num_items=(number of elements)
  3: fega_type=AllElementVariable
  4: label=Flag
  5: format=i4
  6: index_byte=4

#########################################################
  Conditions
#########################################################
[Properties]
  1: content_type=FEGenericAttribute
  2: num_items=0
  3: fega_type=AllElementConstant
  4: label=Options
  5: format=
  6: index_byte=4
  7: ADVMAG_NAME=(name of module  "ADVENTURE_Magnetic")
  8: N_VERSION=(the version of the module)
  9: DirichletBCs_Axn0=NEED
  10: DirichletBCs_Axn0_EF=NO_NEED
```

B. 2. HDDM-type analysis model file

This file is ADVENTURE binary format file made by ADVENTURE_Metis. See the manual of ADVENTURE_Metis for details.

B. 3. Condition of analysis file

The conditions of analysis are on this file.

B. 4. Analysis results

The results of analysis are on this file.

B. 5. Material data file

The user should edit this file. This file set material data and special regions shown below.

- Magnetic reluctivity [m/H] (essential)

- Coil regions and excitation current density [A/m^2] in the coil (optional)
- Permanent magnet regions and magnetization vector [T] in the permanent magnet (optional)

Each one is essential

- Magnetic body and filename of *B-H* curve data (essential in Non-Linear Analysis)
- Conducting part and conductivity [S/m] (essential in Time-Harmonic Eddy Current Analysis)
- Angular frequency [rad/s] of alternating current (essential in Time-Harmonic Eddy Current Analysis and Non-Steady Eddy Current Analysis)

How to set each material data is as follows.

(1) Magnetic reluctivity [m/H] (essential)

```
MagneticReluctivity 4     <- Keyword and number of material
 0 7.957747e+05           <- Material number and magnetic reluctivity [m/H]
 1 7.957747e+05                  :
 2 7.957747e+05                  :
 3 7.957747e+05                  :
```

(2) Coil regions and excitation current density [A/m^2] in the coil

Coil regions are set with “material number”. Next, ways of input of excitation current density are set. Two ways of input are able to selected.

- `rf` : Read values of excitation current density from “Excitation current density data” file.
- `md` : Make values of excitation current density from definitions. The definitions are read from “Definition of shape” file.

At last filenames of “Excitation current density data” file or “Definition of shape” file are set. And filenames are specified by relative path from *data_dir*.

```
Coil 2                 <- Keyword and number of coils
 1 rf Jo               <- Material number, way of input and filename
 3 md coil.dat                  :
```

By the way, filenames of “Excitation current density data” file are used after adding a character, `s` (Non-Linear Magnetostatic Analysis) , `r` (real part in Time-Harmonic Eddy Current Analysis) or `i` (imaginary part in Time-Harmonic Eddy Current Analysis). In this case, filenames are as follows.

- *data_dir*/`Jos` : Excitation current density data (Non-Linear Magnetostatic Analysis)
- *data_dir*/`Jor` : Excitation current density data (Time-Harmonic Eddy Current Analysis, real part)
- *data_dir*/`Joi` : Excitation current density data (Time-Harmonic Eddy Current Analysis, imaginary part)
- *data_dir*/`coil.dat` : Definition of shape, this file is not adding a character to the filename.

(3) Permanent magnet regions and magnetization vector [T] in the permanent magnet (optional)

Permanent magnet regions are set with “material number”. Next, ways of input of magnetization vector are set. Four ways of input are able to selected.

- `rf` : Read values of magnetization vector from “Magnetization vector data” file.
- `md` : Make values of magnetization vector from definitions. The definitions are read from “Definition of shape” file.
- `nl_rf` : Read values of magnetization vector from “Magnetization vector data” file as initial value and

consider non-linear characteristic of permanent magnet. (only in Non-Linear Magnetostatic Analysis)

- `nl_md` : Make values of magnetization vector from definitions as initial value. The definitions are read from "Definition of shape" file and consider non-linear characteristic of permanent magnet. (only in Non-Linear Magnetostatic Analysis)

At last filenames of "Magnetization vector data" file or "Definition of shape" file are set. And filenames are specified by relative path from *data_dir*.

```
PermanentMagnet 4             <- Keyword and number of permanent magnets
 1 rf M                       <- Material number, way of input and filename
 3 md pmagnet.dat                          :
 4 nl_rf M2 pmagnet_bh.dat                 :
 6 nl_md pmagnet_nl.dat pmagnet_bh2.dat    :
```

By the way, filenames of "Magnetization vector data" file are used after adding a character, **s**. In this case, filenames are as follows.

- *data_dir*/Ms : Magnetization vector data
- *data_dir*/pmagnet.dat : Definition of shape, this file is not adding a character to the filename.
- *data_dir*/M2s : Magnetization vector data
- *data_dir*/pmagnet_bh.dat : *B-H* curve data
- *data_dir*/pmagnet_nl.dat : Definition of shape, this file is not adding a character to the filename.
- *data_dir*/pmagnet_bh2.dat : *B-H* curve data

(4) Magnetic body and filename of *B-H* curve data (necessary in Non-Linear Magnetostatic Analysis and Non-Steady Eddy Current Analysis)

Magnetic bodies are set with "material number". Here, the magnetic bodies are parts we consider non-linear characteristic. Next, filename of *B-H* curve data is set in each body.

```
NonLinear 2                   <- Keyword and number of magnetic bodies
 1 bh_curve01                 <- Material number and filename
 3 bh_curve03                          :
```

And filenames are specified by relative path from *data_dir*.

- *data_dir*/bh_curve01
- *data_dir*/bh_curve03

(5) Conducting part and conductivity [S/m]

Conducting parts are set with "material number". Next, conductivity is set in each part.

```
Conductor 1                   <- Keyword and number of conducting parts
 0 7.700000e+06                <- Material number and conductivity[S/m]
                                       :
```

(6) Angular frequency [rad/s] of alternating current (essential in Time-Harmonic Eddy Current Analysis)

This value is set common value in all coils.

```
CoilOmega                     <- Keyword
 3.769911e+02                 <- Angular frequency [rad/s]
```

Fig. 8 shows an example of material data file.

```
MagneticReluctivity    4
  0    7.957747e+05
  1    7.957747e+05
  2    7.957747e+05
  3    7.957747e+05

Coil    1
  2    md    coil.dat

Conductor    1
  0    7.700000e+06

CoilOmega
  3. 769911e+02
```

Fig. 8 Example of material data file (sample_data/cake/decomposed/mtrl.dat)

B. 6. Excitation current density data

This file is used, when rf (Read values of excitation current density from "Excitation current density data" file) is set in material data file. In this file, values of excitation current density are given on each node.

```
27                                                  <- Number of nodes that are given data
18   0.000000e+00   5.000000e+01   0.000000e+00     <- Excitation current density [A/m^2]
20   0.000000e+00   5.000000e+01   0.000000e+00        (3-D vectors)
                         :                                   :
                         :                                   :
```

B. 7. Magnetization vector data

This file is used, when rf (Read values of magnetization vector from "Magnetization vector data" file) or nl_rf (Read values of magnetization vector from "Magnetization vector data" file as initial value and consider non-linear characteristic of permanent magnet) are set in material data file. In this file, values of magnetization vector are given on each node.

```
32                                                  <- Number of nodes that are given data
27 -1.000000e+00   0.000000e+01   0.000000e+00      <- Magnetization vector [T]
92 -1.000000e+00   0.000000e+01   0.000000e+00         (3-D vectors)
                         :                                   :
                         :                                   :
```

B. 8. Definition of shape

This file is used, when md (Make values of excitation current density or magnetization vector from definitions. The definitions are read from "Definition of shape" file) or nl_md (Make values of magnetization vector from definitions as initial value. The definitions are read from "Definition of shape" file and consider non-linear characteristic of permanent magnet) are set in material data file. In this file, values of excitation current density or magnetization vector are defined with information of geometry. You can use two geometries.

- Sectorial circular cylinder
- Parallelpiped (a rectangular parallelepiped or a cube, etc.)

Furthermore, time change is defined in this file, too.

And format of this file is as follows.

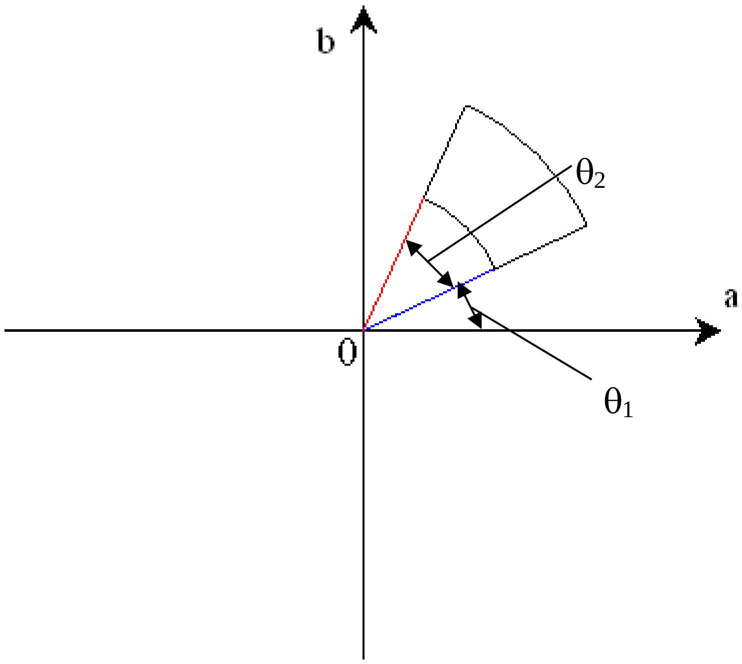
Whole

```
TH-Eddy            <- Kind of analysis
                      Time-Harmonic eddy current analysis: TH-Eddy
                      Non-Linear magnetostatic analysis: Static
                      Non-steady eddy current analysis: NS-Eddy
  :
  :  Definitions of geometry and time change
  :
```

Sectorial circular cylinder

```
DoubleSectorialCylinder     <- Keyword of sectorial circular cylinder
x y z                       <- Coordinates of a cardinal point [m]
(x, y or z)  h              <- Direction of height (x, y or z) and height
(deg or rad)  θ1 θ2         <- Selection of unit of angle and angles
(Inside radius [m]) (Outside radius [m])
(Absolute value of excitation current density [A/m2] or magnetization vector [T])
```

First, a keyword of geometry is written. The keyword of sectorial circular cylinder is "DoubleSectorialCylinder". Next, the coordinates of a cardinal point are specified. In third line, the direction of height is specified by x, y or z. And the value of height is specified. In fourth line, the unit of angle and angles are specified. The unit of angle is specified by "deg" (degree) or "rad" (radian). In addition, angles θ_1 and θ_2 are specified as Fig. 9. In fifth line, the inside radius and outside radius are specified. At last, absolute value of excitation current density or magnetization vector is specified, in sixth line. The direction of these values is from blue line to red line in Fig. 9 (see Fig. 10). In case of use of this file for definition of coil, if kind of analysis is time-harmonic eddy current analysis, two absolute values are specified. And if kind of analysis is non-linear magnetostatic analysis, one absolute value is specified.



If x is selected as the direction of height, a = y and b = z.
If y is selected as the direction of height, a = z and b = x.
If z is selected as the direction of height, a = x and b = y.

Fig. 9 θ_1 and θ_2

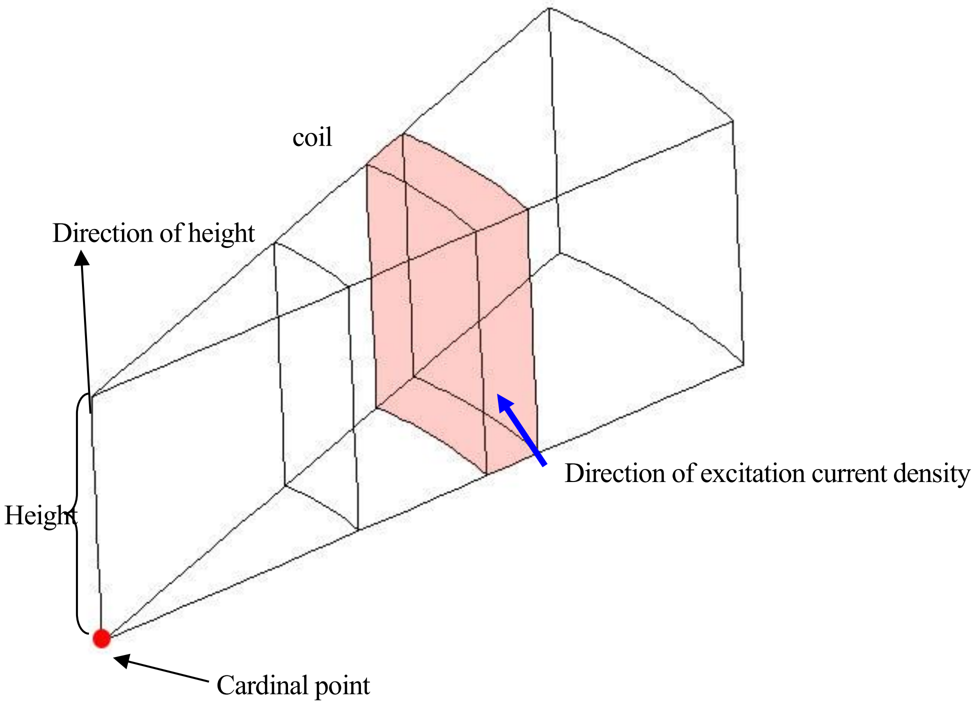


Fig. 10 Example of definition of coil (sectorial circular cylinder)

```
TH-Eddy

DoubleSectorialCylinder
0.0 0.0 0.0
z 0.1
deg 0.0 20.0
0.15 0.17
50.0 0.0
```

Fig. 11 Definition of shape file of Fig. 10

Parallelpiped (a rectangular parallelepiped or a cube, etc.)

Parallelpiped	<- Keyword of Parallelpiped
x_0 y_0 z_0	<- Coordinates of a cardinal point [m]
x_1 y_1 z_1	<- Coordinates of a neighbor point 1 [m]
x_2 y_2 z_2	<- Coordinates of a neighbor point 2 [m]
x_3 y_3 z_3	<- Coordinates of a neighbor point 3 [m]
(Excitation current density [A/m^2] or magnetization vector [T])	

First, a keyword of geometry is written. The keyword of parallelpiped (a rectangular parallelepiped or a cube, etc.) is "Parallelpiped". Next, the coordinates of a cardinal point are specified. In third, forth and fifth lines, the coordinates of neighbor points are specified (see Fig. 12). At last, excitation current density or magnetization vector is specified, in sixth line. In case of use of this file for definition of coil, if kind of analysis is time-harmonic eddy current analysis, two vectors are specified. And if kinds of analysis is non-linear magnetostatic analysis and non-steady eddy current analysis, one vector is specified.

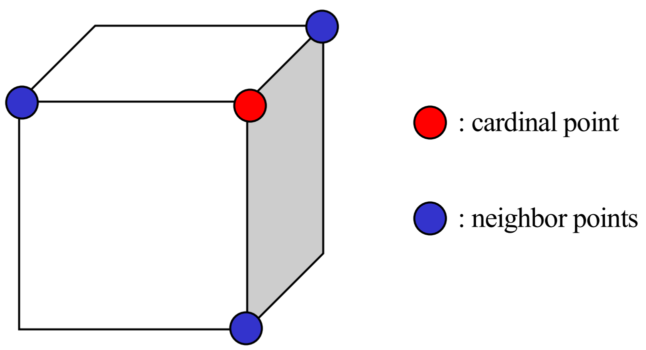


Fig. 12 Definition of shape (parallelpiped)

When you edit "definition of shape" file, pay attention to following things.

- You can use more than one geometry.
- Definition of shape should be a little larger than actual shape.
- If definition of shape falls on other definition, the definition that is defined ahead has priority.

Fig. 13 and Fig. 14 shows an example of “Definition of shape” file of TEAM Workshop Problem 7.

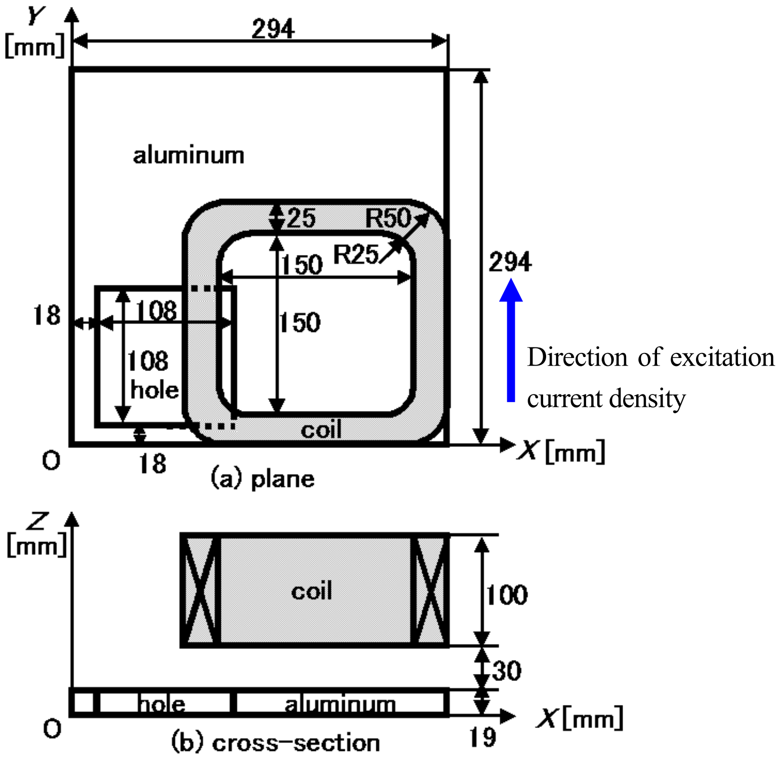


Fig. 13 TEAM Workshop Problem 7

```
TH-Eddy

Parallelpiped
0.089  0.050  0.044
0.089  0.050  0.154
0.089  0.150  0.044
0.124  0.050  0.044
0.0  -1.0986e+6  0.0   0.0  0.0  0.0

Parallelpiped
0.144  -0.005  0.044
0.144  -0.005  0.154
0.144   0.030  0.044
0.244  -0.005  0.044
1.0986e+6  0.0  0.0   0.0  0.0  0.0

Parallelpiped
0.264  0.050  0.044
0.264  0.050  0.154
0.264  0.150  0.044
0.299  0.050  0.044
0.0  1.0986e+6  0.0   0.0  0.0  0.0

Parallelpiped
0.144  0.170  0.044
0.144  0.170  0.154
0.144  0.205  0.044
0.244  0.170  0.044
-1.0986e+6  0.0  0.0   0.0  0.0  0.0
```

```
DoubleSectorialCylinder
0.144  0.050  0.044
z  0.110
deg   170.0  110.0
0.020  0.055
1.0986e+6  0.0

DoubleSectorialCylinder
0.244  0.050  0.044
z  0.110
deg  -100.0  110.0
0.020  0.055
1.0986e+6  0.0

DoubleSectorialCylinder
0.244  0.150  0.044
z  0.110
deg   -10.0  110.0
0.020  0.055
1.0986e+6  0.0

DoubleSectorialCylinder
0.144  0.150  0.044
z  0.110
deg    80.0  110.0
0.020  0.055
1.0986e+6  0.0
```

Fig. 14 Definition of shape file of TEAM Workshop Problem 7 (Fig. 13)

Time change

Time period

```
TimeEvolution 1.0        <- Keyword of time evolution and end time [s]
```

First, a keyword of time evolution is written. The keyword of time evolution is “TimeEvolution”. Next, the end time of the time zone of time changes to be specified after it is specified.

Sinusoidal wave

```
TimeEvolutionSinusoidal        <- Keyword of sinusoidal wave
(rad, deg or Hz) ω             <- Selection of unit and angular frequency or frequency
(rad or deg) α                 <- Selection of unit and phase
a C                            <- Magnification and constant value
```

First, a keyword of sinusoidal wave is written. The keyword of sinusoidal wave is "`TimeEvolutionSinusoidal`". Sinusoidal wave notate by following formulation.

$$a \sin (\omega t + \alpha) + C$$

Here, a is the magnification, ω is the angular frequency, α is the phase, C is the constant value and t is the time. In the second line, the unit of the angular frequency or the frequency is specified by "deg" (degree), "rad" (radian) or "Hz". In addition, the angular frequency or the frequency is specified. Next, the unit of the phase is specified by "deg", "rad" and the phase is specified. In the last line, the magnification and the constant value are specified.

Linear

```
TimeEvolutionLinear        <- Keyword of linear
α β                        <- Magnifications at start time and end time
C                          <- Constant value
```

First, a keyword of linear is written. The keyword of linear wave is "`TimeEvolutionLinear`". Linear notate by following formulation.

$$(\beta - \alpha)(t - t_1)/(t_2 - t_1) + \alpha + C$$

Here, t_1 is the start time, t_2 is the end time, α is the magnification at the start time, β is the magnification at the end time, C is the constant value and t is the time. In the second line, the magnifications at the start time and the end time are specified. Next, the constant value is specified.

Here, some examples of time change are shown.

```
NS-Eddy

DoubleSectorialCylinder
 0.0 0.0 -0.05
 z 0.2
 deg -10.0 40.0
 0.14 0.18
 50.0

TimeEvolution 1.0
TimeEvolutionSinusoidal
  Hz 1
  deg 90.0
  1.0 0.0

TimeEvolution 2.0
TimeEvolutionLinear
  1.0 -1.0
  0.0
```

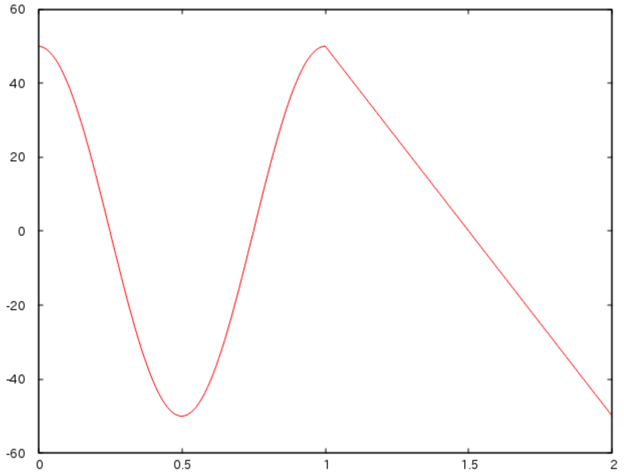


Fig. 15 Change from sinusoidal wave to linear

```
NS-Eddy

DoubleSectorialCylinder
 0.0 0.0 -0.05
 z 0.2
 deg -10.0 40.0
 0.14 0.18
 50.0

TimeEvolution 1.0
TimeEvolutionSinusoidal
  Hz 1
  deg 90.0
  1.0 0.0
TimeEvolutionSinusoidal
  Hz 2
  deg 0.0
  1.0 0.0
```

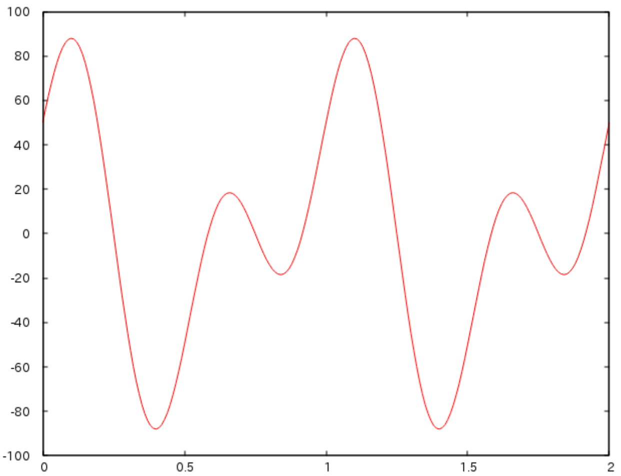


Fig. 16 Superimpose of sinusoidal waves

```
NS-Eddy

DoubleSectorialCylinder
 0.0 0.0 -0.05
 z 0.2
 deg -10.0 40.0
 0.14 0.18
 50.0

TimeEvolution 1.0
TimeEvolutionSinusoidal
  rad 31.4159
  rad 0.0
  1.0 0.0
TimeEvolutionLinear
  -1.0 1.0
  0.0
```

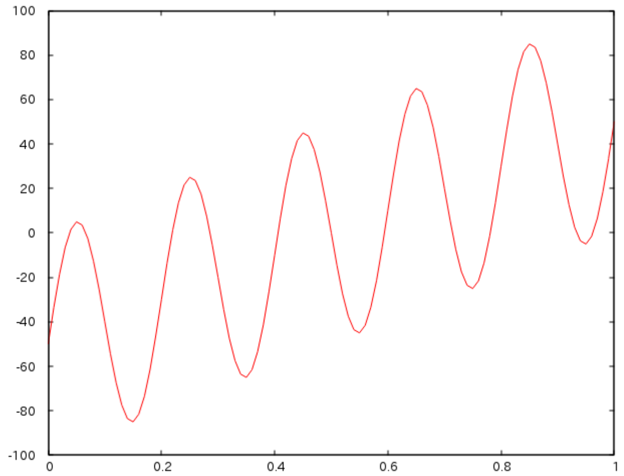


Fig. 17　Superimpose of sinusoidal wave and linear

```
NS-Eddy

DoubleSectorialCylinder
 0.0 0.0 -0.05
 z 0.2
 deg -10.0 40.0
 0.14 0.18
 50.0

TimeEvolution 0.5
TimeEvolutionLinear
  0.0 1.0
  0.0

TimeEvolution 1.5
TimeEvolutionLinear
  1.0 -1.0
  0.0
```

```
TimeEvolution 2.5
TimeEvolutionLinear
  -1.0 1.0
  0.0

TimeEvolution 3.5
TimeEvolutionLinear
  1.0 -1.0
  0.0

TimeEvolution 4.5
TimeEvolutionLinear
  -1.0 1.0
  0.0

TimeEvolution 5.5
TimeEvolutionLinear
  1.0 -1.0
  0.0
```

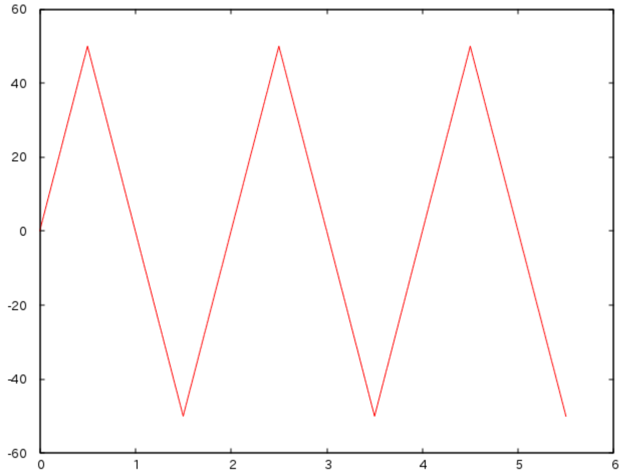


Fig. 18 Triangle wave

```
NS-Eddy

DoubleSectorialCylinder
 0.0 0.0 -0.05
 z 0.2
 deg -10.0 40.0
 0.14 0.18
 50.0

TimeEvolution 1.0
TimeEvolutionLinear
  0.0 0.0
  1.0

TimeEvolution 2.0
TimeEvolutionLinear
  0.0 0.0
  -1.0
```

```
TimeEvolution 3.0
TimeEvolutionLinear
  0.0 0.0
  1.0

TimeEvolution 4.0
TimeEvolutionLinear
  0.0 0.0
  -1.0

TimeEvolution 5.0
TimeEvolutionLinear
  0.0 0.0
  1.0

TimeEvolution 6.0
TimeEvolutionLinear
  0.0 0.0
  -1.0
```

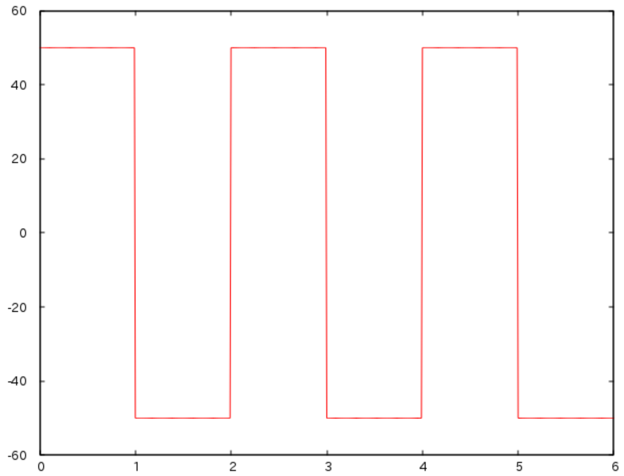


Fig. 19 Square wave

B. 9. ***B-H* curve data**

This file is used to specify non-linear characteristic of magnetic bodies. And non-linear characteristic is given by *B-H* curve.

```
(Number of points)
 (Magnetic filed |H|[A/m]) (Magnetic flux density |B|[T])
                    :
                    :
```

B. 10. Physical quantity file

The physical quantities are on this file.

```
(Number of elements)
 (Physical quantity in element 0)
                  :
                  :
```

```
(Number of nodes)
 (Physical quantity in node 0)
                  :
                  :
```

B. 11. HDDM-type physical quantities data file

This file is ADVENTURE binary format file made by advmag_dd_data-(s/p).

References

[1] ADVENTURE Project Home Page : http://adventure.sys.t.u-tokyo.ac.jp/

[2] Ryuji SHIOYA and Genki YAGAWA, "Iterative domain decomposition FEM with preconditioning technique for large scale problem", *ECM'99 Progress in Experimental and Computational Mechanics in Engineering and Material Behaviour*, pp.255-260, 1999.

[3] Hiroshi KANAYAMA, Ryuji SHIOYA, Daisuke TAGAMI and Satoshi MATSUMOTO, "3-D eddy current computation for a transformer tank", *COMPEL*, Vol.21, No.4, pp.554-562, 2002.

[4] Hiroshi KANAYAMA and Shin-ichiro SUGIMOTO, "Effectiveness of A-ϕ method in a parallel computation with an iterative domain decomposition method", *COMPUMAG2005*, 2005.

[5] Hiroshi KANAYAMA, Hongjie ZHENG and Natsuki MAENO, "A domain decomposition method for large-scale 3-D nonlinear magnetostatic problems", *Theoretical an Applied Mechanics*, 52, pp.247-254, 2003.

[6] Message Passing Interface Forum: http://www.mpi-forum.org/

[7] MPICH: https://www.mpich.org/

[8] OpenMPI: https://www.open-mpi.org/

[9] Shin-ichiro SUGIMOTO, Hiroshi KANAYAMA, Shuuji ASAKAWA and Shinobu YOSHIMURA, "Time-harmonic eddy current analysis of 44 million complex DOF problem with hierarchical domain decomposition method", *Transactions of JSCES*, 2007027, 2007 (in Japanese).

[10] Kohji FUJIWARA and Takayoshi NAKATA, "Results for benchmark problem 7 (asymmetric conductor with a hole), *COMPEL*, Vol.9, No.3, pp.137-154, 1990.

[11] Shin-ichiro SUGIMOTO, Masao OGINO, Hiroshi KANAYAMA and Shinobu YOSHIMURA, "Introduction of a Direct Method at Subdomains in Non-linear Magnetostatic Analysis with HDDM", 2010 International Conference on Broadband, Wireless Computing, Communication and Applications, pp.304-309, 2010.