

***SimulMag* Version 1.0**

Micromagnetic Simulation Software

User's Manual

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The calculated results do not necessarily describe what would be realized from an actual experimental measurement. All magnetic simulators perform idealized calculations and cannot necessarily describe effects resulting from fine details inherently present in real magnetic samples. This program is based on a relatively simple single-domain model for speed of calculation. Other techniques may produce different results.

Nevertheless, the simulator may provide useful results when used cautiously by a well-trained scientist or engineer.

Abbreviations and list of Symbols

<u>Abbreviation/Symbol</u>	<u>Term</u>
AMR	Anisotropic magnetoresistance
GMR	Giant magnetoresistance
E	Total free energy density of a system of elements
e_i	Free energy density of element
g	Gyromagnetic ratio
H_T	Total effective field acting on element excluding self-demagnetizing fields
H_{eff}	Total effective field acting on element
H_o	Externally applied field acting on element
H_p	Characteristic pinning field of element
H_m	Inter-element magnetostatic field acting on element
H_{ex}	Effective exchange field acting on element
H_k	Effective magnetic uniaxial anisotropy field acting on element
M	Magnetization vector of element
\hat{u}	Self-demagnetizing tensor of element
N_x, N_y, N_z	Demagnetizing factors of element along x , y and z axes
$*E$	Variation of total free energy density of a system of elements
$*e_i$	Variation of free energy density of element

$2_M, N_M$	Spherical coordinate variables of element magnetization
\mathbf{J}_i	Torque per unit volume acting on element
ζ	Gyromagnetic factor
δ	Damping factor
$l_i^>$	Length of the side of the i th element parallel to coordinate axis $>$
A_i^A	Area of the face of the i th element parallel to coordinate plane A
$''_{ij}^A$	Inter-element area intersection coefficient
$\$_{ij}^>$	Inter-element length intersection coefficient
$\ddot{\mathbf{o}}$	Inter-element magnetostatic interaction tensor
D_{xy}, D_{xy} etc.	Components of inter-element magnetostatic interaction tensor
H^{ex}	Magnitude of exchange field
A_{Elem}^j	Cross-sectional area of element normal to current direction in j th element
\mathbf{H}_I^j	Volume-average field at element due to current in j th neighbor
\mathbf{h}_{Ik}^j	Field due to current flowing in the k th rod element of the j th element
\mathbf{M}_G	Group magnetization vector
V_i	Element volume
N_G	Number of elements in group
N_c	Number of elements in common electrical circuit of group
g_i	Phenomenological reduced conductance of element
\star_a	Reduced AMR amplitude
$)_{GMR}$	GMR ratio

γ_{AMR}	AMR ratio
G_{sat}	Total reduced conductance of group at saturation
G_T	Total reduced conductance of group
G_{ref}	Total reduced reference conductance of group used in calculating AMR
F_i	Conductivity of element
L_i	Length of element in direction of current flowing in it
Δg_i	Change in reduced conductance of element due to GMR or AMR
N_{gmr}	Number of neighbors that are GMR-coupled to element
α_{ij}^*	Arbitrary GMR coupling ratio
R_i	Angle between current and magnetization in element
ΔD_i	Amplitude of anisotropic magnetoresistance in element
K	Magnetic anisotropy constant
\mathbf{k}	Magnetic anisotropy unit vector

1. Introduction

The Micromagnetic Simulator (*SimulMag*) is a easy-to-use PC-based magnetic design tool. The simulator allows one to simulate the system response of a magnetic device or circuit under the influence of external magnetic fields, currents, or local field sources.

The analysis is based on a collection of single-domain elements whose size and position can be specified by the designer. The elements may be magnetic or nonmagnetic, a conductor, or an insulator. The element's magnetic properties, such as magnetization, anisotropy, pinning fields, and resistivity must be specified or selected from a library of materials. Electrical circuits can be specified and currents applied. The elements interact through magnetostatic interactions and user-specified exchange interactions. The elements are arranged in groups to allow different structures to be built up and manipulated independently. Relative motion between the groups can be specified. For example one can design a group that describes an advanced recording head and a group describing the magnetic structure in media. These two groups can then be moved relative to each other in a way to simulate the recording process.

Two types of calculations are currently implemented. One is an energy minimization calculation in which a local energy minimum is calculated for a given value of applied and current-generated magnetic fields. The local energy minimum depends on the history and the initial state of the element moments. The second is a dynamic calculation based on the Landau-Lifshitz equation. The moments of each element are allowed to precess and relax under the influence of external fields, anisotropy fields, magnetostatic interaction fields, and exchange interaction fields.

The program output consists of a movie of the evolution of magnetic moments of all of the elements, plots of the magnetization and magnetoresistance of user-defined groups making up a system. The system configuration and the output data can be conveniently saved to disk files for further analysis.

The design of the micromagnetic simulator is based on a "top-down" approach in which a device can be very quickly simulated as a collection of a small number of single-domain elements. After the basic system response is determined, the engineer can then make the device more complex by subdividing the elements to include micromagnetic effects. The complexity is determined by the user and by the time he or she wants to spend on device design and computation.

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2. Getting Started

This chapter describes the system requirements for the software, the installation of the software and a design example to acquaint the user with the workings of the software. It is highly recommended that a new user go through every step of this example before proceeding further. More detailed descriptions of the software are provided in the remaining chapters of this manual.

2.1. System Requirements

The software requires any of the 32-bit operating systems, Windows 95 or Windows NT 3.51 or higher, to run. The system should have a 80386 or higher microprocessor, a VGA or higher resolution screen supported by Microsoft Windows and a minimum of 4 megabytes of RAM. For best performance it is recommended that the system have a processor speed of 133 MHz or greater and a RAM capacity of 8 megabytes or more.

2.2. Installation

There are two ways of installing the software: (a) By using a set of installation floppy disks or (b) by means of a single installation file obtainable from a variety of sources.

(i) Installation from floppy disks

Insert the disk labeled *Disk 1* into a floppy drive of your system and execute the *setup.exe* program located on it from the *File Manager*, command line prompt, or by running the *Add/Remove* application under your system's *Control Panel* group.

(ii) Single-file installation

Download a free copy of the single-file installation program *setupmms.exe* to a temporary directory in your computer and run it. A copy of this program is currently available over the Internet from the anonymous ftp site *central.blr.nist.gov*, under the directory */pub/oti*, and from the world wide web site *http://emtech.boulder.nist.gov/div814/magsim*.

Follow the setup instructions to complete the installation. A new program group called *Micromagnetics Design Tool Ver. 1.0* will be created in your system. To launch the Micromagnetics Simulator click on the *SimulMag 1.0* icon in this group. The software can be removed from your computer by clicking the *Uninstall* icon in the group. A set of disks (labeled *Examples*) accompanying the installation disks contain sample designs created with the software.

2.3. The MMS Viewer

The *MMS Viewer* is a program for viewing designs created with the simulator program SimulMag. It automatically plays back recorded simulations and permits viewing and saving to file of all simulation data. A single-file installation program for the viewer (*setupmmv.exe*) is available for downloading from the same Internet sources for obtaining the simulator (see *Sec. 2.2*). The system requirements for the viewer program are the same as for the simulator. The MMS Viewer requires a much smaller memory than the simulator to run. It can be very effectively used as a plug-in in a web browser for convenient online viewing of design examples posted on the world-wide web.

2.4. Design Example

In this section we begin our acquaintance with the software by going through the steps needed to design the system of interacting objects displayed in Fig. 2.1. and running a simulation (calculation) on it. This simulation will be recorded and stored in a file for later playback. Visible in the figure are graphs of certain data output generated by the simulation. During the simulation, object 1 will move along the indicated path. The system consists of the several objects indicated by the numbers in the figure. (Note that the numbers and path of motion shown in figure are for illustration only, they are not generated by the software). The objects are (following the numbering in the figure):

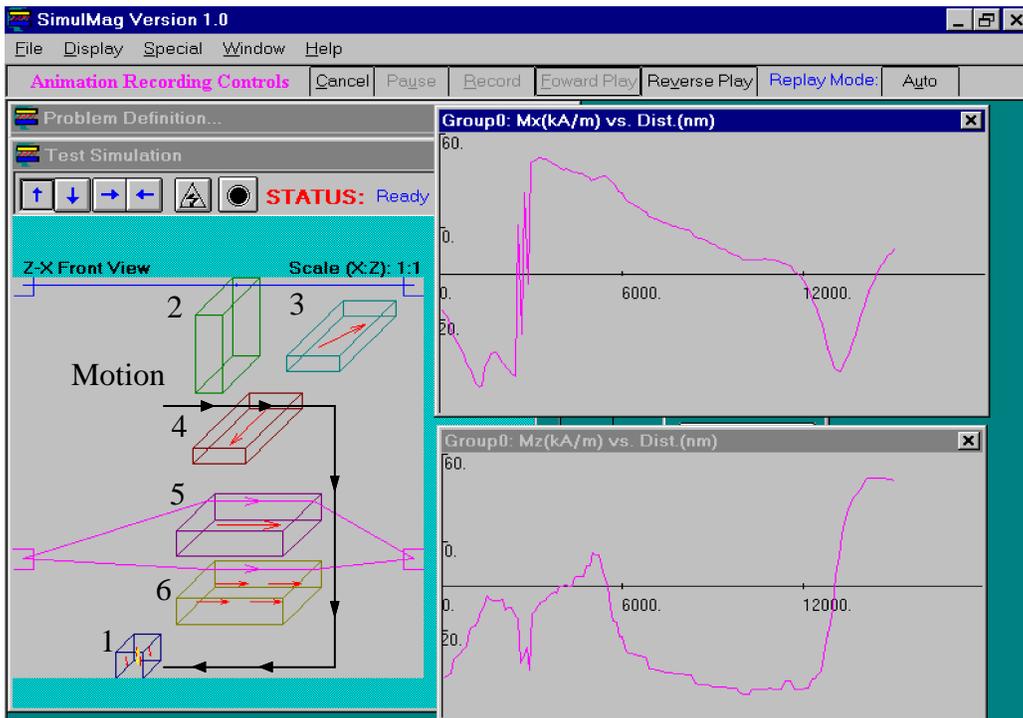


Fig. 2.1. Design example (left) and graphs of data output (right).

1. A magnetic cube that will be moved among the other objects
2. A nonmagnetic prism fed by an independent current source
3. A permanent magnet slab
4. A Permalloy slab
5. and 6. Permalloy slabs connected in a parallel electric circuit.

The design process generally involves assembling a *system* composed of several functionally distinct *groups* that are made up of *elements*. An element is shaped as a rectangular prism and may be magnetic or nonmagnetic, a conductor or an insulator. The magnetic elements are single-domain (or uniformly magnetized). Their magnetization can therefore be represented by a single vector. A more formal discussion of the concept of a system and the groups and elements it contains is given in [Sec. 3.2., Design Hierarchy and Coordinate System.](#)

2.4.1. Defining the first group

Start the program, the screen shown in Fig. 2.2. will be displayed. The dialog with the caption “Problem-Definition” is the interface for adding groups to the system. The **Description** box which initially contains the entry “Untitled” is used to enter a name for the system, such as a useful description of it. Change this entry to “Test Simulation.” The type of calculation (*Static* or *Dynamic*) is specified using the **Calculation Method** drop-down list. For this example we will use static calculation. A further description of calculation procedures is given in [Sec. 4.2.](#) of this manual.

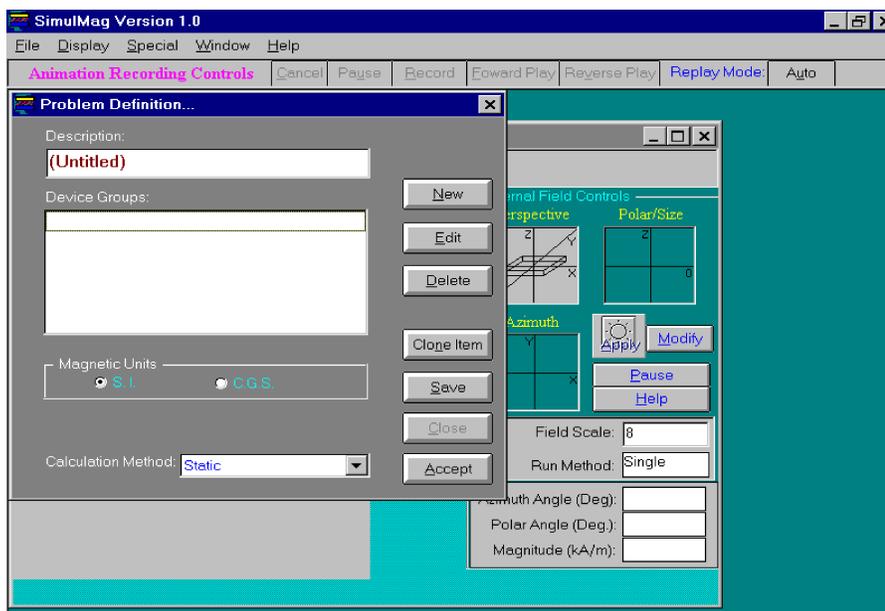


Fig. 2.2.

The option **S.I.** is the default selection under the **Magnetic Units** group. This indicates that S.I. units will be used by the program in interpreting magnetization and magnetic field data and in generating and displaying magnetic data output. The S.I. unit for magnetization and field is A/m. In C.G.S. units magnetization is expressed in emu/cm³ and field is expressed in Oe. All relevant dialog boxes and graphs will display magnetic units in accordance with the system of units specified in the Problem-Definition dialog.

We will now add object 1 to the system. This object will form a group by itself. In other words we will create a new group containing just one element. To add the group, press the **New** button on the **Problem Definition** dialog. You are prompted to enter the name for the new group (Fig. 2.3.). The default name “(Noname1)” is supplied by the program. Type over this name with the more meaningful “Moving Cube group” and press **OK**. A new dialog with the caption “Device group Editor” is launched. This dialog provides the interface for adding elements to the group and contains

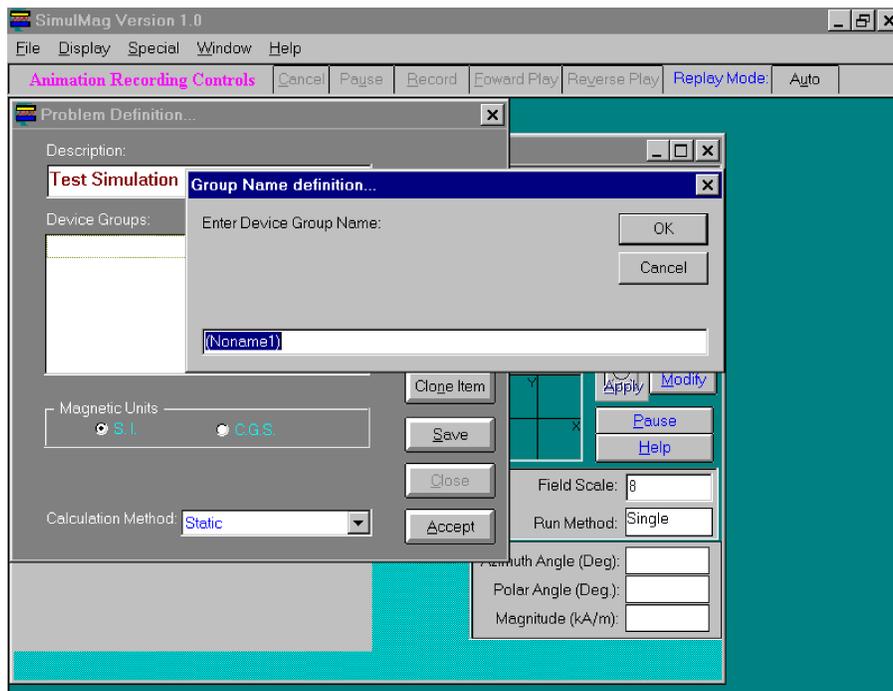


Fig. 2.3.

the just entered group name in its **Title** box. Press the **Add** button; this launches the dialog with the caption “Media-Characteristics” shown in Fig. 2.4. The geometric, electric and magnetic properties of the element can now be specified by filling in the dialog with appropriate values. The **Dynamic Properties** button is currently disabled because at the start of the design we selected the static calculation method. For dynamic calculations, it is enabled and used to specify the dynamic

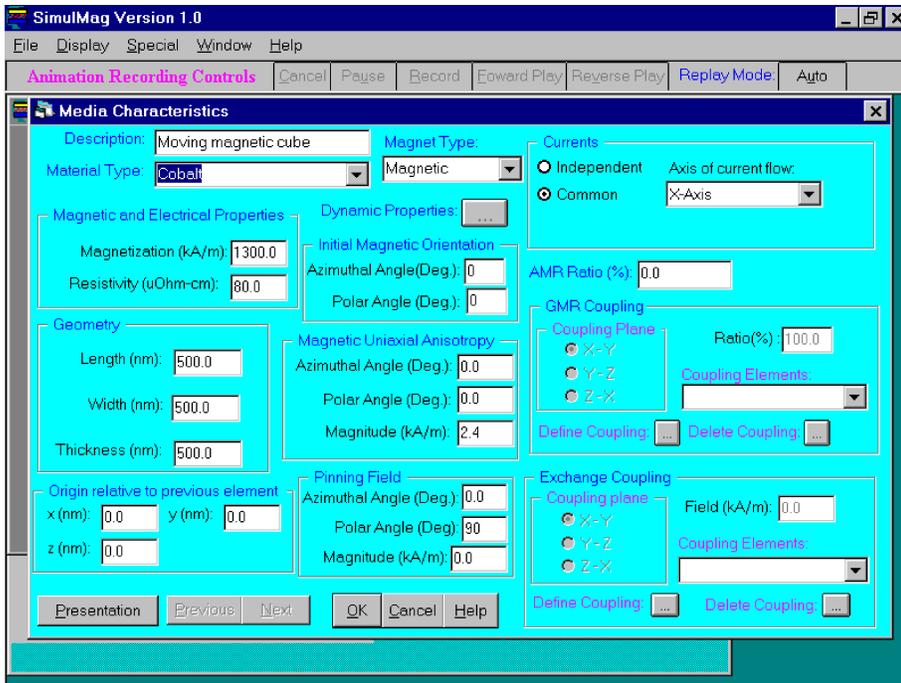


Fig. 2.4.

properties of the element. Enter the following inputs in the **Media Characteristics** dialog:

<u>Box</u>	<u>Entry</u>
-------------------	---------------------

Description	Moving magnetic cube
-------------	----------------------

Material Type	Cobalt
---------------	--------

Geometry

Length (nm)	500
-------------	-----

Width (nm)	500
------------	-----

Thickness (nm)	500
----------------	-----

Magnetic Uniaxial Anisotropy:

Azimuthal Angle (Deg.)	0
------------------------	---

Polar Angle (Deg.)	0
--------------------	---

Magnitude (kA/m)	2.4
------------------	-----

When you select cobalt from the **Material Type** drop-down list, the **Magnetization** and **Resistivity** boxes are filled with values corresponding to the default nominal bulk magnetization and resistivity values for cobalt. These and the other inputs can be manually altered by the user. With above specifications, we have defined an element that is a 500 nm (half-micrometer) magnetic cube with Cobalt properties, and which is characterized by a uniaxial magnetic anisotropy of magnitude 2.4 kA/m whose easy-axis is parallel to the direction given by the specified azimuthal and polar angular coordinates. Press the **OK** button of the **Media Characteristics** dialog. This closes the dialog and returns you to the **Device Group Editor** dialog. Notice that the description of the just added element is now listed in the **Group Elements** list. This list contains the description of all elements that belongs to a group regardless of its complexity. An element can be re-edited by double-clicking its entry on the list with the mouse, or by selecting it on the list and pressing the **Edit** button. In both cases a **Media Characteristics** dialog containing the properties of the element is launched. The **Problem Definition**, **Device Group Editor** and **Media Characteristics** dialogs are described in detail in *Sec. 3.3, Specification of System*, *Sec. 3.3, Specification of Element Group* and *Sec. 3.4., Specification of Basic Element*.

Press the **OK** button, a window is displayed on which is drawn a cube with 4 arrows pointing down (Fig. 2.5.). This is the **System Display Window** and is described in detail in *Sec. 3.6*. The caption of this window is the system description that was previously entered in the **Description** box of the **Problem Definition** dialog. The cube represents the element and the arrows represent its unit magnetization vector. The configuration of the system will be continually updated in this window as new elements and groups are added. Now bring the **Problem Definition** dialog to the front by clicking on it, pressing the F7 key or by selecting it from the Window menu. Notice that the group name of the first group is listed in the **Device Groups**' list of the dialog. All groups forming the system will eventually be listed here. Groups are also identified by their position in the system starting from 0 onwards; the group we just added is Group 0. Each group can be edited by double-clicking it in the list or selecting it with the mouse and pressing the **Edit** button. Return to the **System Display Window** by clicking on it. We are now ready to interact with our first group.

2.4.2. Working with the group

Pull down the **Display** menu in the main window. Notice that the item **Show Magnetization Vectors** is checked. Select this item. This un-checks it, and notice that the magnetization vectors of the cube have now disappeared. Selecting the **Display|Show Magnetization Vectors** item again restores the magnetization vectors. This way you can control whether magnetization arrows are to be displayed or not. The fact that arrows are not displayed does not mean the element has been transformed into a nonmagnetic element. It still retains all its properties, except that its magnetic state is no longer visible. Now remove the magnetization vectors and select the **Display|Show Uniaxial Magnetic Anisotropy Axes** menu item. A double-tipped yellow arrow oriented vertically is displayed within the cube. This arrow represents the magnetic anisotropy easy-axis of the cube and is oriented according to the angular coordinates defined earlier for the element. Redisplay the magnetization from the **Display** menu. The **Display** menu enables displaying and removing those items listed under it.

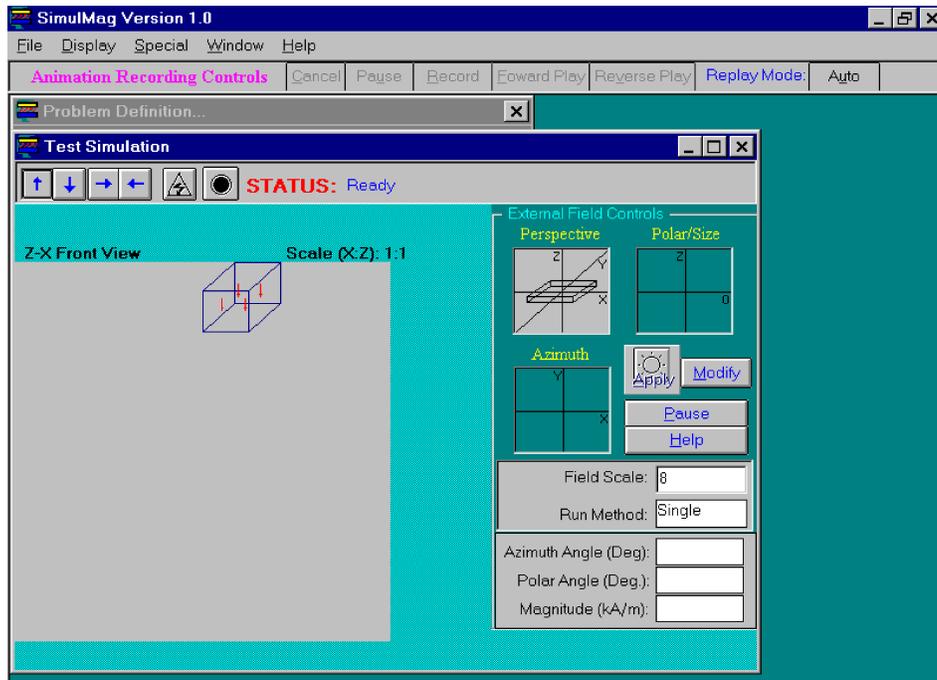


Fig. 2.5.

Before proceeding further let us save the design we have so far. To do this, select the item **File | Save** from the main menu. You are prompted for the name of the file to save the design to. Enter a file name such as “test” or any other name of your choice and press **Save**. The design has now been saved to the specified file. If the entered file name has no extension, it is saved with the default extension *.mms* (for example as “test.mms”). It is always a good idea to periodically save your designs. After the design have been saved once, selecting **File | Save** again saves it to the previously entered file without prompting for a new file name. To save the design to a different file, select the **File | SaveAs** item from the menu. A saved design can be loaded into the program by selecting the **File | Open** menu item.

We will now apply a magnetic field to our cube using the **External Field Controls** which are grouped on the right side of the **System Display Window**. Click anywhere within the small square window labeled **Polar/Size**. An arrow drawn from the origin (center of the box) to the point clicked appears. Now press the **Apply** button. Notice how the magnetization of the cube rotates. Experiment with this by clicking a few more times in the **Polar/Size** window, following each click with a press of the **Apply** button. Observe how the magnetization of the cube changes each time you press the **Apply** button. Clicking of the **Polar/Size** window lets the user interactively specify the magnitude and polar angle of the field to apply, and pressing the **Apply** button invokes the underlying *physical model* which calculates the response of the cube to an applied field, resulting in the rotation of its magnetization. For the static calculation method currently in use, the displayed magnetic states are

the equilibrium states corresponding to energy minima of the system. For dynamic calculations, nonequilibrium intermediate states are also displayed, permitting the observation of magnetic *precession*. The azimuthal angle of the field can be specified by clicking in the **Azimuth** window. The current azimuthal and polar angles and the magnitude of the field are displayed in the **Azimuthal Angle**, **Polar Angle** and **Magnitude** boxes. The **Perspective** window displays the direction and magnitude of the applied field relative to the system. The rectangular box in the center of this window represents the system. As you click around in the **Polar/Size** and **Azimuth** windows, a changing arrow representing the different fields is drawn in the **Perspective** window. The **Field Scale** box contains the current scale of the half-widths of the **Polar/Size**, **Azimuth** and **Perspective** windows. Changing this entry re-scales the windows, permitting the specification of a range of field magnitudes. The **Run-Method** box contains information about the type of *field sequence* that is to be applied to the system, or its external field application *mode*. Currently it reads “Single.” This means that a single field is to be applied to the system. Other field modes exist in addition to the Single mode. We will discuss these shortly.

Press the **Modify** button. A dialog with caption “Field Data” is launched. This dialog offers an alternative means of specifying a single field to apply to the system and allows for a more exact specification of fields other than by using the mouse. Notice that the *Single* mode is selected in the **Run-Method** drop-down list of this dialog. The other possible modes are the *Loop* and *Rotation* modes. In the Loop mode the system is subjected to a cyclic sequence of fields in a fixed direction. In the Rotation mode, a rotating field of fixed magnitude is applied to the system. Let us apply a cyclic field to the system. To do this we first specify the field mode by selecting Loop from the **Run-Method** list. Notice how the **Field-Data** dialog box changes into the one shown in Fig. 2.6. Enter the following inputs in the boxes:

<u>Box</u>	<u>Entry</u>
No. of Data Pts.	200
Max. Field (kA/m)	4
Min. Field (kA/m)	-4
Polar Angle (Deg.)	90
Azimuth. Angle (Deg.)	0

The above specifications prepare us to apply a sequence of fields to the system in 200 equal increments, from 4 kA/m to -4 kA/m and back to 50 kA/m, along an axis specified by the angular coordinates. Press the **Accept Data** button to close the dialog. Now press the **Apply** button to subject the system to above field sequence. Notice the resulting real-time changing of the magnetization of the cube and the field information at the field controls. This produces a “movie” effect of the magnetization and applied field. While the simulation is running, notice that the caption

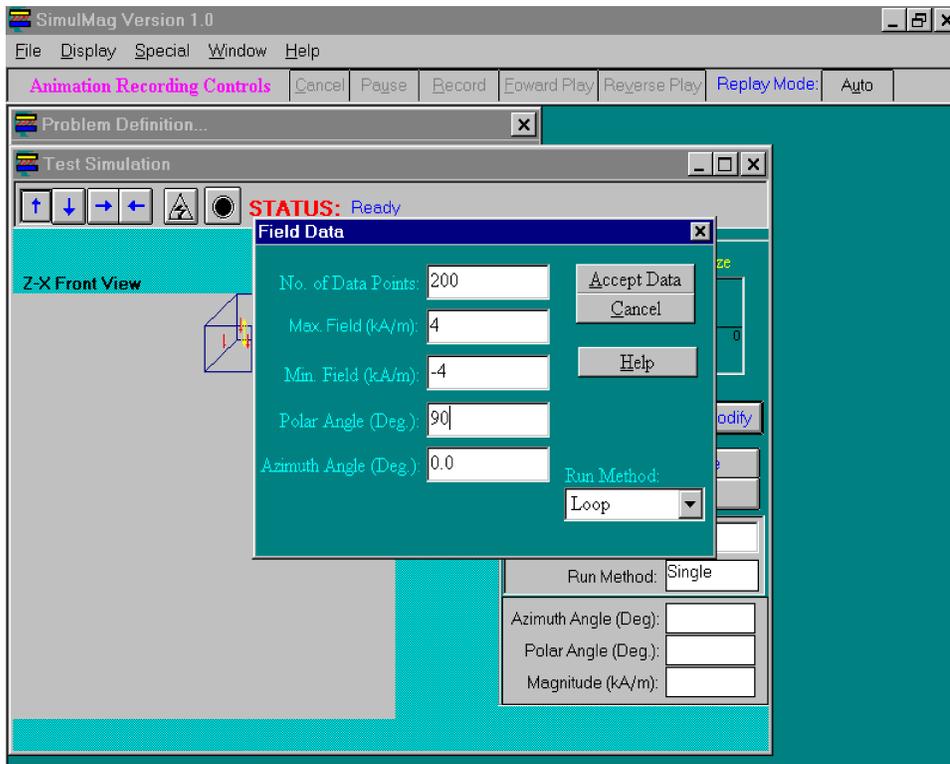


Fig. 2.6.

of the **Apply** button has temporarily changed to “Cancel.” Pressing the button in this state cancels the simulation; the button caption reverts back to “Apply” after the simulation terminates. Pressing the **Pause** button during the simulation pauses it, and the button caption changes to “Continue”; pressing the button again continues the simulation. Click on the front face of the displayed cube using the right mouse button. A window with caption “Group 0: Moving magnetic cube,” is displayed. This is the *profile* window of the cube. Examine its contents, which contains useful information about the properties and magnetic state of the cube at the instance it was clicked, which may even be in the middle of a simulation. The profile of any element in a design can be viewed this way. Close the profile window. Magnetization and magnetoresistive data are generated during a simulation (see [Sec. 3.8., Data Output and Saving Data](#) for a description of the organization and saving of output data). All data output generated by the simulation can be saved by selecting the Special|Save Calculation Results menu item.

2.4.3. Plotting data

Let us generate our first graph which will be the magnetization versus field (M vs. H) plot for the cube due to above field sequence. Data output and graphical plots are generated only for groups in a system. Since the cube by itself constitutes our first group, the plot will portray the behavior of the cube. But first we have to tell the program which output to plot. Double-click on the front face of

the cube, the **Device Group Editor** dialog for the group is launched. Double-clicking the element is another way of launching this dialog other than by selecting the group from the **Problem Definition** dialog. Press the **Data Output** button of the **Device Group Editor** dialog, the dialog shown in Fig. 2.7. is launched. Check the *Magnetization along field vs. External Field* box and press the **OK** button. Press the **OK** button of the **Device Group Editor** dialog to close it. Back in the **System Display Window**, press the **Apply** button of the **Field Controls**. This repeats our last simulation except that this time a window displaying a graph of the M vs. H curve is launched. This window is at first hidden behind other windows; bring it to the fore by selecting it from the **Windows** menu (its entry will read “Group 0: M(kA/m) vs. H(kA/m)”); resize and move it to a location such as in Fig. 2.8. where it is always visible. Halt and restart the simulation and observe how the M vs. H curve is progressively traced out during the simulation.

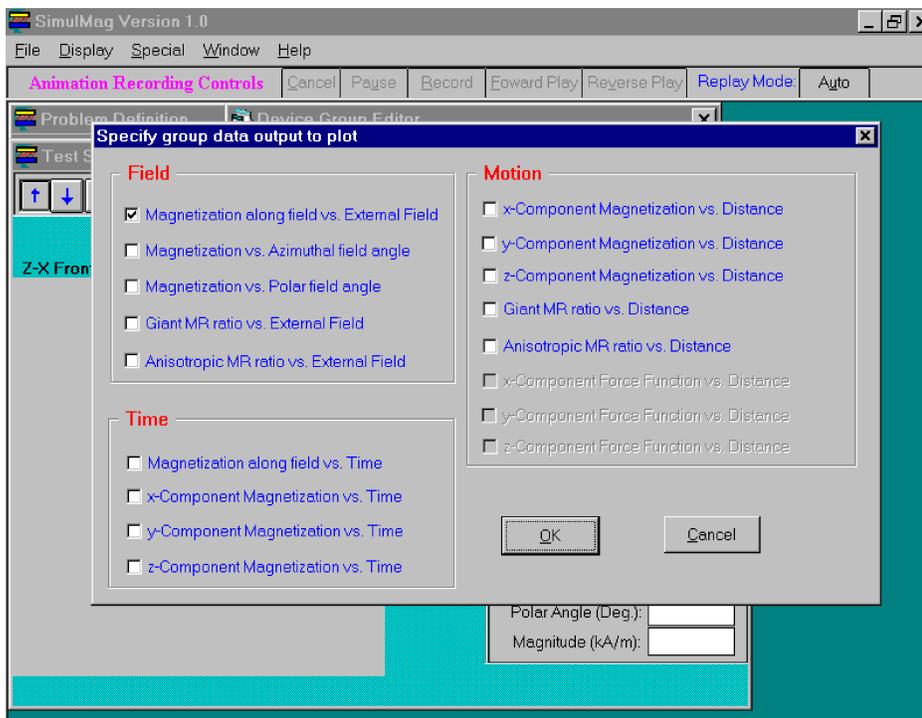


Fig. 2.7.

By positioning the mouse pointer anywhere in the plot window, pressing and holding down the left mouse button, the coordinates in *plot units* of the location of the mouse pointer is displayed on the status bar at the top of the window. Holding down the right mouse button over a plot launches a pop-up menu with which the plotted data could be stored to file or its graph sent to be printed on a printer. Now that we know how to apply fields and to graph outputs, we can now proceed with designing the rest of the system.

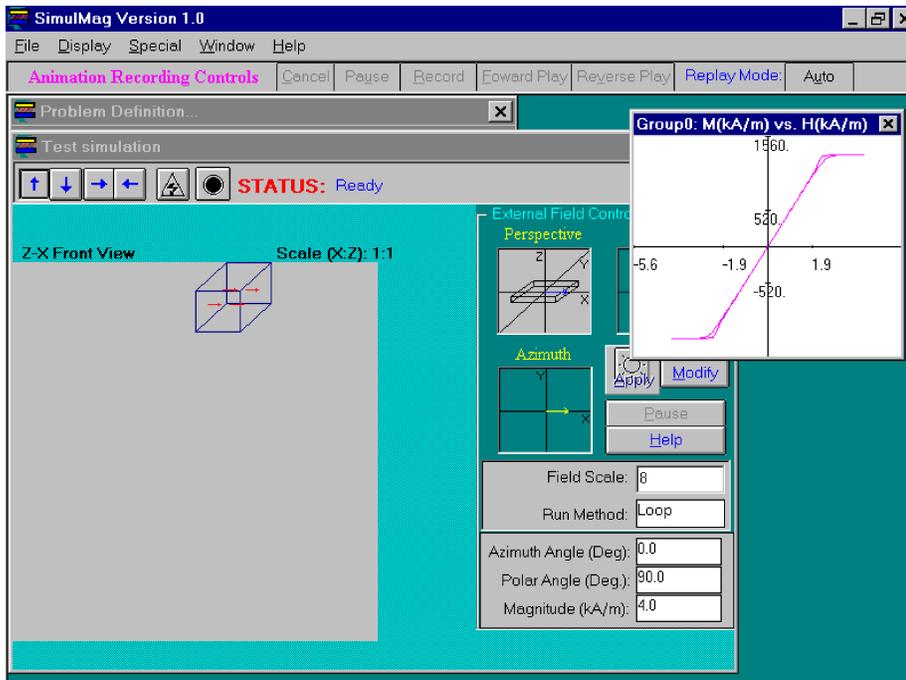


Fig. 2.8.

2.4.4. Completing the design

First let us make some modifications regarding the graphs to plot. Using the method for specifying plots described above, de-select the M vs. H curve and select the x -Component Magnetization vs. Distance (M_x vs. Dist.) and z -Component Magnetization vs. Distance (M_z vs. Dist.) curves. These selections will be more relevant to our subsequent simulation, as the cube will be brought to move among the other elements in the system. Add two new groups (1 and 2) using the specifications given below. To begin a new group, use the **New** button of the **Problem Definition** window. To add a new element to a group, use the **Add** button in its **Device Group Editor** dialog. Complete the design of a group by selecting the **OK** button of its **Device Group Editor** dialog. Group 1 consists of the elements 2, 3 and 4 in Fig. 2.1., and group 2 consists of elements 5 and 6.

(1) Group 1

Device Group Editor dialog:

Box

Entry

Title

Group of 3 different types of objects

Coordinate displacement from previous group

x (nm)	1500
y (nm)	0
z (nm)	-2000

Media Characteristics dialog for first group element (element 2 in Fig. 2.1.)

<u>Box</u>	<u>Entry</u>
Description	Nonmagnetic object
MagnetType	Nonmagnetic

Currents	
Independent	Checked
Current (mA)	5
Axis of current flow	X-Axis

Geometry	
Length (nm)	500
Width (nm)	1000
Thickness (nm)	1500

Media Characteristics dialog for second group element (element 3 in Fig. 2.1.)

<u>Box</u>	<u>Entry</u>
Description	Permanent magnet
MagnetType	Fixed Magnet

Initial Magnetic Orientation	
Azimuthal Angle (Deg.)	45
Polar Angle (Deg.)	90

Geometry

Length (nm) 1000

Width (nm) 1500

Thickness (nm) 300

Origin relative to previous element

x (nm) 1000

y (nm) 1000

z (nm) 0

Presentation

Arrow Density 1

Media Characteristics dialog for third group element (element 4 in Fig. 2.1.)**Box****Entry**

Description Normal magnet

MagnetType Magnetic

Initial Magnetic Orientation

Azimuthal Angle (Deg.) 0

Polar Angle (Deg.) 90

Geometry

Length (nm) 1000

Width (nm) 1500

Thickness (nm) 300

Origin relative to previous element

x (nm) 0

y (nm) -2500

z (nm)	-300
--------	------

Presentation

Arrow Density	1
---------------	---

(2) Group 2

Device Group Editor dialog:

Box

Entry

Title	Magnetic slabs forming parallel electric circuit
-------	--

Electric Circuit Type	Parallel
-----------------------	----------

Common Current (mA)	10
---------------------	----

Coordinate displacement from previous group

x (nm)	-1000
--------	-------

y (nm)	1000
--------	------

z (nm)	2000
--------	------

Media Characteristics dialog for first group element (element 5 in Fig. 2.1.)

Box

Entry

Description	Top element
-------------	-------------

MagnetType	Magnetic
------------	----------

Geometry

Length (nm)	2000
-------------	------

Width (nm)	1000
------------	------

Thickness (nm)	500
----------------	-----

Presentation

Arrow Density	1
---------------	---

Media Characteristics dialog for first group element (element 6 in Fig. 2.1.)

<u>Box</u>	<u>Entry</u>
Description	Bottom element
MagnetType	Magnetic
Geometry	
Length (nm)	2000
Width (nm)	1000
Thickness (nm)	500
Origin relative to previous element	
x (nm)	0
y (nm)	0
z (nm)	800

After making these entries, select from the main window the menu item `Display|Show Electrical Circuits`. The resulting view of the system is shown in Fig. 2.9. The achieved spatial displacement of the groups from each other results from the careful choice of coordinates in the dialog launched by pressing the button, **Coordinate displacement from previous group**, of the **Device Group Editor** dialog. The location of an element within a group is set by the inputs specified in the **Origin relative to previous element** group of controls of the **Media Characteristics** dialog. The coordinate system used by the program is described in *Sec. 3.2., Design Hierarchy and Coordinate System*. An *independent* electrical circuit is defined for element 2 using the **Currents** group of controls in the **Media-Characteristics** dialog. A parallel *common* circuit is defined for Group 2 by filling the **Electric Circuit Type** and **Common Current** boxes of its **Device Group Editor** dialog. Electrical circuits are discussed in *Sec. 4.1., System Electrical Circuit*. The **Arrow Density** selection represents a measure of the number of arrows to be used for drawing the magnetic state of an element. In general an arrow density of n means that $n \times n$ arrows are to be used in drawing the magnetization. Any magnetization values specified as input for nonmagnetic elements are neglected in calculations, and magnetization is also not displayed for these elements. *Fixed Magnets* are ideal permanent magnets; their magnetic states remain unchanged during a simulation.

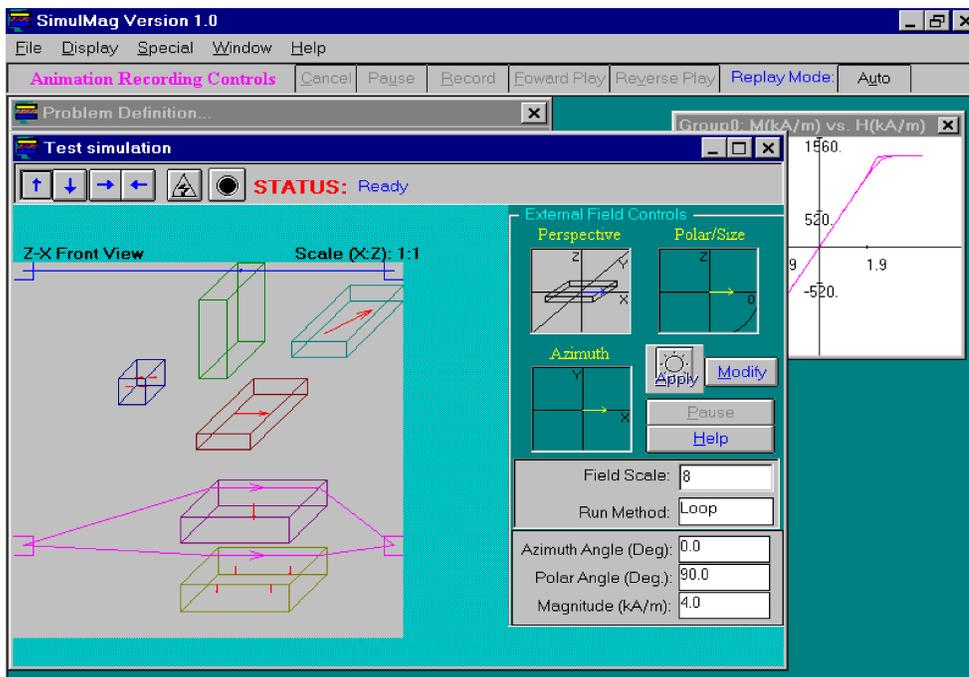


Fig. 2.9.

2.4.5. Defining motion

Motion is defined for groups. The group moves as one whole and its geometrical structure is preserved. Let us define some motion for element 1; launch its **Device Group Editor** dialog. Press the **Group Motion Specs** button, a dialog with caption “Device Motion description” is launched (Fig. 2.10.). This dialog is used to specify the motion for the group. Group motion is defined as an arbitrary sequence of displacement *legs*. A leg describes a translation along a straight line. We will define 3 legs for the cube’s motion. Legs are numbered starting from 0 onwards. We are currently ready to define leg 0 as indicated by the entry in the **Motion Leg No.** box. Enter the following inputs:

<u>Box</u>	<u>Entry</u>
Velocity Coordinates	
Azimuthal (Deg.)	0
Polar (Deg.)	90
Magnitude (nm/step)	100
No. of displacement steps	50

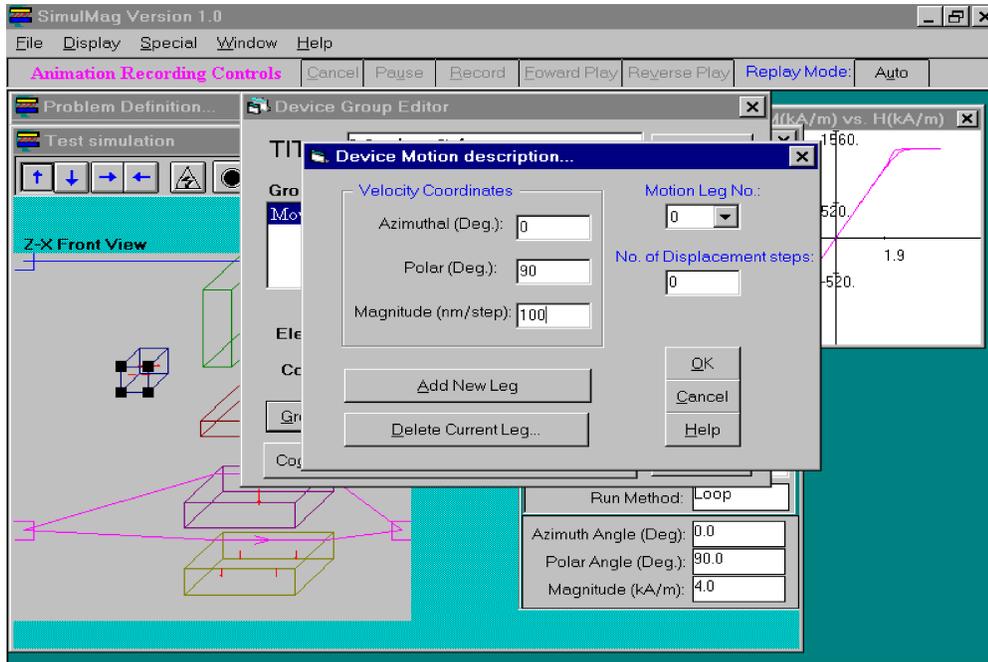


Fig. 2.10.

Above specifications define a leg consisting of fifty 100 nanometer steps in the direction given by the angular coordinates. To add the next leg, press the **Add New Leg** button and enter the following:

Box	Entry
Velocity Coordinates	
Azimuthal (Deg.)	0
Polar (Deg.)	0
Magnitude (nm/step)	100
No. of displacement steps	50

and finally define a third leg with the entries:

Box	Entry
Velocity Coordinates	
Azimuthal (Deg.)	0

Polar (Deg.)	-90
Magnitude (nm/step)	100
No. of displacement steps	50

Press the **OK** button to complete the specification of motion. Close the **Device Group Editor** dialog by pressing its **OK** button. To view the motion just defined, press the **Show Motion** button of the **System Display Window**. This is the button closest to the status bar at the top of the **System Display Window**, with a black circle in the middle. Element 1 moves according to the motion we defined and then returns to its starting position.

2.4.6. Running and recording the simulation

Our design is now complete, all that remains to be done is to run a simulation. We will simulate the interaction of element 1 with the other elements of the system, as it moves among them, in the absence of an applied external field. Remove the external field as follows: Press the **Modify** button; select *Single* from the **Run-Method** list and set all inputs to 0; close the dialog by pressing the **Accept Data** button. Press the **Apply** button to begin the simulation. After a few seconds, the windows for the previously selected M_x vs. Dist. and M_z vs. Dist. graphical plots for element 1, are launched and become hidden behind other windows. Bring them to the fore, resize and position them where they are visible, such as is done in Fig. 2.1. Now you can observe the full simulation of the interaction between the elements as element 1 moves about the system. Wait for the simulation to complete (the information on the status bar of the **System Display Window** will read “Ready,” and the caption of the **Apply** button will change from the run-time “Cancel” back to “Apply”).

Let us run the simulation again, but this time we will record it. The ability to record is particularly useful for later rapid replay and analysis of lengthy simulations which may be very time consuming to run over and over again. Recording is carried out using the **Animation Recording Controls** which are a set of buttons located just below the menu bar of the main program window. Press the **Apply** button of the **System Display Window** to repeat the simulation. When recording can begin, the **Record** button of the **Animation Recording Controls** becomes enabled and assumes a red color. Press it to begin the recording; its caption changes to “Stop.” At the end of the simulation, the caption of the **Record** button reverts back to “Record,” and the **Forward Play** button becomes enabled. Pressing the **Forward Play** button replays the saved simulation. If the design is now saved to a file, the recorded information is saved as well. The recording can be played back later on by loading in the file. A full description of recording controls is given in *Sec. 3.9., Recording of Simulations.*

3. System Design

The software imposes some structure to the design of devices. The logical design components implemented in the software are described in this chapter. Also described are the specification of system geometry, and the functions of all user-interface controls of the software. The following topics are covered in this chapter:

- ! Main program window
- ! Design hierarchy and coordinate system
- ! Specification of system
- ! Specification of element group
- ! Specification of basic element
- ! System display window
- ! Specifying motion
- ! Data output and saving data
- ! Recording of simulations

3.1. Main Program Window

The start-up screen of the program shown in Fig. 2.2., is repeated in Fig. 3.1. This screen consists of a **Main Window** (in the background with caption *SimulMag Version 1.0*), the **Problem Definition** dialog and **System Display Window** with a **System Display Pane** on which a design is drawn. These windows are described in detail later on in the chapter. The display pane is initially empty. The main window consists of a menu and a set of **Animation Recording Controls**. These later controls which are used to record and playback animations of calculations are described in detail in *Sec.3.6. System Display Window*. Some of the menu items of the main window (File|Exit, Window|Cascade, etc.) play their usual standard roles in Windows' applications. The functionality of the other menu items are described below.

3.1.1. File

New Problem. Resets the program and user interface in readiness for the design of a new problem consisting of a system of objects. If this item is selected in the middle of a design that has not been saved, the user is prompted for verification on whether the current design should be deleted

or not.

Open. Prompts for a *problem file* to open. A problem file contains the full description of the geometric, magnetic and electric properties, and recording information of a design that was saved using the software. Problem files by convention have the default extension *mms*. Problem files are in ASCII format.

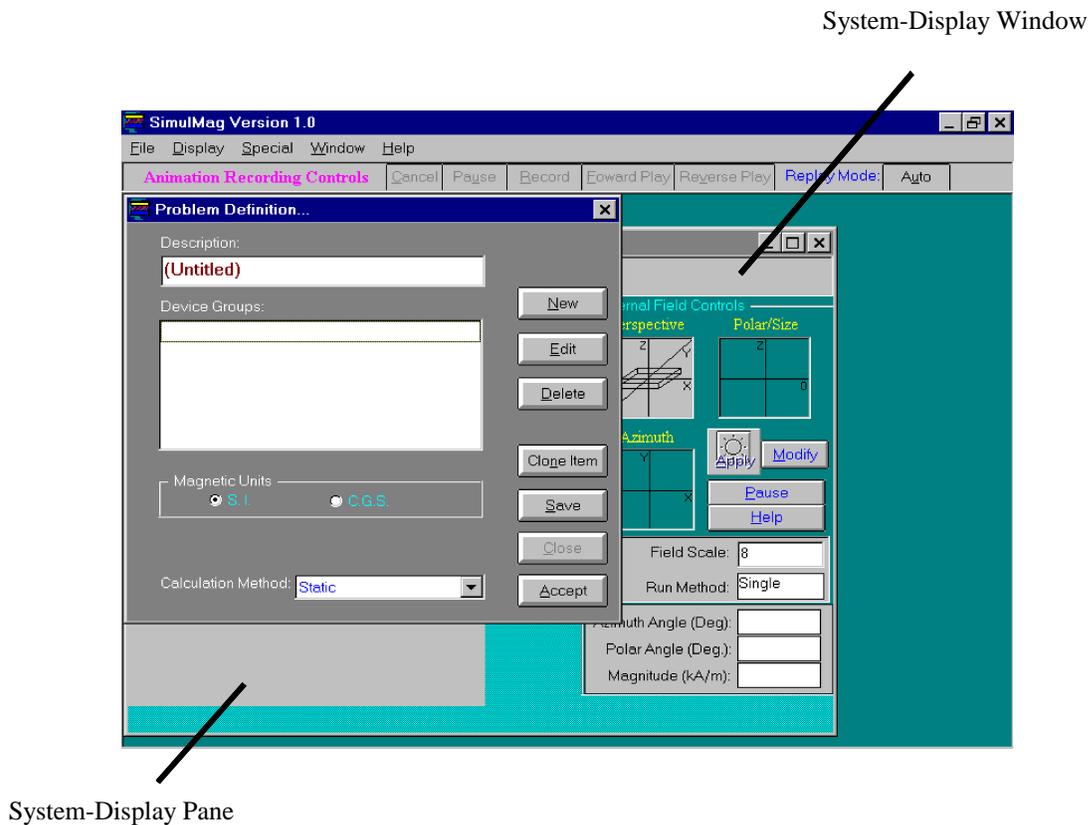


Fig. 3.1. Main program window

Save. Saves the design to a problem file. This is the file specified during a previous save of the problem, or the source file for a problem that was loaded using the `File | Open` menu item. If this is the first time the problem is being saved, the user is prompted for the name of the problem file to save the design to.

SaveAs. Prompts the user for the name of a problem file to save the design to.

Print. Sends to a printer the drawing and summary information of a design displayed on the **System Display Window**. Printers are specified using the `File | Print-Setup` menu item,

3.1.2. Display

Display Problem Window. Displays the **Problem Definition** dialog. This is useful in cases when the **Problem Definition** dialog has been inadvertently closed and the user needs to define new group items or modify old ones (see [Sec. 3.2.](#) for definition of groups).

Show Magnetization Vectors. Checking this item displays on the **System Display Window**, the magnetization vectors of all magnetic objects. This item is checked by default for a new design.

Show Electrical Circuits. Checking this item displays on the **System Display Window**, the electrical circuits specified in the design.

Show Pinning Fields. Checking this item displays on the **System Display Window**, the directions of characteristic *pinning fields* defined for magnetic objects of the design.

Show Uniaxial Magnetic Anisotropy Axes. Checking this item displays on the **System Display Window**, the directions of *uniaxial magnetic anisotropy axes* defined for magnetic objects of the design.

3.1.3. Special

Save Calculation Results. Prompts the user for the calculated data to save and the file name to save the data to (see [Sec. 3.8. Data Output and Saving data](#)).

3.2. Design Hierarchy and Coordinate System

3.2.1. Elements, Groups and System

The software uses a “top-down” design hierarchy for specifying and organizing the components of the *system* representing the problem to simulate, and for specifying the nature of output to generate. In this approach the basic design unit is an *element* shaped as a rectangular prism. The element is oriented parallel to the coordinate axes of the system (see [Sec. 3.2.2. Coordinate System](#)); the element may be *magnetic* or *nonmagnetic*, and may be an *electrical conductor* or an *insulator*. A magnetic element is a *single-domain element*, which means that it is uniformly magnetized and can thus be characterized by a single three-dimensional magnetization vector. Magnetic elements are further classified as *ferromagnetic* and *fixed-magnetic* elements. The magnetization vector of a ferromagnetic element is free to rotate in three dimensions under the influence of magnetic fields; the magnetization vector of a fixed-magnetic element remains always fixed in space.

The elements are organized into logical *element groups* or *groups* for short. A system in general is composed of several groups. Output data is calculated separately for each group and the groups may

be brought to relative motion with each other. Simple electrical circuits can be defined for each group (see *Sec. 4.1. System Electrical Circuits*). A three-dimensional wire-frame rendering of the system with all its elements is drawn on the **System Display Window** (see *Sec. 3.6.*).

The classification of elements into groups facilitates the design of systems composed of functionally separate devices. Groups can vary widely in complexity, from the simplest group consisting of a single element, to one composed of many elements with different shapes and sizes and different electrical and magnetic properties. The careful choice of the dimensions and properties of elements of the groups permits the modeling of a wide range of technologically interesting systems (see *Chapter 5, Design Examples*). Groups are defined for the system using the **Problem Definition** dialog (*Sec. 3.3.*) and elements are added to a group using the **Device Group Editor** (*Sec. 3.4.*). The properties of an element are specified using the **Media Characteristics** dialog (*Sec. 3.5.*) . Usually the **Media Characteristics** dialog is launched from the **Device Group Editor**, which in turn is launched from the **Problem Definition** dialog. Views of these dialog controls are shown in Fig. 3.2. An ordering is defined for the elements making up a group and for the groups making up the system. The program uses an ordinal numbering scheme starting with 0, to identify elements and groups. The *first element* of a group (element 0) is the one listed first in its **Device Group Editor**, the second element (element 1) is the one listed second, etc.; the *first group* of a system (Group 0) is the one listed first in the **Problem Definition** dialog, etc.

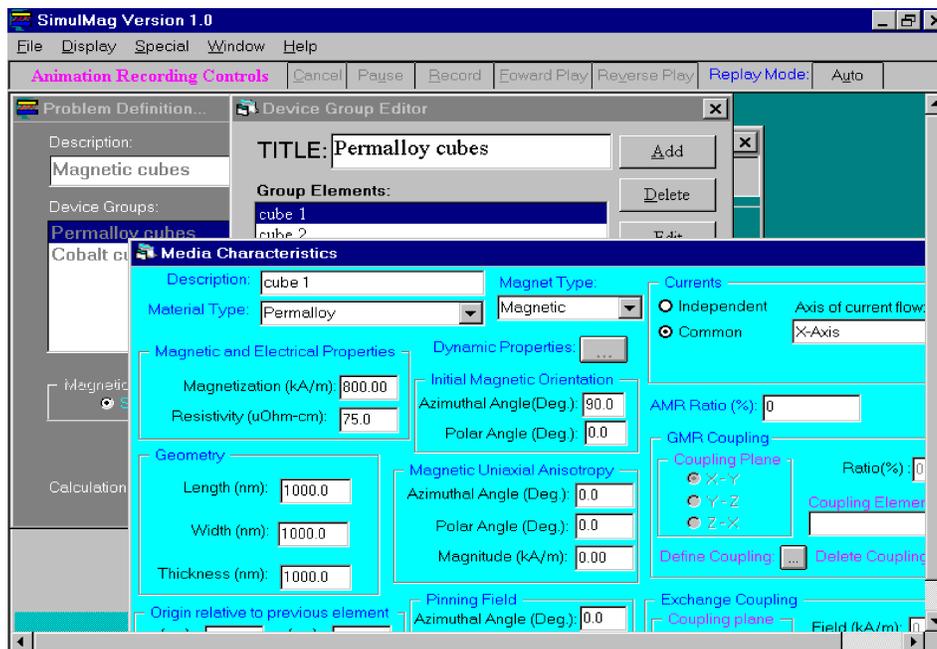


Fig. 3.2. Problem Definition, Device Group Editor and Media Characteristics dialogs.

3.2.2. Coordinate system

A Cartesian coordinate system xyz is defined for the system being modeled. Figure 3.3. shows how it is oriented relative to the *front* view of the **System Display Pane**. Also shown in the figure are definitions of spherical angular coordinates (*azimuthal* and *polar*) which are used in the software to specify directions relative to the coordinate system. The y -axis is inclined at an angle to the x -axis in Fig. 3.3., to conform to the three-dimensional perspective way of displaying elements. This angle by default is 45° but may be changed to a different value using the **Scale Factors** dialog (see Sec. 3.4.). Several views of the system (*front*, *back*, *right* and *left*) can be displayed on the **System Display Window** (see Sec. 3.4.). The discussion in this section applies to the front view.

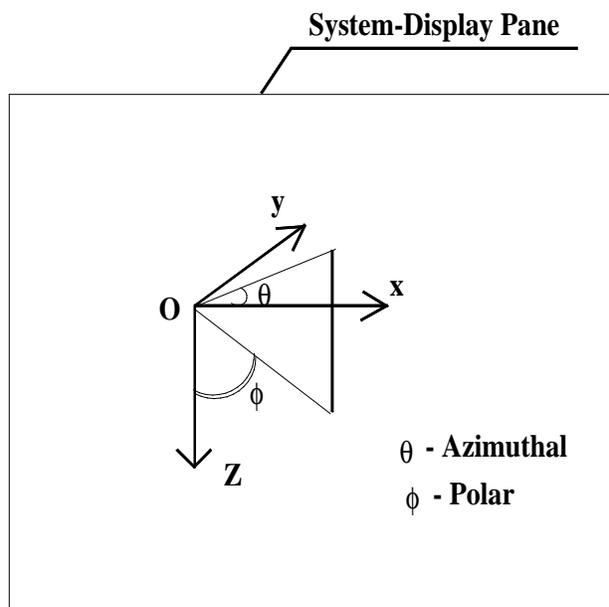


Fig. 3.3. Coordinate system.

For an empty system (one containing no elements) the origin of coordinates is located at the center of the top edge of the **System Display Pane**. The location of the origin in the pane may change as elements are added to the system. This is because the pane is continually re-scaled so as to *always* accommodate the whole system as new elements are added.

The origin of an element is defined as the front-top-left corner of the element. The origin of a group is the origin of its first element. The relative displacement of origins of groups from each other are specified using the **Device Group Editor**. The relative displacement of an element within a group is specified using the **Media Characteristics** dialog.

3.3. Specification of System

Groups are introduced into a system using the **Problem Definition** dialog shown in Fig. 3.4. This dialog is displayed whenever the program is first ran. It can also be displayed at any time by selecting the `Display | Display-Problem-Window` menu item in the main application window (see [Sec. 3.1. Main Program Window](#)). The **Description** box provides a means for the user to enter a textual description of the system being designed. It contains the entry "Magnetic objects" in the figure. This information is displayed in the caption of the **System Display Window** when the system is drawn. The **Device Group** list shows the groups that have been defined for the system. The system in Fig. 3.4. contains the groups "Copper slab," "Permalloy cube" and "Biased magnet." The method of calculation (*static* or *dynamic*, see [Chapter 4](#)) is selected from the **Calculation Method** drop-down list. The **Magnetic Units** group provides a means for specifying the units (**S.I.** or **C.G.S.**) in which the program is to interpret magnetization and magnetic field quantities, and in which magnetic data is to be generated and displayed. The default selection is **S.I.** The S.I. unit for magnetization and magnetic field is A/m. In C.G.S. units magnetization is expressed in emu/cm³ and field is expressed in Oe. All relevant dialog boxes and graphs will display (and will be re-drawn if necessary to display) magnetic units in accordance with the system of units that is chosen.

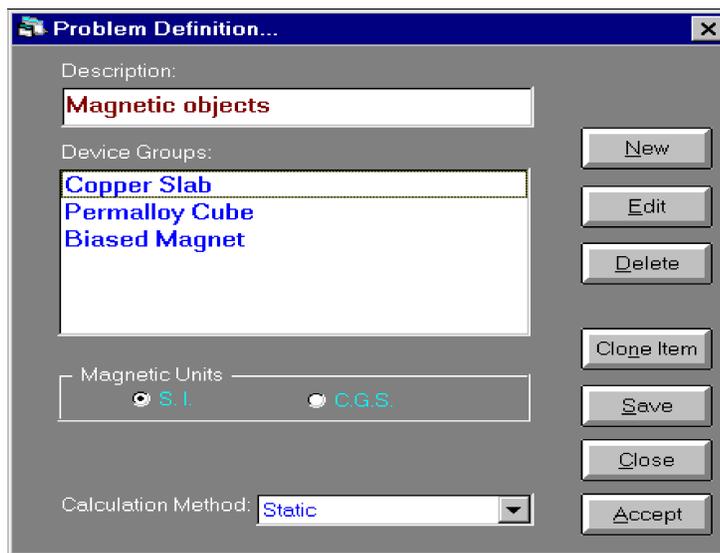


Fig. 3.4. Problem-Definition dialog

The functionality of the buttons on the dialog are as follows:

New. Initiates the definition of a new group of the system. The user is first prompted for the name of the new group and then the **Device Group Editor** dialog is launched for specifying the

components of the group. A default group name "(Noname#)" is generated, where "#" is the ordinal number of the group in the system. This name which can be modified by the user, is displayed in the **Title** box of the **Device Group Editor** (see [Sec. 3.4](#)); it is the last entry displayed after the group has been added. The **System Display Window** is redrawn to reflect the changes made to the system after a group is added.

Edit. Launches the **Device Group Editor** dialog for a group selected in the **Device Group** list.

Delete. Deletes a group that is selected in the **Device Group** list. The user is prompted for verification of the deletion. After a group is deleted, its entry in the **Device Group** list is removed and the **System Display Window** is redrawn to reflect the changes made to the system.

Clone Item. Clones (replicates identically) a group that is selected in the **Device Group** list and launches the **Device Group Editor** dialog for the new group. The new group is given the name "Copy of xxx," where "xxx" is the name of the group cloned.

Save. Performs the same function as the **File | Save** menu item of the **Main Window** (see [Sec. 3.1. Main Program Window](#)).

Accept. Redraws system in **System Display** window.

3.4. Specification of Element Group

The specification of a group entails the addition and specification of the geometric and electromagnetic characteristics of the elements making up the group. The addition of elements and the specification of certain group properties are carried out by means of the **Device Group Editor** dialog shown in Fig. 3.5. The **Media Characteristics** dialog described in [Sec. 3.5](#) is used to define the properties of an element. A textual description of the group can be entered in the **Title** box. When the editing is complete the contents of this field is listed in the **Device Group** list of the **Problem Definition** dialog (see [Sec. 3.1](#)). The **Group Elements** list shows the elements that have been defined for the group. The specification of a serial or common electrical circuit connection for elements of the group is carried out using the **Electrical Circuit Type** list, and the current that will flow through the circuit is specified in the **Common Current** box. A description of electrical circuits is given in [Sec. 4.1., System Electrical Circuit](#). The functionality of the buttons on the dialogs are as follows:

Add. Initiates the addition of a new element to the group by launching a default **Media Characteristics** dialog for specifying the properties of the new element (see [Sec. 3.5](#)). The entry for a new element appears as the last entry in the **Group Elements** list.

Delete. Deletes from the group an element selected in the **Group Elements** list. The user is prompted for verification of the deletion. After an element is deleted its entry is removed from the

Group Elements list.

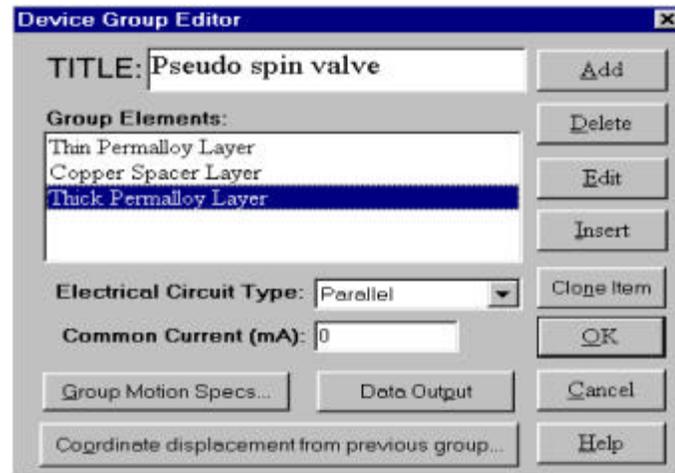


Fig. 3.5. Device-Group Editor dialog.

Edit. Launches the **Media Characteristics** dialog for an element selected in the **Group Elements** list.

Insert. Initiates the insertion of a new element one position behind an element selected in the **Group Elements** list, by launching a default **Media Characteristics** dialog for specifying the properties of the new element.

Clone Item. Clones (replicates identically) an element that is selected in the **Group Elements** list and launches the **Media Characteristics** dialog for the new element. The new element is given the name "Copy of xxx," where "xxx" is the name of the element cloned.

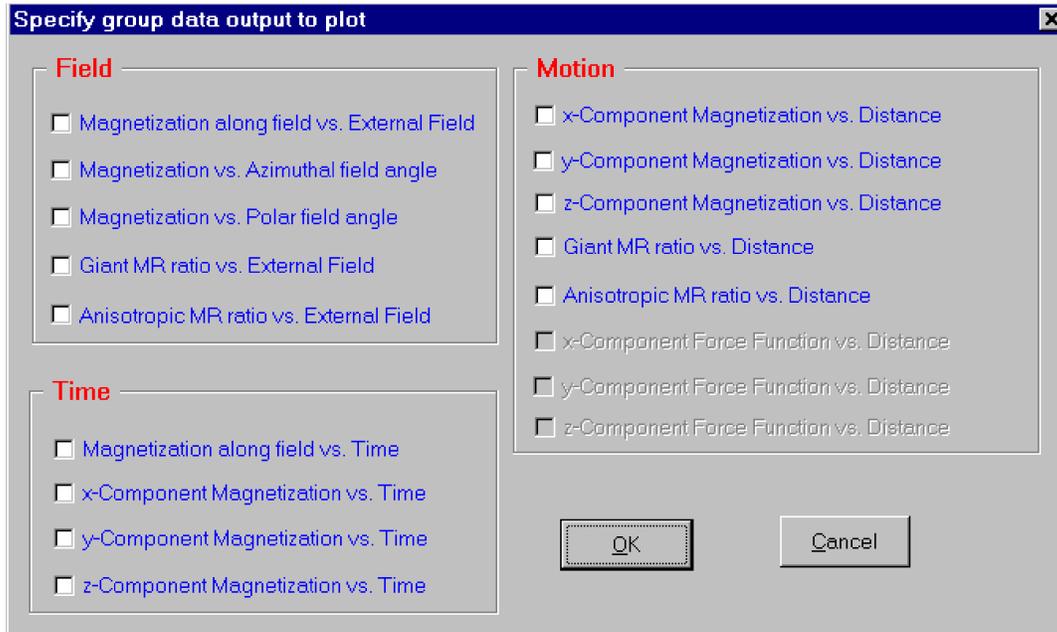
Data Output. Launches the dialog shown in Fig. 3.6. for selecting group data output that are to be plotted during calculations. The organization of output data is described in ***Sec. 3.8., Data Output and Saving Data.***

OK. Closes the **Device Group Editor** dialog and retains all changes that were made to the group.

Cancel. Closes the **Device Group Editor** dialog and discards all changes that were made to the group. The user is prompted for verification to proceed if any changes were made to the group.

Group Motion Specs. Launches a dialog for specifying motion for the group. This dialog is described in ***Sec. 4.7. Specifying Motion.***

Coordinate displacement from previous group. Launches the dialog shown in



**Fig .
3.6.**

Fig. 3.7. for specifying the displacement of the current group from the one a position behind it in the system (see [Sec. 3.2.2. Coordinate System](#)).

3.5. Specification of Basic Element

The properties of an element in a group are defined using the **Media Characteristics** dialog shown in Fig. 3.8. The **Description** box is used for entering a textual description of the element, and becomes the entry for the element in the **Group Elements** list of the **Device Group Editor** dialog (see [Sec. 3.4](#)). The element magnetic type (*Magnetic*, *Nonmagnetic* and *Fixed Magnet*, see [Sec. 3.2](#)) is selected using the **Magnet Type** drop-down list. The **Material Type** drop-down list is used to select pre-defined material profiles (for *Cobalt*, *Copper*, *Permalloy* and *Other*). Each selection fills the fields of the **Magnetic and Electrical Properties** group with typical bulk values appropriate for the chosen material profile, and selects an appropriate type from the **Magnet Type** drop-down list. The selection, *Other*, is redundant in the current version of the program, but may be useful in future versions. The properties of the elements can be manually changed regardless of the material profile selected. The functionality of the remaining group of controls and buttons are as follows:

Geometry. Used for the specification of the linear dimensions of the element. The length is measured along *x*-axis, the width - along the *y*-axis and the thickness - along the *z*-axis.

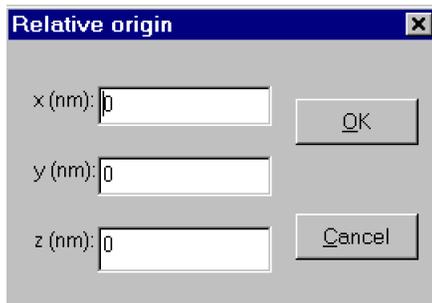


Fig. 3.7.

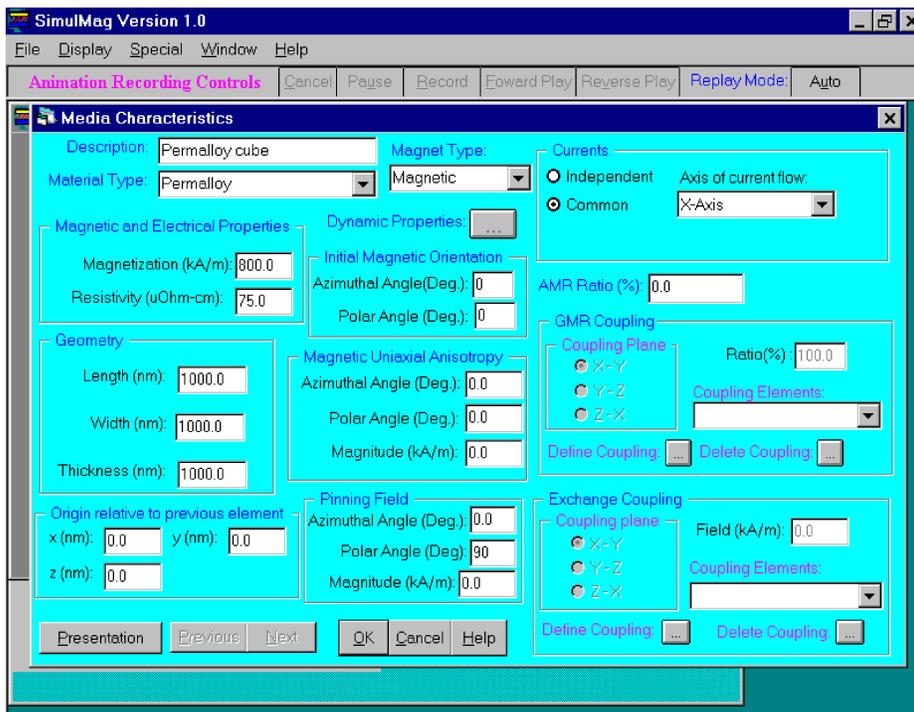


Fig. 3.8. Media-Characteristics dialog.

Origin relative to previous element. Used for the specification of the origin of the element relative to that of the one a position behind it in the group (see *Sec. 3.2.2. Coordinate System*).

Dynamic Properties. This button is enabled only if the calculation method is dynamic. Pressing it launches a dialog box that permits the specification of dynamic characteristics of the element. These characteristics are the *Damping Constant* and the *Gyromagnetic Ratio* (see [Sec. 4.2.2. Dynamic Calculation](#)).

Presentation. Pressing this button launches a dialog that permits making the following changes to the drawing of an element on the **System Display Window**: Changing the color with which the outline of the element is drawn; changing the color with which the magnetization arrow of the element is drawn; changing the *arrow density* of the element. The magnetization arrows are centered at points that are uniformly distributed on a rectangular grid pattern in the mid-plane of the element, parallel to the x - y plane. The arrow density is defined as the number of arrows on a side of this grid. The default arrow density for an element is 2. When an element with this value is drawn, 4 arrows are displayed. For an arrow density of 1, one arrow is displayed and in general for an arrow density of n , $n \times n$ arrows are displayed. The components of an arrow along the coordinate axes are drawn using scales that are proportional to the corresponding sides of the element.

Initial Magnetic Orientation. Used for the specification of the initial angular coordinates (*azimuthal* and *polar*) of the magnetization vector of the element.

Magnetic Uniaxial Anisotropy. Used for the specification of the angular coordinates (*azimuthal* and *polar*) and magnitude of the magnetic uniaxial anisotropy of the element (see [Sec. 4.4.5. Uniaxial Magnetic Anisotropy field](#)).

Pinning Field. Used for the specification of the angular coordinates (*azimuthal* and *polar*) and magnitude of the characteristic unidirectional pinning field of the element (see [Sec. 4.4.3. Pinning field](#)).

Currents. Used for defining the electrical circuit that the element belongs to and the way the element is connected in the circuit. For a description of electrical circuits that can be defined in a system see [Sec. 4.1. System Electrical Circuit](#).

AMR Ratio. Used for defining the anisotropic magnetoresistive (AMR) ratio of the element. For a detailed description of the modeling of giant magnetoresistance see [Sec. 4.5.3. Anisotropic Magnetoresistive \(AMR\) Ratio](#).

GMR Coupling. Used for defining giant magnetoresistive (GMR) coupling with other elements in the group. A new coupling is defined by clicking the **Define Coupling** button which launches a dialog that enables the selection of an element to couple to. The **Coupling Plane** group is used to specify the plane over which the coupling occurs, and the **Ratio** box holds a model-dependent GMR parameter. For a detailed description of the modeling of giant magnetoresistance see [Sec. 4.5.2. Giant Magnetoresistive \(GMR\) Ratio](#). The **Coupling Elements** drop-down list contains all elements being coupled to. The coupling-plane and ratio information for each coupling is displayed in the appropriate boxes for each item selected from the **Coupling Elements** drop-down list. An arbitrary

number of couplings can be defined. This includes any number of couplings with the one and the same element, and the coupling of the element being edited with itself. An element selected in the **Coupling Elements** drop-down list can be removed from this list by clicking the **Delete Coupling** button. The user is prompted for confirmation before the deletion takes place.

Exchange Coupling. Used for defining exchange coupling with other elements in the group. A new coupling is defined by clicking the **Define Coupling** button which launches a dialog that enables the selection of an element to couple to. The **Coupling Plane** group is used to specify the plane over which the coupling occurs, and the **Field** box holds the magnitude of the exchange-coupling field. For a detailed description of the modeling of exchange interaction field see [Sec. 4.4.4. Exchange Interaction Field](#). The **Coupling Elements** drop-down list contains all elements being coupled to. The coupling-plane and field information for each coupling is displayed in the appropriate boxes for each item selected from the **Coupling Elements** drop-down list. An arbitrary number of couplings can be defined. This includes any number of couplings with one and the same element, and the coupling of the element being edited with itself. An element selected in the **Coupling Elements** drop-down list can be removed from this list by clicking the **Delete Coupling** button. The user is prompted for confirmation before the deletion takes place.

Previous. Pressing this button displays on the **Media Characteristics** dialog the properties of an element one group position behind the current element. All changes that were made in the characteristics of the replaced element are retained.

Next. Pressing this button displays on the **Media Characteristics** dialog the properties of an element one group position ahead of the current element. All changes that were made in the characteristics of the replaced element are retained.

3.6. System-Display Window

The **System Display Window** (Fig. 3.9.) is used for displaying a three-dimensional image of the system and providing the interface for simulating the application of magnetic fields to the system. The window consists of several controls, buttons and displays: The **System Display Pane**, **View** buttons, the **Scale** button, the **Show Motion** button, the **Status bar** and **Field Controls**.

3.6.1. System Display Pane

A three-dimensional wire-frame drawing of the elements making up the system is displayed on the **System Display pane** together with the magnetization vectors, electrical circuits, uniaxial magnetic anisotropy axes and pinning field directions. The magnetization vectors are drawn by default for a new design using an arrow density of 2 (see [Sec. 4.5.](#)). Electrical circuits, magnetic anisotropy axes, pinning field directions are displayed by choosing the appropriate selection from the main program window menu (`Display|Show Electrical Circuits` etc., see [Sec. 3.1.](#)). An element is selected by clicking once anywhere within its front-most face. This is indicated by displayed handles in the form of small black rectangles drawn at the corners of the side of the element. The handles

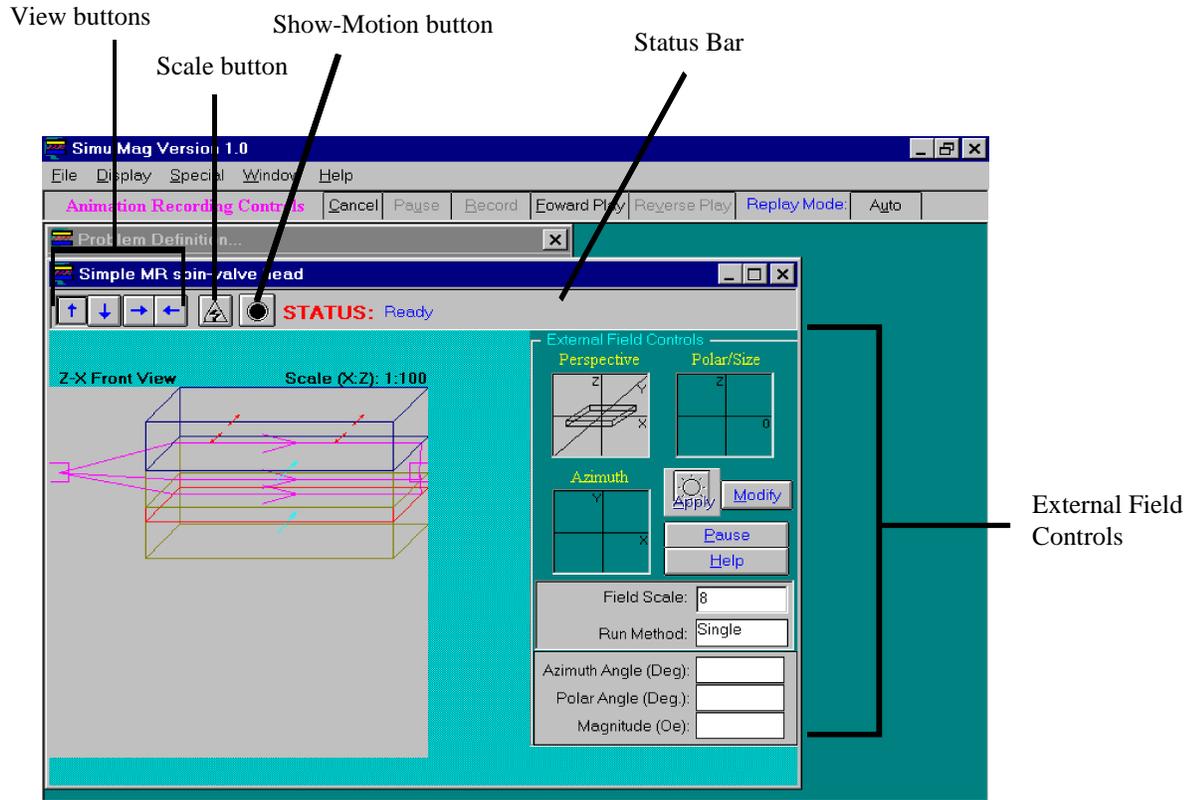


Fig. 3.9. System-Display Window

currently serve the limited role of visually highlighting the selected element. This may change in future versions of the software where the handles may become useful for implementing mouse-driven interactive resizing and moving of elements in the **System Display Pane**. Clicking once with *right* mouse button on the face of an element, launches a window displaying information about the magnetic, electrical and geometric properties of the element, its coupling properties and the components of internal magnetic interaction fields acting on it (window with caption “Group 0: Copper spacer layer” in Fig. 3.10). This is the *Material Profile* window of the element. Double-clicking the front face of an element launches the **Device Group Editor** dialog for the group to which the element belongs, and the entry for the element is selected in the **Device Group** list of the dialog (see [Sec. 3.4](#)).

3.6.2. View, Scale and Show-Motion buttons. Status bar

The **View** buttons are used to display different views of the system on the **System Display Pane**. These are the *front*, *back*, *left* and *right* views. The front and back views are the views of the system seen by an observer looking from the negative and positive *y*-directions; the left and right views are the views from the negative and positive *x*-directions. Pressing the **Scale** button launches a dialog

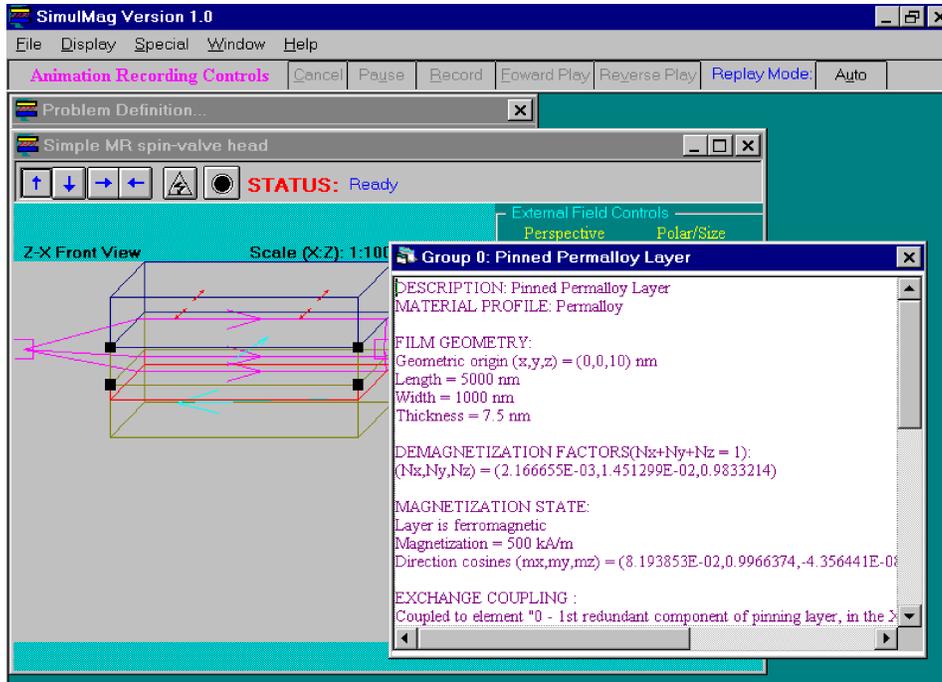


Fig. 3.10. Material Profile window.

that is used to define by how much the displayed system is to be “stretched” or “shrunk” horizontally or vertically, and the angle of inclination of the y -axis from the x -axis used in the three-dimensional perspective drawing of the system. The re-scaling of the drawing only alters its appearance on the **System Display Pane**, the physical dimensions of the system remain the same. This feature is particularly useful for displaying those elements of a system having some of their linear dimensions many orders of magnitude larger than others. This is for example the case with elements in the form of *thin films*. Information on the current view and scaling of the drawing is printed at the top of the **System Display Pane**.

Pressing the **Show Motion** button displays any motions that have been defined for the groups making up the system (see *Sec. 3.7. Specifying Motion*). The system is reset to its initial state when the display is complete. A display in progress can be terminated at any time by pressing the **Show Motion** button again. The system is returned to its initial state after the termination. The **Status Bar** prints information about the status of on-going calculations and the replay of recorded simulations (see Table 3.1.) and also displays coordinate information of data plots.

3.6.3. External Field Controls

The **External Field Controls** provide the interface for simulating the interactive application of external magnetic fields to a system. The magnitude and angular coordinates of the field to apply

TABLE 3.1. Status Bar Messages

Message	Meaning
Backward Replay	Recorded simulation is currently being replayed forward
Forward Replay	Recorded simulation is currently being replayed backward
Kill Signal sent	Termination of a simulation is currently underway, after the user have pressed the Apply button of the External-Field Controls (now with caption “Cancel”) in the middle of a simulation
Paused	The currently running simulation is paused after the user have pressed the Pause button of the External Field Controls in the middle of a simulation
Ready	The physical model is idle and ready for further simulation
Recording Paused	A recording currently being played back is paused after the user have pressed the Pause button of the Animation Recording Controls
Run terminated	The simulation was terminated by the user pressing the Apply button of the External Field Controls (now with caption “Cancel”) in the middle of a simulation
Simulation Running	A simulation is currently in progress
Updating Tables	The physical model is updating a table of parameters that are used in the calculations
Group <i>n</i> : [<i>plot caption</i>]: [<i>plot coordinates</i>]	Generic message format when the left mouse button is held down in a graphical output plot window: <i>n</i> is group number of the plot. For example the status bar message from holding down the left mouse button over an M vs. H plot might read “Group 0: M (kA/m) vs. H (kA/m): -381.4 : 6.4 ”

can be specified by clicking with the mouse anywhere in the two windows labeled **Polar/Size** and **Azimuthal**. On clicking at a point in the **Polar/Size** window, an arrow is drawn from the origin to that point to reflect the new polar coordinate and magnitude of the field to apply. An arrow drawn from the origin of the **Azimuthal** window represents the projection of the field on the azimuthal (x - y) plane. Clicking in this window changes the orientation (the azimuthal coordinate) of the arrow but not its length. The new orientation is such that the arrow lies on the straight line connecting the origin to the point at which the mouse was clicked. The length of the arrow in the **Azimuthal** window changes to conform to any changes in the **Polar/Size** window. The **Perspective** window displays a three-dimensional schematic of the relative orientation of the system and the applied field (represented by an arrow drawn in perspective in the window).

A field that has been defined is applied to the system by pressing the **Apply** button. This invokes the underlying *physical model* of the program to calculate the response of the system (see [Chapter V, Detailed Description of Model and Calculations](#)). For *static* calculations the new magnetic state of the system is displayed on the **System Display Pane** when the calculation is complete and the system is at an equilibrium state. For *dynamic* calculations the time evolution of magnetization changes between equilibrium states, is continually displayed. During calculations the caption on the **Apply** button changes to “Cancel.” Pressing the button again in this state terminates the calculation and the caption is changed back to “Apply.” The external magnetic field is applied uniformly throughout the system. Pressing the **Pause** button pauses an ongoing simulation, and the button caption changes to “Continue”; pressing the button again continues the simulation. Three labeled boxes located in the lower part of the **External Field Controls** display the current angular coordinates and magnitude of the magnetic field. The magnitude of the half-widths of the **Perspective** and **Polar/Size** windows is given by the entry in the **Field Scale** box. This can be changed by the user and permits the application of a range of fields using the mouse.

Several types of external field sequences can be applied to a system. These are distinguished from each other by their *modes* which is displayed at the **Run Method** field of the **Field Controls**. Three modes are defined: *Single*, *Loop* and *Rotation* modes. A Single mode refers to the one-time application of a field. Applying a field with the mouse as described above is an example of using the single-mode method. The Loop mode refers to the application of a closed field excursion to the system in a fixed direction in space. In the Rotational mode a fixed-magnitude field which rotates in space is applied to the system. All three modes can be specified by pressing the **Modify** button which launches the **Field Data** dialog which can be any of the three shown in Fig. 3.11., depending on the selection of the **Run Method** drop-down list. Applying a field by this means, in contrast with using only the mouse, permits the user to be more specific about the field to apply in Single mode. In the Loop mode, the external field is uniformly decremented (or incremented as the case may be) from the maximum field to the minimum field and back to the maximum field in a number of equal incremental steps specified in the **No. of Data Points** box. In the Rotation mode the polar and azimuthal coordinates of the field vary through the specified ranges in a number of steps indicated in the **No. of Data Points** box. After exiting the dialog the system as before can be subjected to the defined field sequences by pressing the **Apply** button of the **External Field Controls**. The states of the system in response to a sequence of external fields and field information are continually

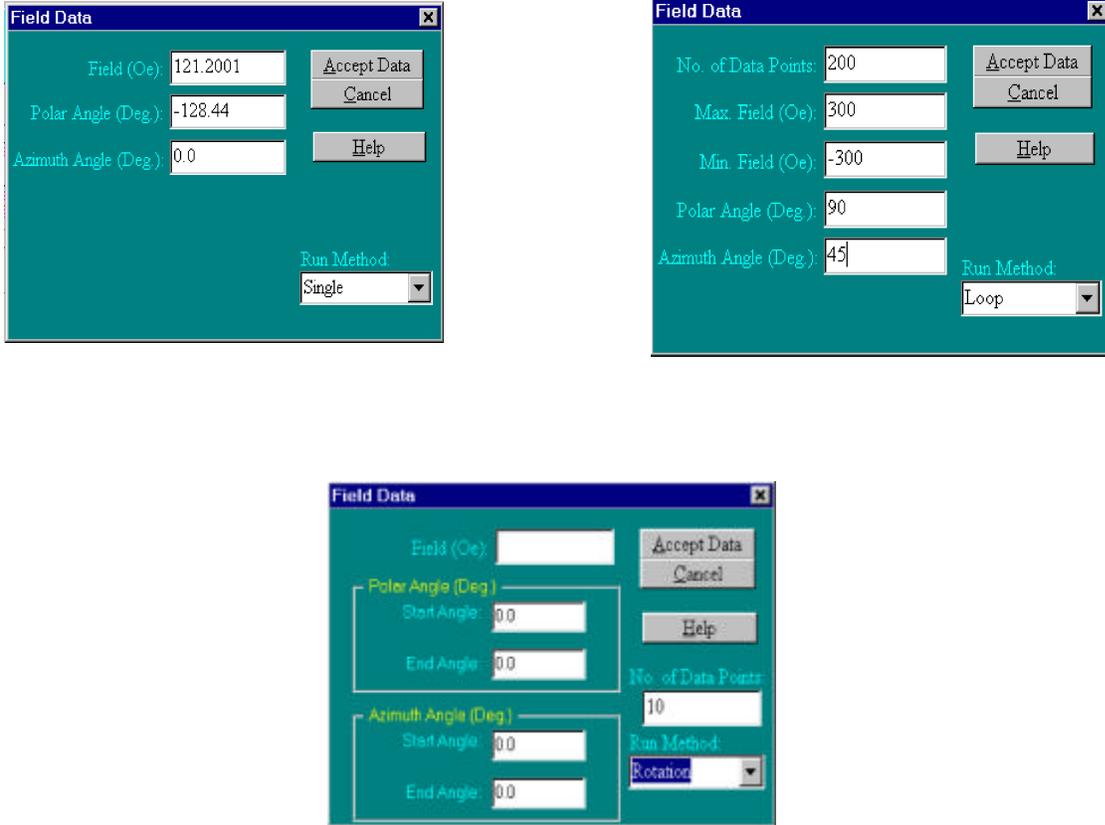


Fig. 3.11. Field-Data dialogs.

updated in the **System Display Pane** and the **Field Control** boxes. This produces an animation effect of the simulation. During calculations plot windows are launched to display any requested data plots specified for the groups of the system (see [Sec. 3.4. Specification of Element Group](#)).

3.7. Specifying Motion

The groups making up a system can be made to move around in space. A sequence of translational motion of virtually any complexity can be defined for a group. This capability permits the simulation of many types of practical systems consisting of interacting objects in relative motion with each other. [Chapter V, Design Examples](#), describes a variety of simulations of interacting devices in motion. The motion of a group is defined in its **Device Group Editor** dialog by pressing the **Group Motion Specs** button (see [Sec. 3.4](#)). This launches the dialogs shown in Fig. 3.12. The full motion for a group consists of a sequence of *legs* each of which defines the translation of the group in a straight line along a certain direction. Each leg is characterized by the velocity

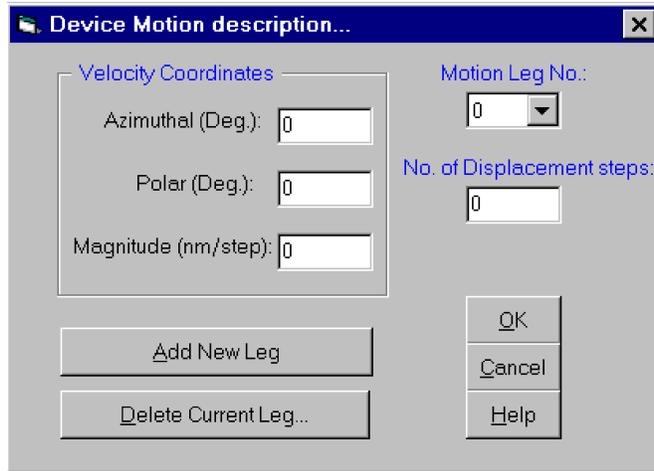


Fig. 3.12. Motion-specification dialog.

coordinates specified using the **Azimuthal**, **Polar** and **Magnitude** boxes, which define the direction and rate of motion for the sequence. The number of displacement steps making up a leg is entered in the **No. of Displacement steps** box. The magnitude of velocity in a leg is expressed in *Distance-per-Step*. For dynamic calculations, the desired time between equilibrium states is entered in the **Time interval between equilibrium states** box. A new leg is defined by pressing the **Add New Leg** button. Defined legs are listed in the **Motion Leg No.** drop-down list and are numbered starting from 0. A selected leg in the **Motion Leg No.** list is removed by pressing the **Delete Current Leg** button. The user is prompted for verification before the deletion takes place.

A visual display of motions defined for a system can be viewed by pressing the **Show Motion** button in the **System Display** window (see [Sec. 4.6.](#)). During simulations the system is calculated to equilibrium at each step of a motion leg.

3.8. Data Output and Saving Data

3.8.1. Output Data Organization

The output generated by the program for a group are organized into three categories:

1. Field

- Magnetization along field vs. External field
- Magnetization along field vs. Azimuthal field angle
- Magnetization along field vs. Polar field angle
- Giant MR ratio vs. External Field

Anisotropic MR ratio vs. External Field

2. Motion

x-Component magnetization vs. Distance
y-Component magnetization vs. Distance
z-Component magnetization vs. Distance
Giant MR ratio vs. Distance
Anisotropic MR ratio vs. Distance

3. Time

Magnetization vs. Time
x-Component magnetization vs. Time
y-Component magnetization vs. Time
z-Component magnetization vs. Time

The calculation of output data is described in detail in [Sec. 4.5. Calculation of Model Output](#). All output are always calculated for all groups, but the ones whose graphs are displayed during a simulation or the playback of recorded data, are those specified by pressing the **Data Output** button in the **Device Group Editor** dialog for the group (see [Sec. 3.4.](#)). The output in the *Field* category are plotted as functions of the applied external field specified by the **External Field Controls** (see [Sec. 3.6.3.](#)), and number of data points is the number of field points specified. In the *Motion* category, the output is generated as function of the total distance traveled due to motion specified using the **Device Motion Description** dialog (see [Sec. 3.7.](#)); the number of data points for this category is the total number of displacement points for all the motion legs specified for the group. The *Time* category which applies to dynamic calculations only, calculates the magnetization as a function of elapsed time. When motion is specified in a system that is also subjected to an external field sequence, a step change in the position of the groups due to motion and a step change in field occur simultaneously. All output data for a simulation can be saved to file by selecting the `Special|Save Calculation Results` menu item of the main program window (see [Sec. 3.1.](#)). This launches a dialog (Fig. 3.13.) that enables the specification of the group data and data category to save.

3.8.2. Graphical-Plot Window

Graphs of data output for a group that were specified using the *Device-Group Editor* dialog are plotted during a calculation or the play back of a recorded simulation. Fig. 3.14. shows a plot window containing the *Magnetization along field vs. External field* plot of a simulation. Pressing and holding down the *left* mouse button anywhere within the plot displays on the **Status-Display Area** of the *System-Display Window* (see [Sec. 3.6.](#)) information on the coordinates (in plot units) of the location of the mouse pointer. Holding down the right mouse button within the window displays a pop-up menu that can be used to save the plotted data to file or print the graph.



Fig. 3.13.

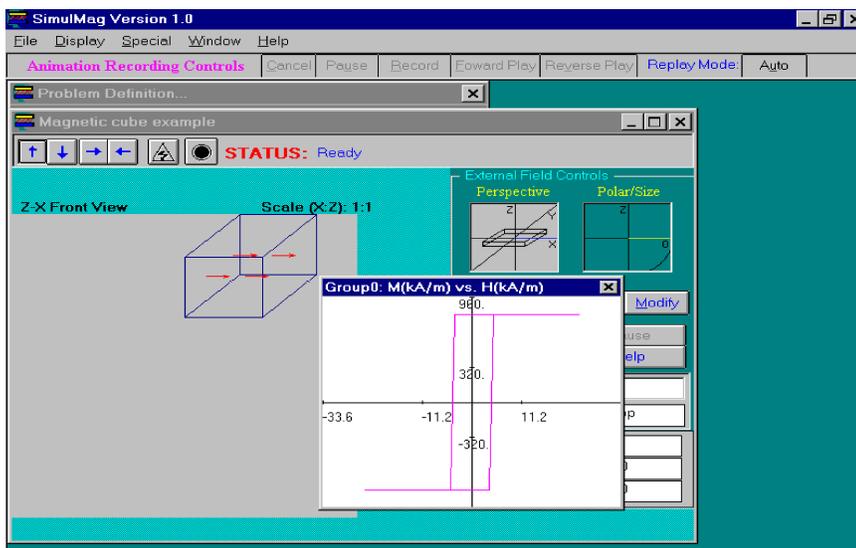


Fig 3.14.

3.9. Recording of Simulations

A convenient feature of the software is the ability to record simulations (including their animations). This is particularly useful for later rapid replay and analysis of lengthy simulations which may be very time consuming to run over and over again. *Chapter 5* describes many examples of recorded simulations in the examples' directory of the installation that can be loaded and played back using the **Animation Recording** group of controls of the main application window (see *Sec. 3.1.*). The recorded data includes all calculated output and a full description of the different states of the system during the simulation. Non-equilibrium states of dynamic calculations can be recorded *only* if the field application mode is Single. The recorded data is saved together with the *problem file* by

selecting the `File | Save` or `File | SaveAs` menu item of the main program window (see [Sec. 3.1](#)). The functionality of the different buttons of the of the **Animation Recording** controls are as follows:

Cancel. Cancels an ongoing replay of recorded data. This button is enabled only if there is recorded data to play back.

Pause. Pauses an ongoing *forward* or *reverse* replay of recorded data. It is disabled whenever data is not being replayed.

Record. Allows the recording of a simulation. The **Record** button is normally disabled if there is no ongoing simulation. During a simulation it becomes enabled and assumes a red color. The recording is started by pressing the button anytime after it has been enabled. The button caption changes to “Stop” during the recording. The recording is terminated whenever the button is pressed in this new state or at the end of the simulation. In the later case the simulation starting from the time the button was pressed till the end of the simulation is recorded. In the former case the simulation between successive pressings of the button is recorded, the caption reverts back to “Record” and the button remains enabled. Starting and stopping a recording at anytime retains only the recorded information between those times.

Forward Play. This replays in the forward (natural) direction a recorded simulation. It is enabled whenever the software can play a recording in the forward direction.

Reverse Play. This replays a recorded simulation backwards. It is enabled whenever the software can play a recording in the reverse direction.

Replay Mode. This button can be toggled between two states with captions “Auto” and “Manual.” In the Auto mode, a recording is replayed to completion whenever the **Forward Play** or **Reverse Play** button is pressed. In the Manual mode, the recording is replayed one step, each time the buttons are pressed. This is useful for slowly stepping through parts of a recorded simulation that may be of special interest to the user, but which may be inconvenient to observe when replayed quickly.

4. Detailed Description of Model and Calculations

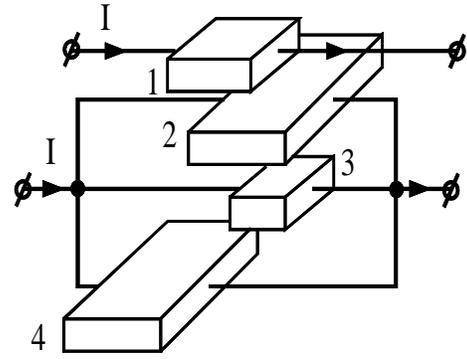
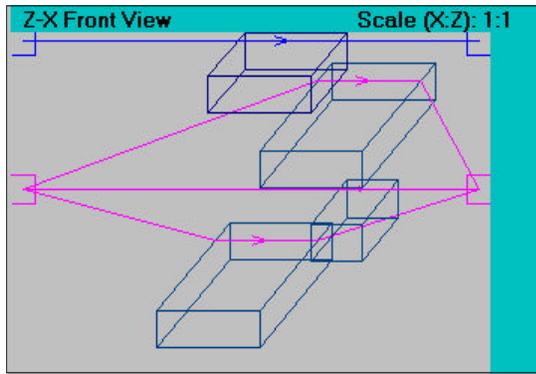
This chapter describes the mathematical implementation of the physical model that represents the electromagnetic calculation aspects of the software. The following topics are discussed in this chapter:

- ! System electrical circuit
- ! System equilibrium calculations
- ! Element intersection coefficients
- ! Calculation of effective fields
- ! Calculation of model data output

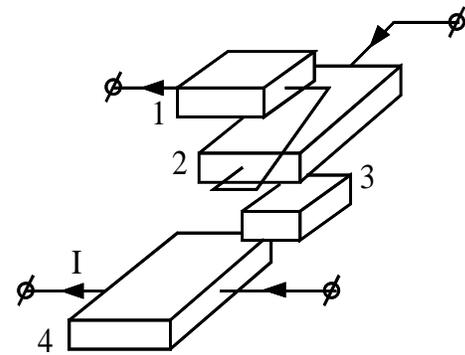
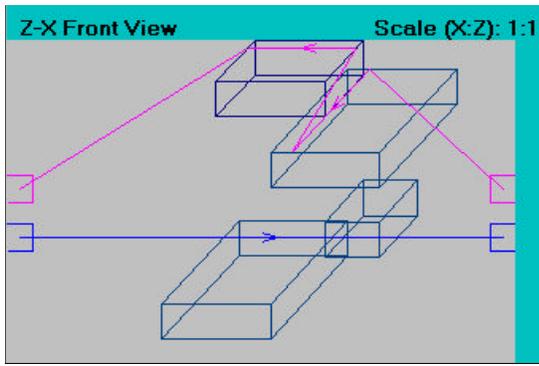
Unless otherwise noted, the discussion below applies to *magnetic* elements specified as such in the **Magnet Type** list of the **Media Characteristics** dialog. These are normal ferromagnetic elements whose magnetization can change. All elements are single-domain with a fixed magnitude moment that is free to rotate in three dimensions. The ambient medium is free space. The **Media Characteristics** dialog is used to specify all the geometric and electromagnetic properties of the element used for the calculations described below. The **Media Characteristics** dialog is described in *Chapter 3, System Design*. Appropriate commentary is provided throughout this chapter concerning the implications, accuracy and limitations of the theory. A list of selected references and a list of symbols is given in the appendix at the end of the chapter.

4.1. System Electrical Circuit

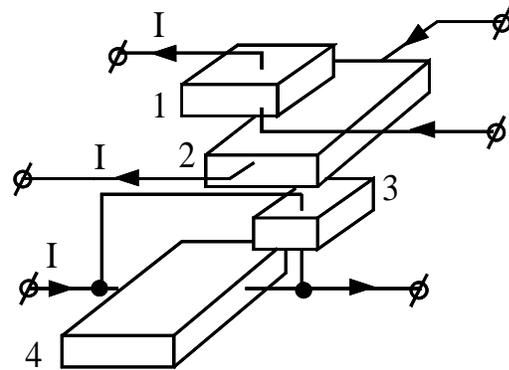
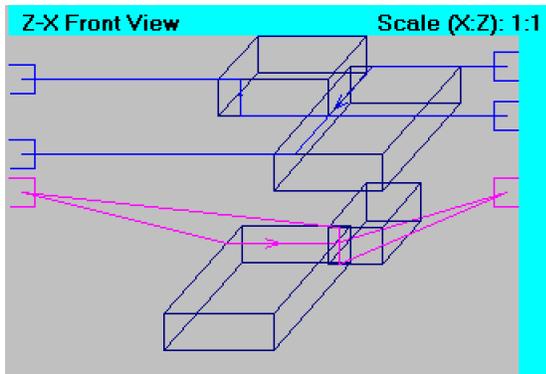
The software supports the specification of limited electrical circuits for element groups of a system. The circuits are fed by external constant currents. Any of the element types (*magnetic*, *nonmagnetic* and *fixed magnet*) can be used in an electrical circuit. Currents flowing through these circuits generate magnetic fields that add to the field components from other sources to affect the magnetic behavior of the system. Currents are assumed to flow uniformly through the elements in directions that are parallel to the coordinate axes. An *independent circuit* can be defined separately for an element, or the element may be part of a *common circuit*, containing other elements in a group. An element cannot have an independent circuit and be part of the common circuit at the same time. The elements of a common circuit may be connected either serially or in parallel to form *serial* or *parallel common circuits*. Elementary electrical circuit theory is used to calculate the currents flowing through the elements. These currents are assumed to be independent of magneto-resistive effects in the system (see *Sec. 4.5.2* and *4.5.3*). The circuits of a group are local to it and cannot be



(a)



(b)



(c)

Fig. 4.1. Examples of the definition of electrical circuits for a group composed of 4 elements (figures on the left depict actual displays of the electrical circuits by the software): (a) An *Independent circuit* with current flowing along the x -axis is defined for element 1 (direction of current is specified by selecting X -axis in the **Axis of current flow** drop-down list of the element's **Media Characteristics** dialog); elements 2, 3 and 4 are connected by a *Common parallel circuit* with current flowing along the x -axis. (b) Elements 1 and 2 form a *Common serial circuit*, current flows in 1 along x -axis and along y -axis in 2; an independent circuit is defined for element 4; no circuit is defined for element 3 (that is, an independent circuit with *zero* current is defined) . (c) Independent circuits with currents along z -and y -axes are defined for elements 1 and 2; elements 3 and 4 are connected to a *Common parallel circuit* with current flowing along z -axis in element 3 and along x -axis in element 4.

connected to the circuits of other groups of the system. An independent circuit cannot be connected to the common circuit within a group. Some examples of independent and common circuits are illustrated in Fig. 4.1.

An element is characterized by an electrical resistivity that is specified using the **Media Characteristics** dialog. The **Currents** group of controls in the **Media Characteristics** dialog is used to specify the type of circuit an element belongs to. If the **Independent** option is selected, a box is displayed for specifying the current that will flow through the element. An external current flows into a group through contacts on the left and right edges of the **System Display Pane** (see. [Sec. 3.6](#)). A *positive* current in the common circuit is one that flows into the circuit from the left contact and flows out through the right contact. The **Axis of current flow** list is used to specify the axis along which positive current will flow through the element. The type of a common circuit (serial or parallel) and the current that will flow through it, are specified with the **Electrical Circuit Type** list and **Common Current** box of the **Device Group Editor**. The **Media Characteristics** and **Device Group Editor** dialogs are described in [Chapter 3, System Design](#). The circuit defined for a system is displayed in the **System Display Window** by selecting in the main program window the menu item `Display|Show Electrical Circuits`.

4.2. System Equilibrium Calculations

Two types of calculation methods, one a *static* method and the other *dynamic*, are implemented for determining the equilibrium magnetization of the elements of a system. The static method is an energy minimization calculation in which an energy minimum is calculated for the system for a given value of applied and current-generated magnetic fields. The dynamic calculation is based on the Landau-Lifshitz equation (Mallinson, 1987) and entails finding the magnetic state corresponding to the vanishing of the torque at all elements of the system. Only one calculation method can be

applied to a simulation at a time. The software does not support specifying a system in which different sets of elements are calculated using different methods. The static method is the default calculation method. The calculation method is selected from the **Calculation Method** list of the **Problem Definition** dialog. For additional information on using the **Problem Definition** dialog see [Chapter 3, System Design](#).

4.2.1. Static Calculation

The equilibrium magnetization states of elements for static calculations are those that yield a minimum of the total free energy density of the system $E = \sum e_i$, where e_i is the free energy density of the element given by the expression

$$e_i = \frac{1}{2} \mathbf{M} \cdot \bar{\mathbf{N}} \mathbf{M} + \mathbf{H}_T \cdot \mathbf{M} , \quad (1)$$

where

$$\bar{\mathbf{N}} = \begin{pmatrix} N_x & 0 & 0 \\ 0 & N_y & 0 \\ 0 & 0 & N_z \end{pmatrix} \quad (2)$$

is the self-demagnetization tensor of the element, \mathbf{M} is the magnetization vector of the element and \mathbf{H}_T is the total effective field from all other sources excluding self-demagnetization. The first term on the right side of (1) represents the self-demagnetization energy of the element and the second term, the energy due to other magnetic interactions. The calculation of field terms is described in [Sec. 4.4. Calculation of Effective Fields](#).

The self-demagnetization tensor $\bar{\mathbf{u}}$ is expressed by a diagonal matrix whose nonzero elements ($N_x, N_y, N_z; N_x+N_y+N_z=1$) are the demagnetizing factors of a uniformly magnetized ellipsoid with the same aspect ratio and principal axes (x, y, z) as the element. Such an ellipsoid is called an *equivalent ellipsoid* of the element (Brown, 1962, pp. 49-53; Moskowitz and Della Torre, 1966). Each of the self-demagnetizing factors is positive. For the rectangular-prismatic shape of the elements, the demagnetizing factors of the equivalent ellipsoid along the principal axes are equal to the magnitudes of the volume-average demagnetizing fields per unit magnetization of the element, when it is magnetized along its principal axes. The self-demagnetizing field sources for a uniformly magnetized element are the magnetic *surface charges* formed on its bounding faces. Such a field can be expressed in closed form (Schabes and Aharoni, 1987; Oti, 1993).

For a system composed of several elements, the field \mathbf{H}_T is a function of the magnetization of all

elements of the system. This necessitates the use of self-consistent iterative methods in obtaining an energy minimum for the system. During an iteration, the magnetization of the elements are rotated in a manner that minimizes their local free energy densities given by (1). This is accomplished by using a numerical implementation of the classical Stoner-Wohlfarth model (Stoner and Wohlfarth, 1948) that is applicable to general single-domain ellipsoids. This method finds the equilibrium magnetization orientation of an element directly from the energy surface $e_i(2_M, N_M)$ of the element, where 2_M and N_M are spherical coordinate variables of the element's magnetization vector (Johnson, 1962; Oti et al., 1996). The updated magnetization values are used to recompute H_T for each element, and this iteration procedure is repeated until the magnetization of the system reaches equilibrium. Equilibrium is detected when the magnetic state of the system is unchanged in two successive iterations as defined by the criterion that the maximum difference in the element-to-element magnetization orientation of the states be no larger than 0.1° . A stationary magnetic state corresponds to an energy extremum since the variations of the free energy density of the system and those of its constituent elements, δE and δe_i , are equal to 0. The equilibrium state is tested for stability by randomly rotating the magnetization of each element within a 1° solid angle and continuing the calculation. The solution is deemed stable if the system relaxes back, within tolerance to the equilibrium state. Energy maxima and saddle points will produce unstable converged solutions.

4.2.2. Dynamic calculation

The variation of the free energy density of an element is related to the torque per unit volume \mathbf{J}_i acting on the element by $\delta e_i = -\mathbf{J}_i \cdot \delta \mathbf{M}$, where $\delta \mathbf{M}$ is an arbitrary angular variation of the magnetization vector. The torque therefore vanishes whenever $\delta e_i = 0$. For dynamic calculations \mathbf{J}_i is expressed by the Landau-Lifshitz equation:

$$\mathbf{J}_i = \frac{d\mathbf{M}}{dt} = \gamma (\mathbf{M} \times \mathbf{H}_{eff}) - \frac{\alpha}{M} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{eff}), \quad (3)$$

where t is time, $\gamma = -1.105 \times 10^5 g$ (m/A-s) is the gyromagnetic factor, g is the gyromagnetic ratio, α is phenomenological damping factor, and $\mathbf{H}_{eff} = \mathbf{H}_T + \mathbf{H}_D$ is the total effective field acting on the element. The field \mathbf{H}_{eff} , unlike \mathbf{H}_T in (1), includes the self-demagnetizing field of the element \mathbf{H}_D . Equation (3) describes the damped gyromagnetic precession motion of the moment in response to an applied field. The first right-hand term of the equation is the precession term and the second term is the damping term. Values for g and α are specified using the **Dynamic-Properties** dialog that is launched by clicking the **Dynamic-Properties** button in **Media-Characteristics** dialog. The gyromagnetic ratio g is allowed to take on only the three values, 0, 1 and 2. The angular velocity of precession is directly proportional to g .

The dynamic method uses an iterative solution technique similar to the one used for static calculations. However, for this method the magnetic state of the system during each iteration is

found by integrating simultaneously the torque equations of the elements of the system. A fourth-order Runge-Kutta method with error control is used to carry out this integration (W. H. Press et al., 1986, Chapter 15). The equilibrium condition is detected in the same manner as in static calculations.

4.3. Element Intersection Coefficients

Two geometric quantities appearing in later expressions of certain field terms and model output are defined in this section. These are the *inter-element area intersection coefficient* and the *inter-element length intersection coefficient*.

4.3.1 Inter-element Area Intersection Coefficient α_{ij}^A

The *inter-element area intersection coefficient* α_{ij}^A expresses the extent by which the surfaces of the i th and j th elements intersect each other in a coordinate plane A . It is equal to the ratio of the area of intersection $A_i^A \cap A_j^A$ to the area A_i^A of the face of the i th element, parallel to A , that is,

$$\alpha_{ij}^A = \frac{A_i^A \cap A_j^A}{A_i^A} . \quad (4)$$

The plane A represents any of the coordinate planes x - y , y - z or z - x . The value of α_{ij}^A varies from 0, if the elements do not intersect, to 1, if they intersect by an area equal to the area of the face of the i th element parallel to A (i.e., $A_i^A \cap A_j^A = A_i^A$). In general $\alpha_{ij}^A \dots \alpha_{ji}^A$. Several examples illustrating the definition of α_{ij}^A are shown in Fig. 4.2.

4.3.2 Length Intersection Coefficient $\beta_{ij}^>$

The *inter-element length intersection coefficient* $\beta_{ij}^>$ expresses the extent of intersection of the sides of the i th and j th along a coordinate axis $>$. It is equal to the ratio of the length of intersection $l_i^> \cap l_j^>$ to the length $l_i^>$ of the side of the i th element parallel to $>$, that is

$$\beta_{ij}^> = \frac{l_i^> \cap l_j^>}{l_i^>} . \quad (5)$$

The axis $>$ represents any of the coordinate axes x , y or z . The value of $\beta_{ij}^>$ varies from 0, if the elements do not intersect, to 1, if they intersect by a length equal to the length of the side of the i th

element along x (i.e. $l_j^x \neq l_i^x$). In general $l_j^x \neq l_i^x$. Several examples illustrating the definition of l_j^x are shown in Fig. 4.2.

4.4. Calculation of Effective Fields

The total effective field H_{eff} acting on an element is the sum of the following components: The externally applied field H_o acting on the device group of which the element is a part; the self-demagnetizing field H_D ; the pinning field H_p due to the unidirectional magnetization pinning property of the element; the inter-element magnetostatic interaction field H_m ; the effective exchange interaction field H_{ex} ; the effective uniaxial magnetic anisotropy field H_k and the field H_l due to applied currents flowing in other elements of the system. With the exception of H_o , the calculation of each of these field terms is described in this section.

4.4.1. Self-Demagnetizing Field H_D

The self-demagnetizing field of an element depends on the magnetization and shape of the element and is given by

$$H_D = -\bar{N}M \quad (6)$$

The self-demagnetization tensor \bar{u} is calculated at the beginning of a simulation and remains unchanged for the duration of the simulation. If a linear dimension of the element is altered between simulations, \bar{u} is re-calculated to reflect the changes. The status bar of the *System-Display Window* reads “Updating tables...” whenever \bar{u} is being recalculated.

4.4.2. Inter-element Magnetostatic Interaction Field H_m

The inter-element magnetostatic interaction field is a long-range interaction field of a dipolar nature between the elements of the system. This field has a strong dependence on the mutual locations of the elements in the system and their linear dimensions. It is given by the expression

$$H_m = \sum_j^N \bar{D}_j M_j \quad (7)$$

where

$$\bar{D}_j = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{pmatrix} \quad (8)$$

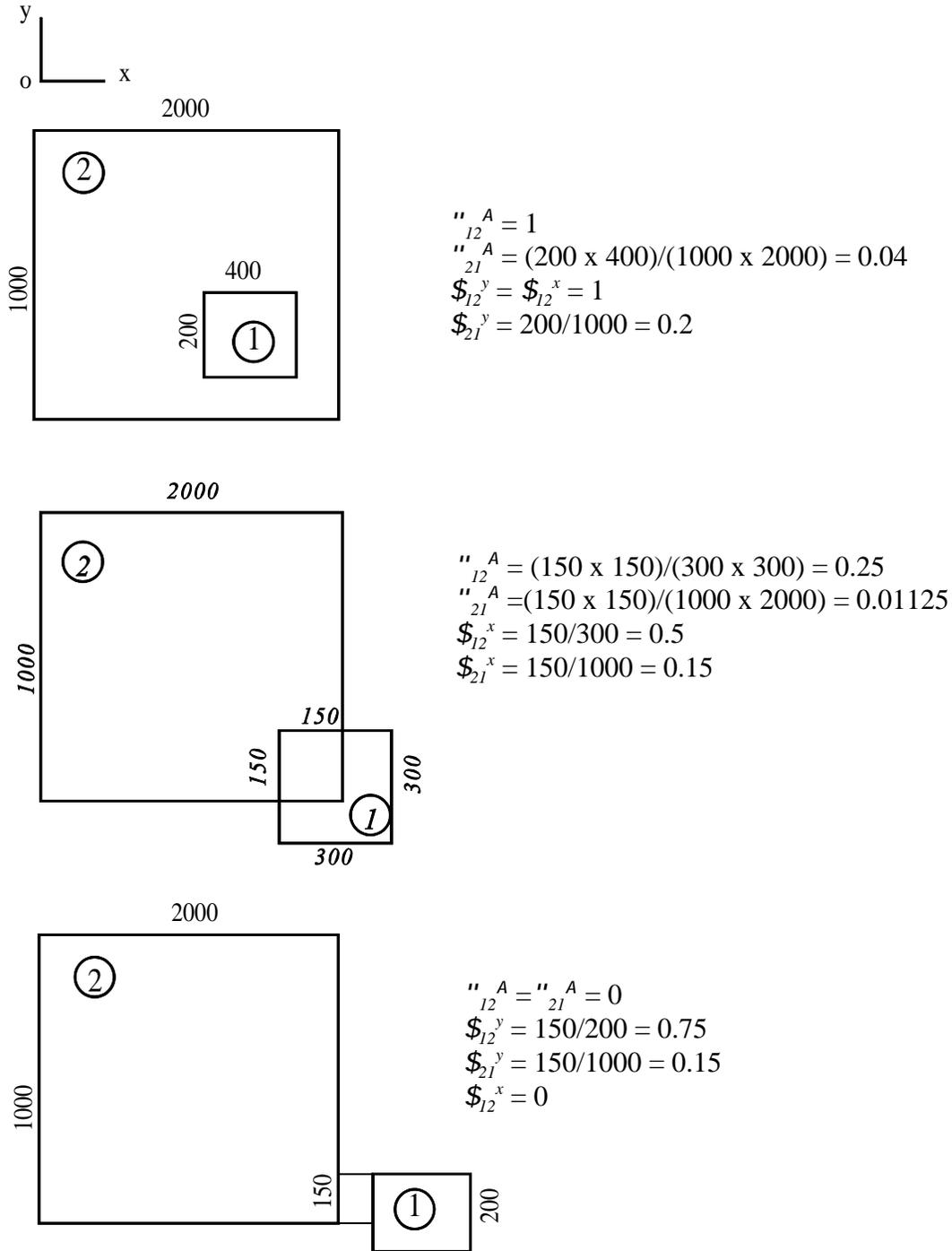


Fig 4.2. Examples of the definition of inter-element area intersection coefficients μ_{ij}^A and length intersection coefficients $\$_{ij}^y$ in the xy -plane. Indicated linear dimensions are in arbitrary units and the figures are not drawn to scale.

is the inter-element magnetostatic interaction tensor of the j th element with respect to the element where \mathbf{H}_m is being evaluated (the field element), and \mathbf{M}_j is the magnetization of the j th element. Summation is over N magnetic elements (ferromagnets and fixed magnets) in the system. The prime in the summation indicates that the field element is omitted while evaluating the sum. This omitted term is equal to the self-demagnetizing field defined by (6). The tensor $\mathbf{\check{o}}_j$, unlike $\mathbf{\check{u}}$, is a nondiagonal tensor. Its elements are equal to the components of the volume-average field per unit magnetization due to the j th element, when it is magnetized along its principal axes. For example, D_{xy} is the y -component of the volume-average field per unit magnetization when the j th element is magnetized along the x -axis; D_{yy} is the y -component of the volume-average field when the element is magnetized along the y -axis, etc.

The magnetostatic tensors for all the source elements are re-calculated whenever the relative locations of the elements change (as for example during motion), or whenever the linear dimensions of any element change. The status bar of the **System Display Window** reads “*Updating tables...*” whenever $\mathbf{\check{o}}_j$ is being re-calculated. The long-range nature of \mathbf{H}_m makes it the most time-consuming field term to calculate. The amount of computation required for this is proportional to the square of the number of elements in the system. This computation is almost always costlier than the computation of another long-range field term, the field due to externally excited currents flowing in the elements \mathbf{H}_l (see [Sec. 4.4.6](#)). This is because all the elements are typically not included in electrical circuits defined for the system, and the calculation of \mathbf{H}_l involves a less costly area averaging of the field, instead of a volume averaging.

4.4.3. Pinning Field \mathbf{H}_p

This field represents a unidirectional anisotropy that may be present in an element due to a variety of causes. It promotes the orientation of the magnetization vector in the pinning field direction. A popular practical example of the existence of a pinning field is the pinning of the magnetization of one of the thin-film layers of a magnetoresistive spin valve by an adjacent antiferromagnetic layer (Dieny et al., 1991). The pinning field is a constant field term in the total field acting on the element. Its direction and magnitude is specified using the **Media Characteristics** dialog for the element (see [Sec. 3.5. Specification of Basic Element](#)).

4.4.4. Exchange Interaction Field \mathbf{H}_{ex}

The exchange interaction field represents short-range exchange interactions between magnetic elements. Exchange interaction has quantum-mechanical origins (Morrish, 1965, Chapter 6). The field expression used by the software is based on an energy that is formally derived from the quantum-mechanical formulation by replacing atomic-spin dot products by dot products of the magnetization vectors (Brown, 1962, pp. 133-137). The exchange interaction promotes the parallel orientation of the magnetization vectors of two coupled elements if they are *ferromagnetically* coupled to each other, or the antiparallel orientation of their magnetization vectors if they are *antiferromagnetically* coupled. The exchange field \mathbf{H}_{ex} acting on the i th element due to a j th element

that is exchange coupled to it is given by

$$\mathbf{H}_{ex} = H^{ex} \mu_{ij}^A \hat{\mathbf{m}}_j, \quad (9)$$

where H^{ex} is the magnitude of the exchange field and μ_{ij}^A is the inter-element area intersection coefficient defined for plane A in which the elements couple (see [Section 4.3, Element Intersection Coefficients](#)).

All exchange couplings to an element are defined in its **Media Characteristics** dialog using the **Exchange Coupling** group of controls (see [Chapter 3, System Design](#)). These controls allow the specification of an arbitrary number of couplings between elements, and even the coupling of an element to itself. The exchange coupling between a pair of elements is nonreciprocal: The manner in which the i th element couples with the j th element is not necessarily the manner in which the j th element couples with the i th element. The **Field** box represents H^{ex} in (9). Positive and negative values for H^{ex} represent ferromagnetic and antiferromagnetic exchange coupling.

4.4.5. Uniaxial Magnetic Anisotropy Field H_k

This field represents the first-order uniaxial magnetic anisotropy of the element and is given by the expression (Zhu and Bertram, 1989)

$$\mathbf{H}_k = H_k (\hat{\mathbf{m}} \hat{\mathbf{k}}) \hat{\mathbf{k}}, \quad (10)$$

where H_k is the magnitude of the anisotropy field and $\hat{\mathbf{k}}$ is a unit vector in the direction of the element's anisotropy (easy) axis. The magnitude of the anisotropy field and the direction of the easy axis are defined using the **Magnetic Uniaxial Anisotropy** group of controls of the **Media Characteristics** dialog (see [Sec. 3.5. Specification of Basic Element](#)). The field H_k is related the magnetization M of the element and its magnetic anisotropy constant K by $H_k = 2K/M$.

4.4.6. Field due to current H_I

Currents excited by external current sources in the elements of a system produce magnetic fields H_I that affect the magnetic state of the system. These are long-range fields. See [Sec. 4.1. System Electrical Circuit](#) for more information on the electrical circuit implementation in the software.

The field H_I is calculated by considering subdivisions of source elements into rectangular rod-like segments in the direction of current I , as illustrated in Fig. 4.3. End effects due to the finite length of the rods are neglected by assuming that they produce the same field as rods of infinite lengths coinciding with them in space. Such a field is a two-dimensional field in a plane normal to the

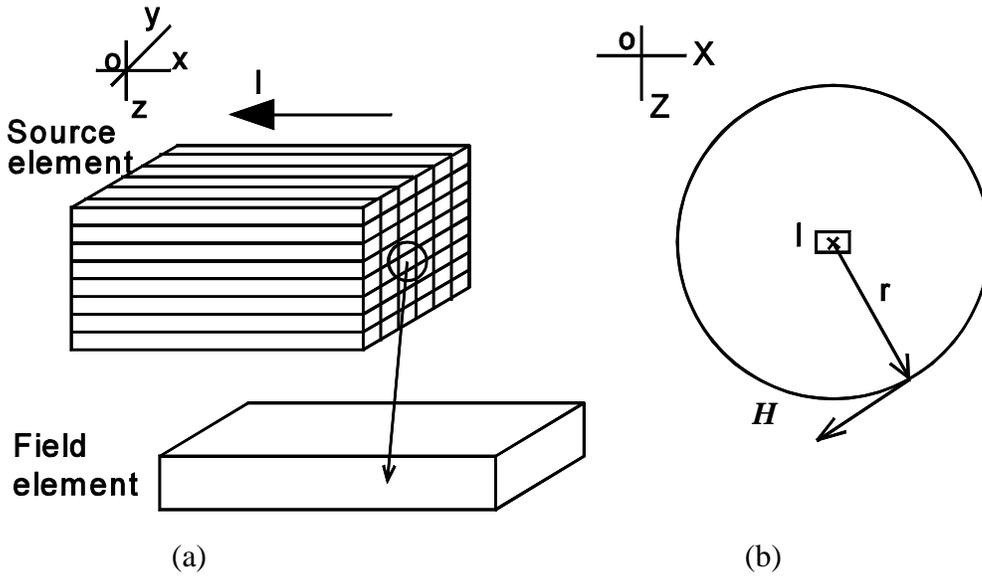


Fig. 4.3.

direction of current. The field \mathbf{H}_I is found as the sum of the volume-average field of each source element weighted by an appropriate geometric factor:

$$\mathbf{H}_I = \mathbf{j}_j \sum_j \mathcal{H}_{ij}^j \mathbf{H}_I^j, \quad (11)$$

where the volume-averaged field \mathbf{H}_I^j of the j th source element is given by

$$\mathbf{H}_I^j = \frac{1}{A_{Elem}^j} \mathbf{j}_k \int \mathbf{h}_{ik}^j dA_{Elem}^j. \quad (12)$$

In (11) and (12), \mathcal{H}_{ij}^j is the inter-element length intersection coefficient (index i denotes the element at which \mathbf{H}_I is calculated, see Sec. 4.3.1. for definition) and A_{Elem}^j is the area of the cross section of the target element normal to the direction of current in the j th element. The area average is equivalent to a volume average, because of the two-dimensional nature of \mathbf{H}_I^j . The summation in (12) is over the k rods into which the j th source element is subdivided, and the prime denotes that the summation

is at source points. The term h_{lk}^j , which is the field of the k th rod of the j th source element, is obtained by Ampere's law. (Ampere's law applied to a line current I states that the line integral of the magnetic field H produced by the current, along a closed path linking the current is proportional to I ($\oint H dl = \mathcal{C}I$, where \mathcal{C} is a unit-dependent proportionality factor). The field of each current-carrying rod is approximated by that of a line current coincident with its axis (Fig. 4.3(b)). Ampere's law is applied along a circle of radius r , the distance of the field point from axis of the rod, to yield a field magnitude $H = \mathcal{C}I/2Br$. The field is directed along the tangent of the circle and is related to the direction of current by the right-hand rule.)

4.5. Calculation of Model Data Output

During a simulation all data quantities described in this section are calculated for all groups of the system as functions of the applied external field sequence, group motions and time (see [Sec. 3.8. Data Output and Saving Data](#)). A graph of any group output can be plotted during a simulation by selecting the graph in the dialog launched after pressing the **Data Output** button of the group's **Device Group Editor** dialog (see [Sec. 3.8.2. Graphical-Plot Window](#)).

4.5.1. Magnetization

The total magnetization M_G of the group is calculated by the expression

$$M_G = \frac{\sum_i^{N_G} V_i M_i}{\sum_i^{N_G} V_i}, \quad (13)$$

where V_i and M_i are the volume and magnetization of the i th element of the group and N_G is the number of elements in the group. The magnetization of nonmagnetic elements is set to 0 in the calculation.

4.5.2. Giant Magnetoresistive (GMR) Ratio

Introduction

Giant magnetoresistance (GMR) is one manifestation of the general magnetoresistive effect in which the the electrical resistance of a magnetic sample changes with applied field. This phenomenon is rooted in the dependence of the scattering of polarized electrons in the sample on magnetization (Baibich, 1988). This mechanism is different from those leading to the anisotropic magnetoresistance (AMR), which is the subject of [Sec. 4.5.3](#). The adjective "giant" in the terminology was inspired by the magnetoresistive effect of the earliest GMR samples studied, which was much larger than effects observed in AMR samples. Great interest in the GMR phenomenon has arisen in the magnetics

community, as indicated by recent studies of multilayer GMR thin-film media and their potential uses for the development of advanced spin-valve magnetic recording heads, magnetic sensors and magnetic random access memory (MRAM) devices.

Lumped-parameter circuits such as are used in the software do not accurately represent the electron transport processes that occur in real devices, which would best be described with more general circuits with distributed parameters. The role of the circuit implementation in the software is to provide a framework for specifying the electrical characteristics of the system. Considerations of the effects of transport processes may influence the estimation of the parameter values which are used for a particular simulation. The complete modeling of GMR systems is still an evolving field. A more thorough discussion of the GMR phenomenon and devices is plentiful in the literature (see for example, Dieny et al., 1991; White, 1992; Gallagher et al., 1997; Daughton, 1997; Zhang et al., 1992; Camley and Barnas, 1989). In this section the relevant calculation formulas implemented in the software are first described. This is followed by a discussion of the rationale for the formulation used and the limitations of the formulas.

Formulation

The giant magnetoresistive effect in a device (represented by an element group) is assumed to occur only in those elements that are part of the *common circuit* of the device. For a description of the implementation of electrical circuits, see **Section 4.1, System Electrical Circuit**. For a given field H , a reduced total conductance is defined for the common circuit as follows:

$$G_T(H) = \mathbf{j}_j^{N_c} g_j, \quad (14)$$

for parallel circuits, or

$$G_T(H) = \left(\mathbf{j}_j^{N_c} \frac{1}{g_j} \right)^{\&1}, \quad (15)$$

for serial circuits, where N_c is the number of elements in the common circuit and g_i is a phenomenological reduced conductance of an element of the circuit (ferromagnetic, nonmagnetic or fixed-magnet). The term g_i , which is defined below, is comprised of two components — a *normal* component and a *magnetoresistive* component. The GMR ratio of a device is given by the expression

$$)_{GMR} = \frac{G_{sat} \& G_T(H)}{G_{sat}}, \quad (16)$$

where G_{sat} is the total reduced conductance at saturation. At saturation, the magnetization of all elements of the device are oriented parallel to each other. This is a state that may arise due to a large external field being applied to the device. For positive GMR effects (see definition below), G_{sat} is the maximum possible reduced total conductance of the device.

The reduced conductance of an element (the i th element) is defined by

$$g_i = \frac{F_i}{\mathbf{j}} \frac{A_z}{F_i L_i} (1\%) g_i, \quad (17)$$

for an element of a parallel circuit, or

$$g_i = 1\%) g_i, \quad (18)$$

for an element of a serial circuit, where $F_i = 1/D_{oi}$ is the conductivity of the element, D_{oi} is the intrinsic resistivity of the element, G F_i is the total conductivity of the parallel circuit, A_z is the cross-sectional area of the element normal to the current, and L_i is the length of the element along the current's path. The value of D_{oi} is specified in the **Resistivity** box of the **Media Characteristics** dialog of the element. The term $) g_i$ represents the GMR component of g_i and is defined by the equation

$$) g_i = \frac{1}{n} \mathbf{j}_j^{N_{gmr}} *_{ij}^{A_j} (1 \% \hat{\mathbf{m}}_i \cdot \hat{\mathbf{m}}_j). \quad (19)$$

The summation in (19) is over N_{gmr} elements that are GMR coupled to the i th element (its GMR-coupling neighbors); $\hat{\mathbf{m}}$ is unit magnetization vector. The factor $*_{ij}$ is an arbitrary GMR coupling ratio, and $^{A_j}_{ij}$ is the inter-element area intersection coefficient defined for appropriate coupling planes A_j (see **Section 4.3, Element Intersection Coefficients**). For a serial circuit, if g_i evaluates to 0, then from (15), $G_T(H)$ is 0 and the GMR ratio at the given field becomes unity.

Current does not appear explicitly in the formulas above. This means that the program will still generate a GMR output even when no current is flowing in the circuit. The resulting output will reflect only the magnetic and geometric dependence of GMR. This corresponds to the case of negligible current effects in real devices. When currents are present, their effects on GMR arise indirectly through the magnetic fields they produce, which modify the magnetic state of the system (see **Section 4.4.6, Field due to current**). Other effects of current in real devices, such as *heating* and *electromigration* (Kos et al., 1997), are not modeled by the software.

The specification of the GMR-coupling neighbors of an element and the terms $*_{ij}$ and A_j is carried

out with the **Media Characteristics** dialog using the **GMR Coupling** group of controls (see *Chapter 3, System Design*). This is a flexible interface, allowing for the specification of an arbitrary number of couplings between elements, and even the coupling of an element to itself. The GMR coupling between a pair of elements is non-reciprocal: The manner in which the i th element couples with the j th element is not necessarily the manner in which the j th element couples with the i th element. The coupling information used in (17) - (19) for calculating g_i , is obtained independently for each element by editing its properties using the **Media Characteristics** dialog. If a parallel circuit contains elements with zero resistivity values, then these elements will shunt all the current flowing in the device. In this case, only the shunting elements are used in (17), and $F_i = 1$ is used in the expression. For mathematical completeness, \star_{ij} is allowed to take on both positive and negative values. These yield *positive*- and *negative*-GMR effects in (19).

Rationale for the forms of equations (17), (18) and (19).

Equations (17) and (18) are phenomenological expressions of the GMR effect. They are not derived from first principles but are formulated to reflect some well-known characteristics of GMR behavior in multilayer thin-film media, as described below. These are explained using the simple spin-valve structures shown schematically in Fig. 4.4. Each spin valve consists of a sandwich structure of two magnetic layers that are separated by a nonmagnetic spacer layer. The two devices shown in the figure differ by the sizes of their magnetic layers. Current flows through both devices along the x -axis as shown in the figure. For GMR to be observed in these samples it is essential that the thicknesses of the magnetic and nonmagnetic layers be smaller than the two characteristic electron transport lengths of the device, the *electron mean free path* and the *electron spin-diffusion length* (Zhang et al, 1992). This defines the range of validity of (17) and (18). By appropriately choosing the dimensions of elements, devices whose dimensions fall within the range of applicability of the formulas can be designed.

(i) Magnetization dependence. Equation (19) expresses with the factor $(1/N_{gmr})(1 + \hat{m}_i \cdot \hat{m}_j)$, the well known dependence of the GMR on the cosine of the angle between the magnetization of the layers (Dieny et al., 1991). An acute angle between the magnetization vectors increments this factor while an obtuse angle decrements it. For the devices shown in Fig. 4.4, $N_{gmr} = 1$. For the general case of $N_{gmr} > 1$, multiplication by $(1/N_{gmr})$ weights equally the contribution to g_i of the magnetization dependence between the i th element and each j th element.

(ii) Geometric overlap of layers. For a given magnetization orientation of the layers, the devices shown in Fig. 4.4(a,b) will not produce the same GMR effect. The difference in the extent of overlapping of the magnetic layers will cause the interlayer transport processes leading to GMR to be different in the two devices. This effect is approximated in (19) through multiplication by the factor \star_{ij}^{Aj} . The less overlapped the two elements are, the more diminished is their GMR coupling. For a nonoverlapping element pair, $\star_{ij}^{Aj} = 0$ and g_i vanishes. The factor \star_{ij} provides an additional degree of freedom for specifying the extent of inter-element GMR coupling.

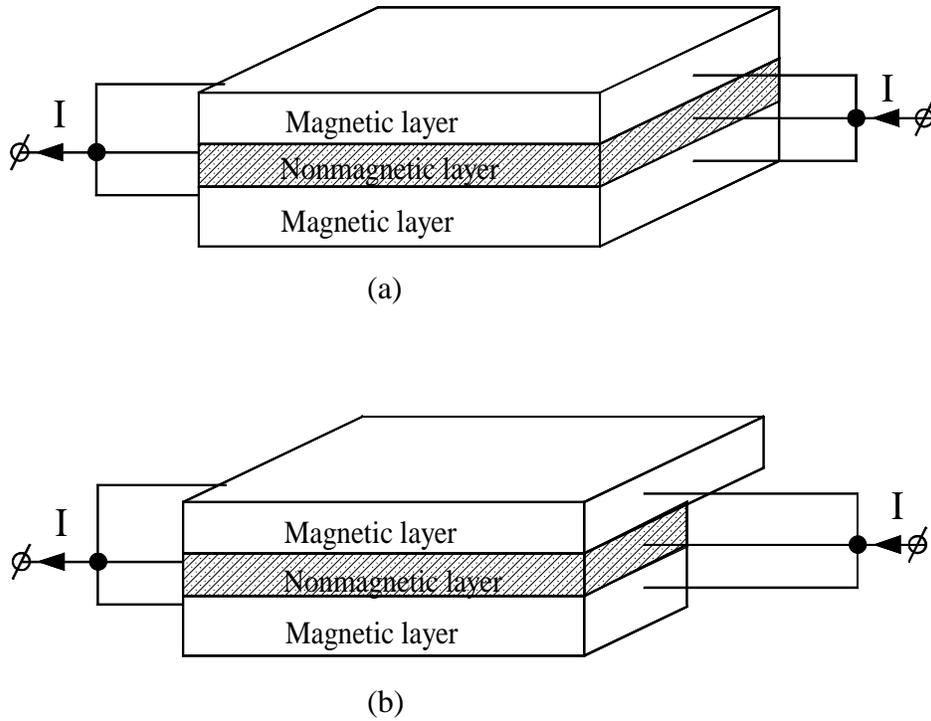


Fig. 4.4. Symmetric and nonsymmetric spinvalve structures. The thicknesses of the layers are exaggerated for clarity.

(iii) Current shunting effects. The shunting effects of current on the GMR response of real devices is well known (Daughton, 1993). Thus, if the conductivity of the spacer layer in Fig 4.4. is much larger than those of the magnetic layers, much of the current will be shunted through this layer, and the GMR effect will be diminished. The GMR component of an element g_i is assumed to be proportional to the fraction of current flowing through the element. This is achieved through multiplication by the factor $(F_i/G F_i)(A_z/L_i)$ in (17). The shunting factor is 1 for a serial circuit, because the same current flows through all the elements of the circuit.

4.5.3. Anisotropic Magnetoresistive (AMR) Ratio

Anisotropy magnetoresistance (AMR) is another manifestation of the magnetoresistive effect, of a different origin than giant magnetoresistance discussed in [Sec. 4.5.2](#). It occurs when the magnetization of a magnetic material changes relative to the direction of current flowing through it. This phenomenon is thought to be caused by the exchange-driven scattering of polarized conduction electrons by spin-orbit electrons (Hunt, 1971; Tsang and Decker, 1984). This phenomenon is exploited in the development of advanced magnetic read heads, magnetic random access memory devices and magnetic sensors. Many good reviews on AMR and their applications exist in the literature (see for example Mee and Daniel, 1995, Chapter 6; Bertram, 1997, Chapter 7). The

resistivity of an element changes by virtue of AMR as follows

$$D_i = D_{oi} \%) D_i \cos^2 R_i , \quad (20)$$

where D_{oi} is the intrinsic resistivity of the element, $) D_i$ is the amplitude of the AMR effect and R_i is the angle between the directions of magnetization and current in the element.

AMR is calculated *only* for the common circuit of a group. The total conductance for parallel and serial circuits are calculated as before using (14) and (15), where the reduced conductances are now given by

$$g_i = \frac{F_i}{j} \frac{A_z}{F_i} (1 \&) g_i , \quad (21)$$

for a parallel circuit and

$$g_i = 1 \&) g_i , \quad (22)$$

for a serial circuit, where $) g_i = * _a \cos^2 R_i$ is the AMR component of the conductance and $* _a =) D_i / D_{oi}$ is the reduced AMR amplitude. The **AMR Ratio** box of the **Media Characteristics** dialog expresses $* _a$ as a percentage. The AMR ratio of a group is given by

$$)_{AMR} = \frac{G_T(H) \& G_{ref}}{G_{ref}} , \quad (23)$$

where G_{ref} is a total reduced reference conductance that would be obtained if the magnetization vectors of all the elements became oriented parallel to the currents flowing through them. As with the calculation of GMR, current does not enter explicitly in the above formulations. The output therefore corresponds to negligible current effects in real devices. Currents have an indirect influence through the magnetic fields they produce (see Section 4.4.6., Field due to current). Shorts are treated the same way as in GMR calculations. The angle R_i is measured from a current direction selected for the element from the **Axis of current flow** list of its **Media Characteristics** dialog (see Sec. 4.1., System Electrical Circuit).

4.6. Selected References

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5. Design Examples

This chapter contains brief descriptions of design examples that are included in the disks labeled *Examples* accompanying the installation disks of the software. To display a design open the corresponding file by selecting the item `File | Open` from the main menu of the program. Most of the files contain recorded simulation data that can be played back using the *Animation Recording Controls* (see [Sec. 3.9](#)). The *Forward-Play* button is enabled when such files are loaded. Press this button to play the recording.

5.1. Simple MR Spin-Valve Head.mms

This is a spin-valve magnetoresistive (MR) read-head structure in which magnetization reversal of magnetic layers is modeled using the single-domain approximation. The device is scaled 100 times vertically when displayed, to aid the visualization of the multilayer structure. The pinning layer is a composite structure of two identical permanent magnets of opposite polarity, occupying the same location in space. The interlayer magnetostatic interaction effects of the pinning layer is thus eliminated. The pinned layer is exchange coupled to one of the permanent magnets. The layers of the device are connected in a parallel electrical circuit. The device is subjected to a cyclic external field in the transverse direction (y -axis).

5.2. MRAM Spin-Valve Gallery.mms

This example models a collection of interacting magnetic random access memory (MRAM) spin valves of different shapes and sizes, using the single-domain approximation. Each device is modeled by a separate design group. The system is scaled 100 times vertically when displayed, to aid the visualization of the device structures. Characteristic pinning fields are defined for the pinned layers. The system is subjected to a cyclic external field along the x -axis.

5.3. MR Read-Head Concept.mms

This example models the concept of an MR read-head moving over perpendicular media. Different device groups are used to model the MR head and the media. The media is modeled using three permanent magnets with alternating magnetization directions.

5.4. Dynamic Cubes.mms

This simulation shows the damped-precession magnetization reversal response of two magnetic cubes having different dynamic properties.

5.5. Dynamic Film.mms

This example illustrates the dynamic magnetization reversal of a magnetic thin film in response to an applied longitudinal field.

5.6. Misc1.mms

This is a design of a system consisting of some recognizable objects. This example illustrates the versatility of the geometric design capabilities of the software.