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(54) **MAGNETIC BODY SIMULATION COMPUTER PRODUCT, SIMULATION APPARATUS, AND SIMULATION METHOD**

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(57) **ABSTRACT**

A non-transitory, computer-readable recording medium stores a magnetic body simulation program that causes a computer to generate an easy axis vector in an area divided from an element of a group of elements forming a magnetic body; calculate magnetic energy of each magnetization of the divided area, select from among the calculated magnetic energies, a magnetic energy that is not the greatest; identify based on the magnetization of an area and a specific easy axis vector in a case of the selected magnetic energy, a reversal angle of magnetization reversal according to a height of an energy barrier that is consequent to pinning in the area; and reverse the magnetization by the identified reversal angle.

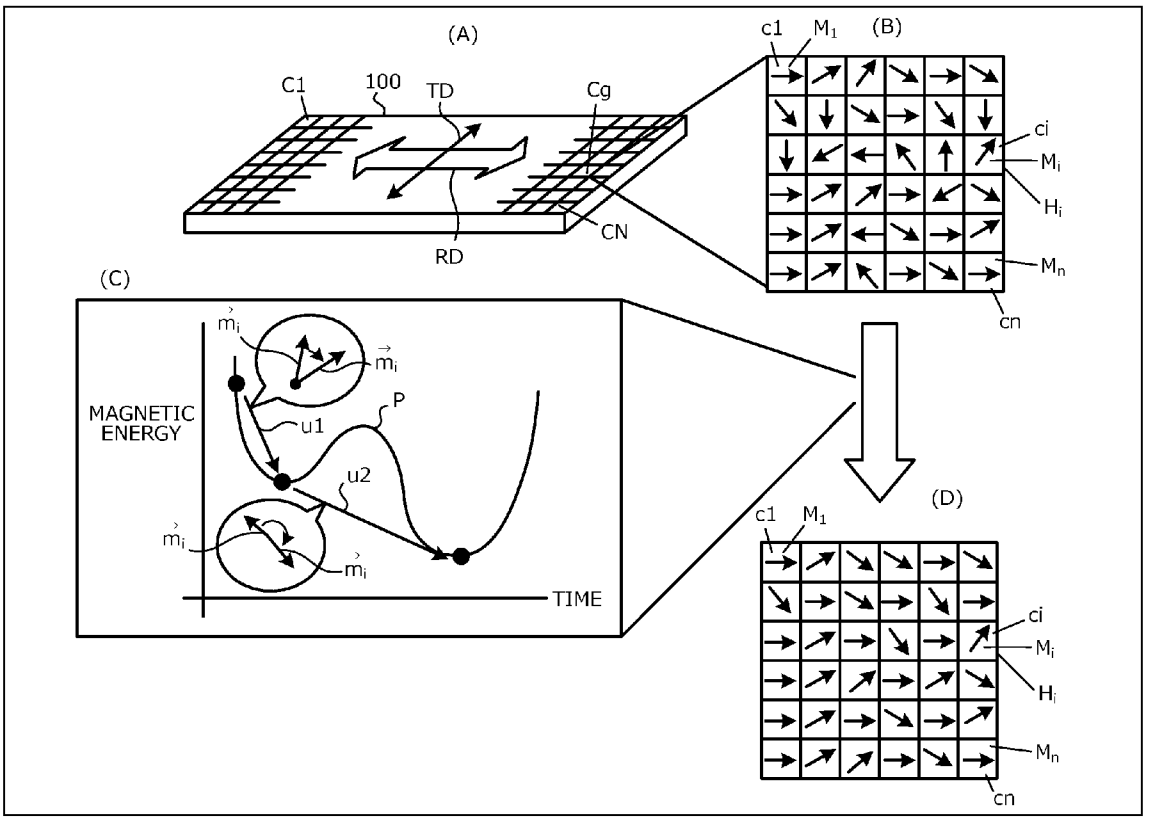


FIG.1

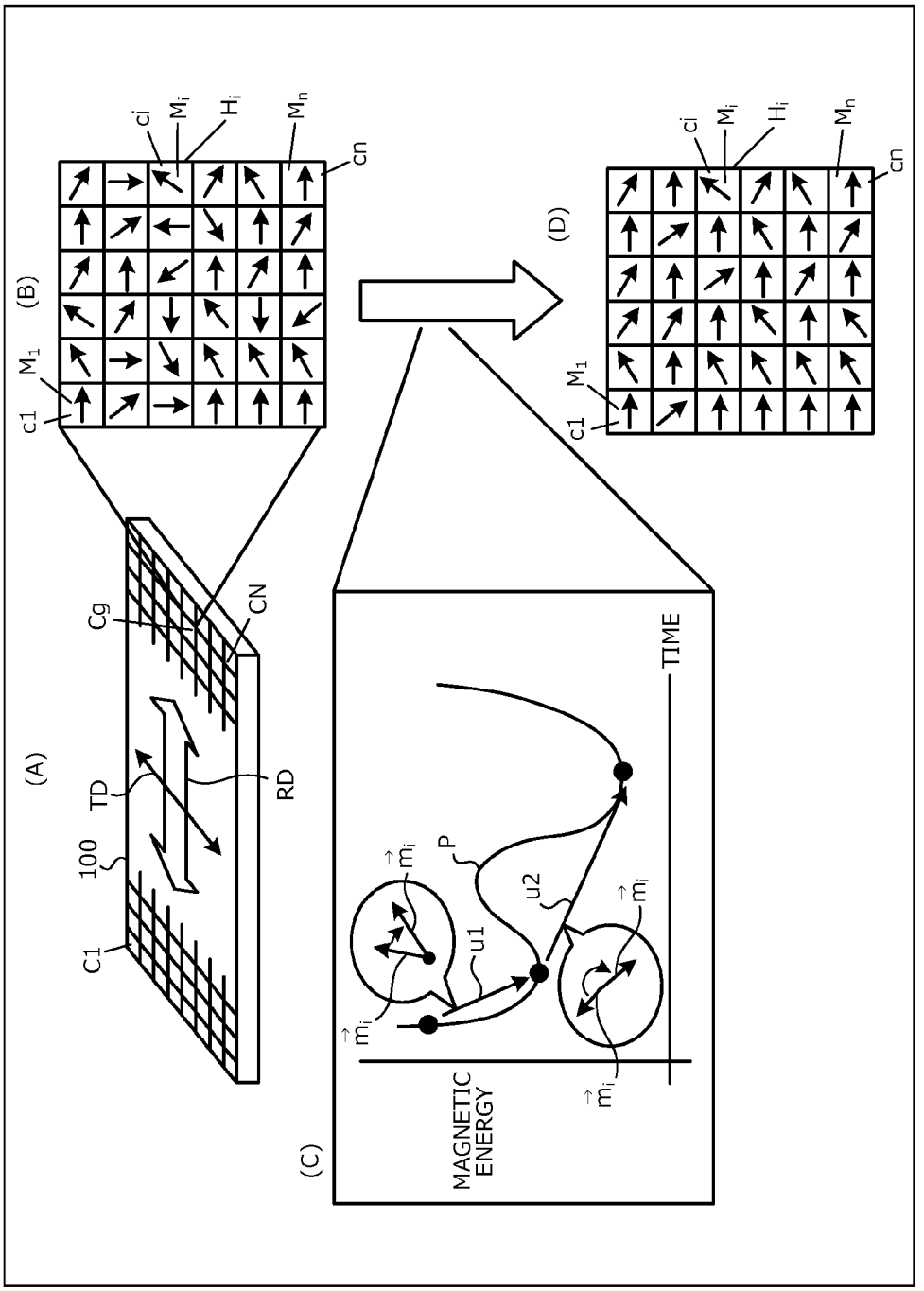

(A)
(B)
(C)
(D)
Cg
CN
TD
RD
100
C1
c1
M1
ci
Mi
Hi
Mn
cn
P
u1
u2
MAGNETIC ENERGY
TIME

FIG.2

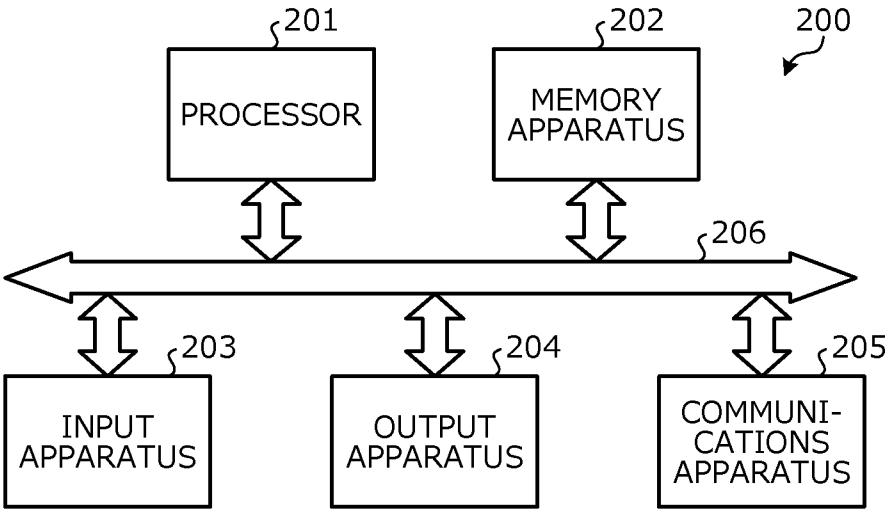

201
PROCESSOR
202
MEMORY APPARATUS
200
206
203
INPUT APPARATUS
204
OUTPUT APPARATUS
205
COMMUNI-CATIONS APPARATUS

FIG.3

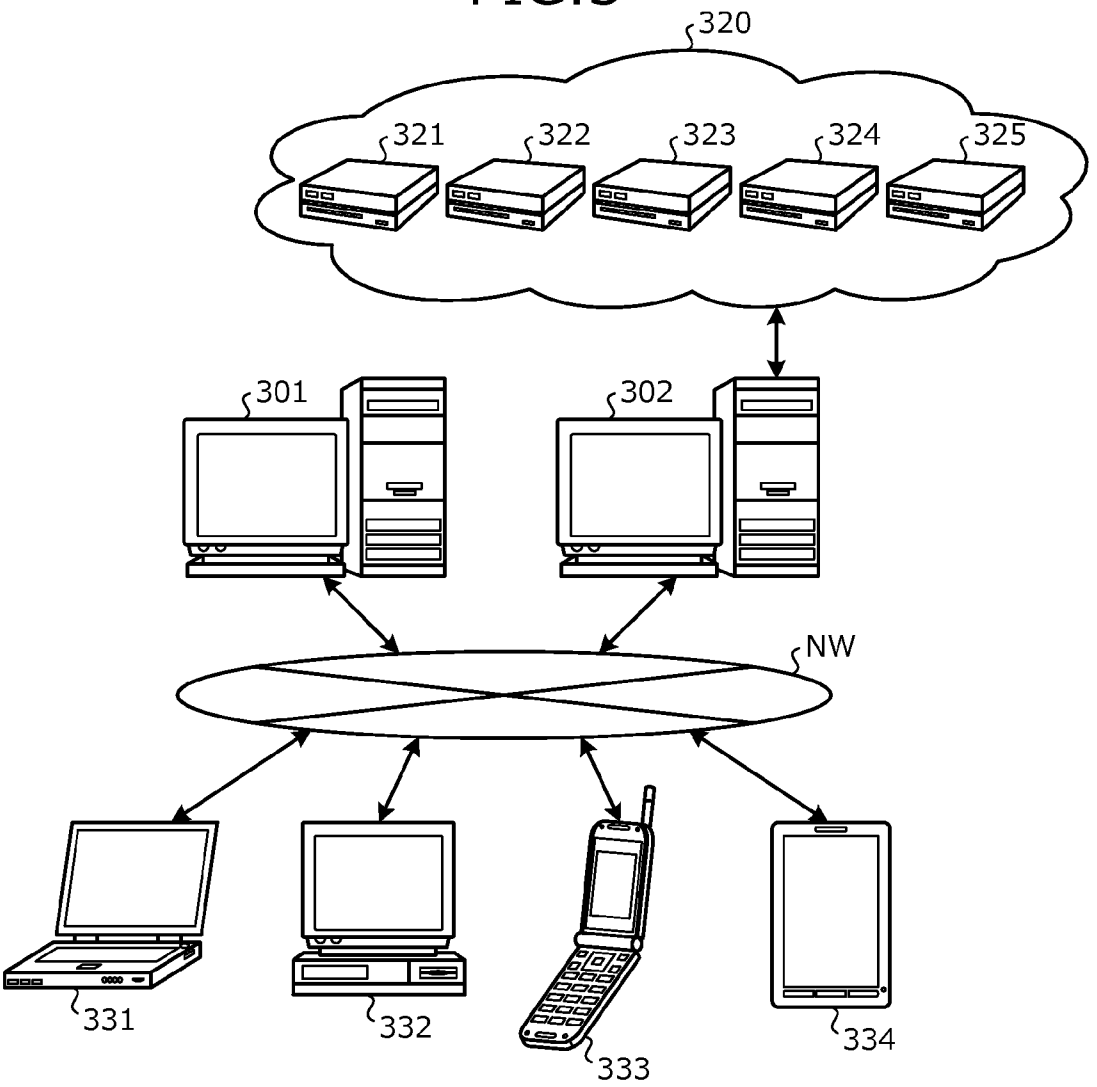


FIG.4

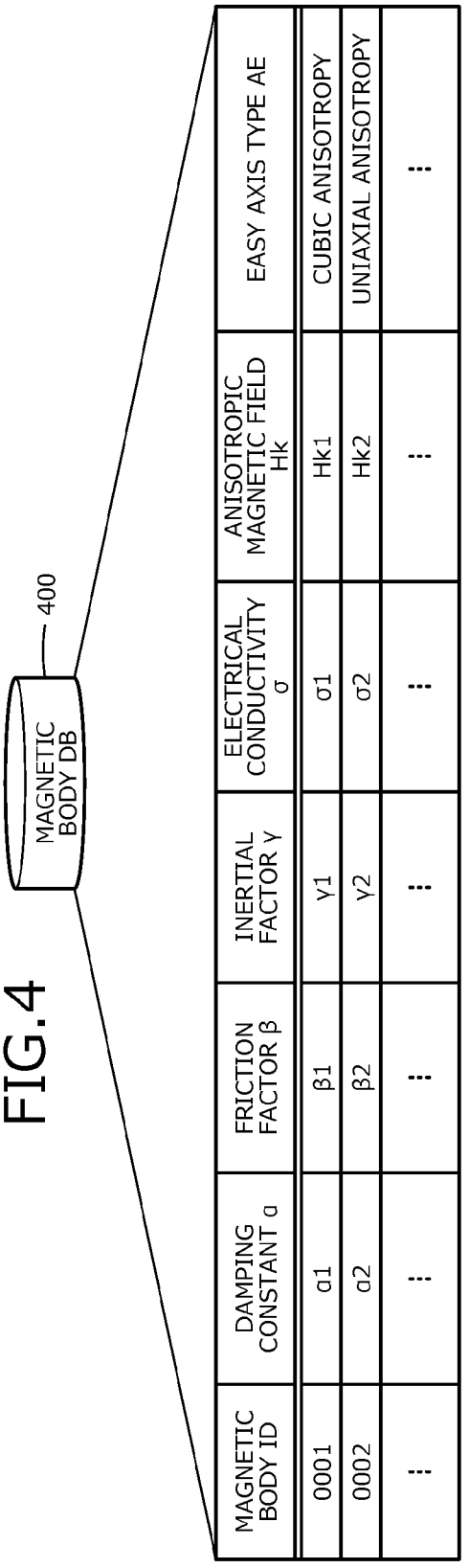

400
MAGNETIC BODY DB
MAGNETIC BODY ID
DAMPING CONSTANT α
FRICTION FACTOR β
INERTIAL FACTOR γ
ELECTRICAL CONDUCTIVITY σ
ANISOTROPIC MAGNETIC FIELD Hk
EASY AXIS TYPE AE
0001
α1
β1
γ1
σ1
Hk1
CUBIC ANISOTROPY
0002
α2
β2
γ2
σ2
Hk2
UNIAXIAL ANISOTROPY
...
...
...
...
...
...
...

FIG.5

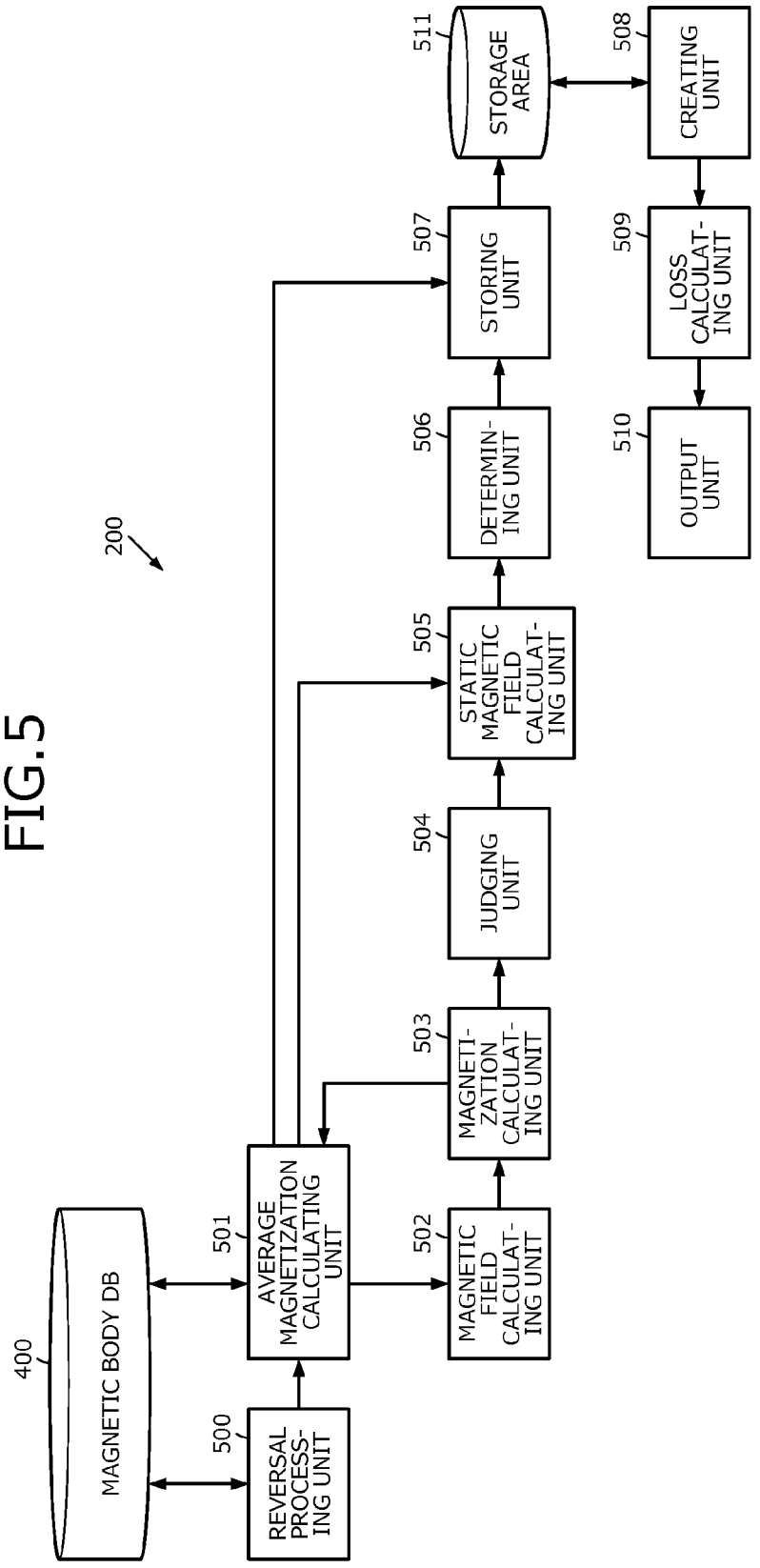

200
400
MAGNETIC BODY DB
500
REVERSAL PROCESSING UNIT
501
AVERAGE MAGNETIZATION CALCULATING UNIT
502
MAGNETIC FIELD CALCULATING UNIT
503
MAGNETIZATION CALCULATING UNIT
504
JUDGING UNIT
505
STATIC MAGNETIC FIELD CALCULATING UNIT
506
DETERMINING UNIT
507
STORING UNIT
508
CREATING UNIT
509
LOSS CALCULATING UNIT
510
OUTPUT UNIT
511
STORAGE AREA

FIG.6

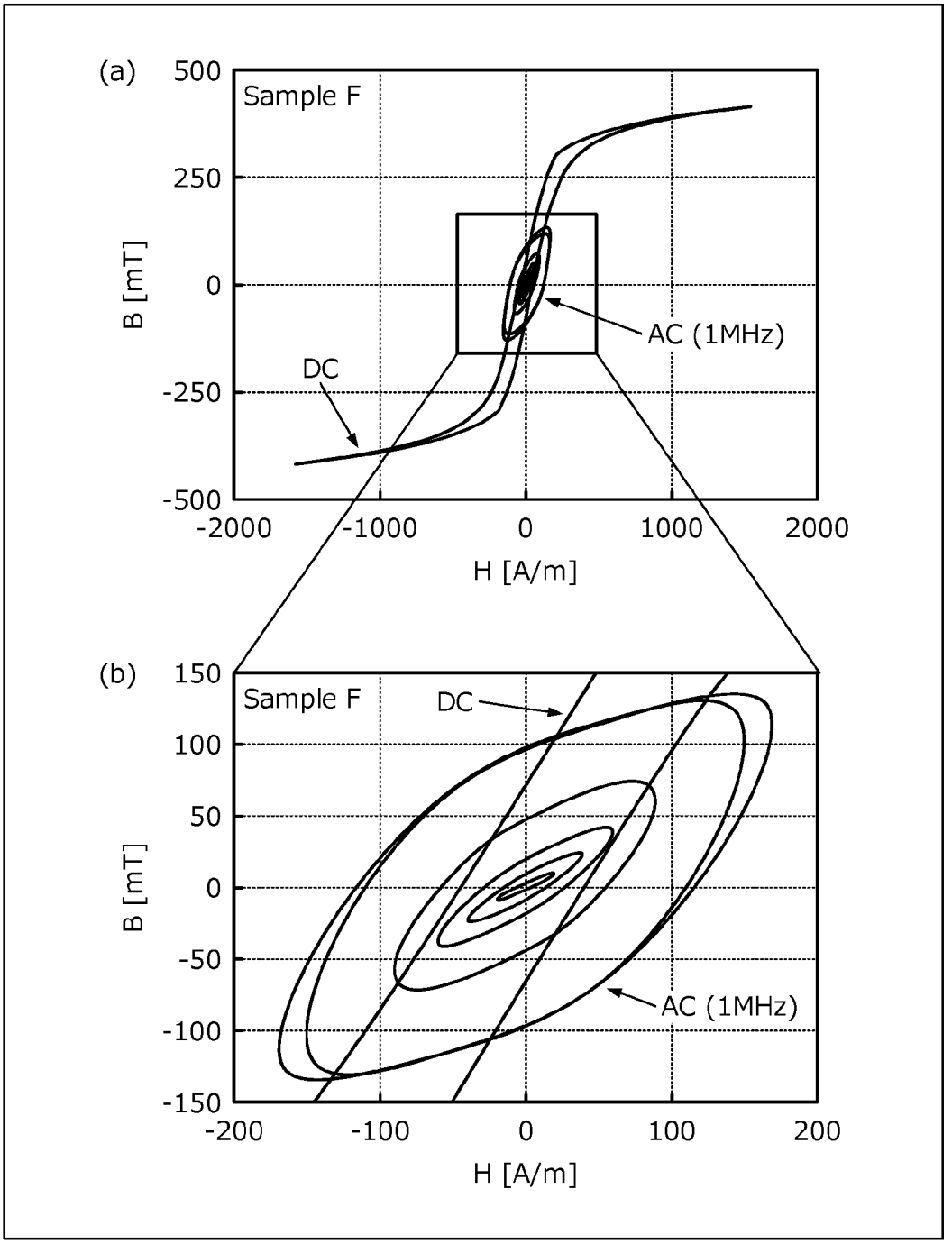

(a)
Sample F
500
250
0
-250
-500
B [mT]
DC
AC (1MHz)
-2000
-1000
0
1000
2000
H [A/m]
(b)
Sample F
DC
150
100
50
0
-50
-100
-150
B [mT]
AC (1MHz)
-200
-100
0
100
200
H [A/m]

FIG.7

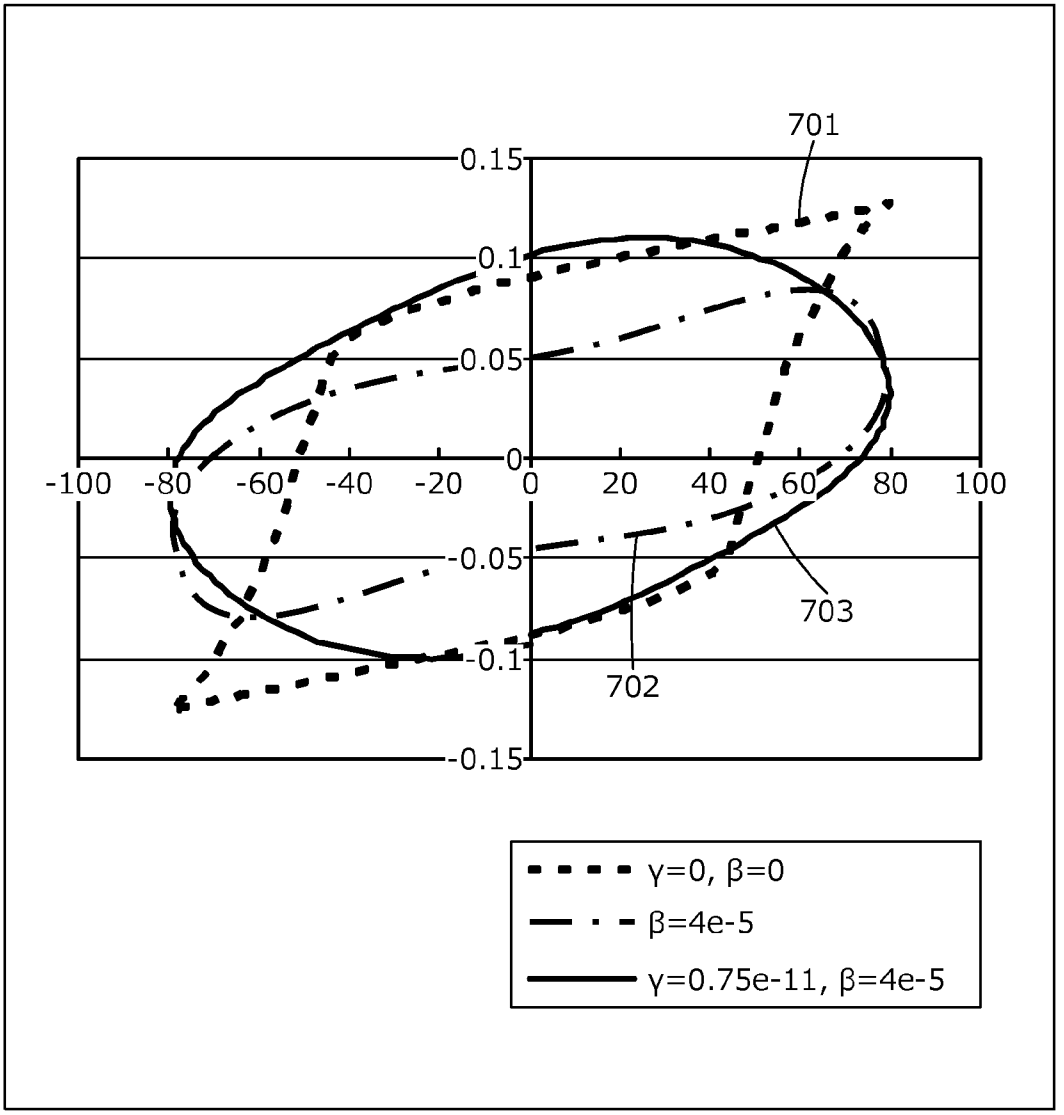

701
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-100
-80
-60
-40
-20
0
20
40
60
80
100
703
702
γ=0, β=0
β=4e-5
γ=0.75e-11, β=4e-5

FIG.8

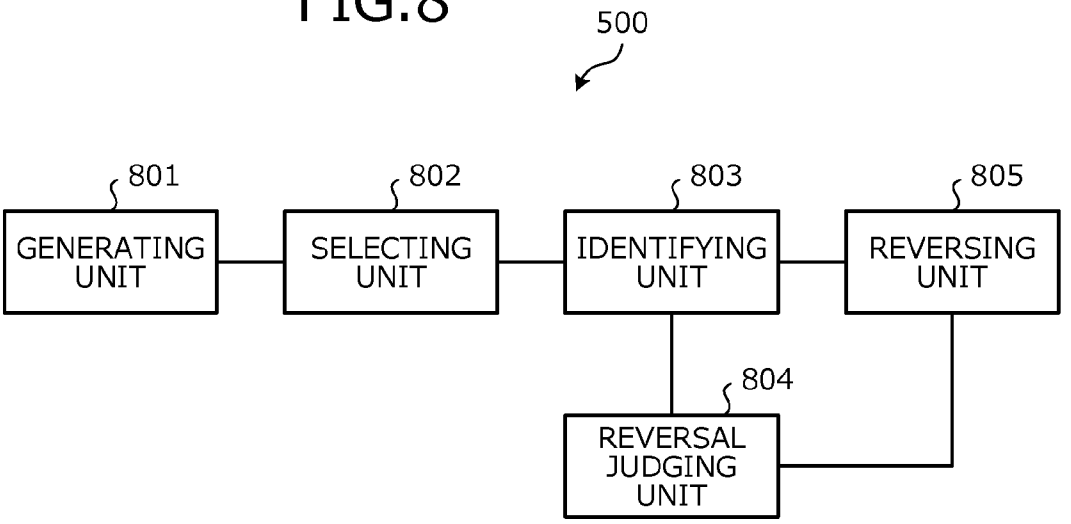

500
801
GENERATING UNIT
802
SELECTING UNIT
803
IDENTIFYING UNIT
805
REVERSING UNIT
804
REVERSAL JUDGING UNIT

FIG.9

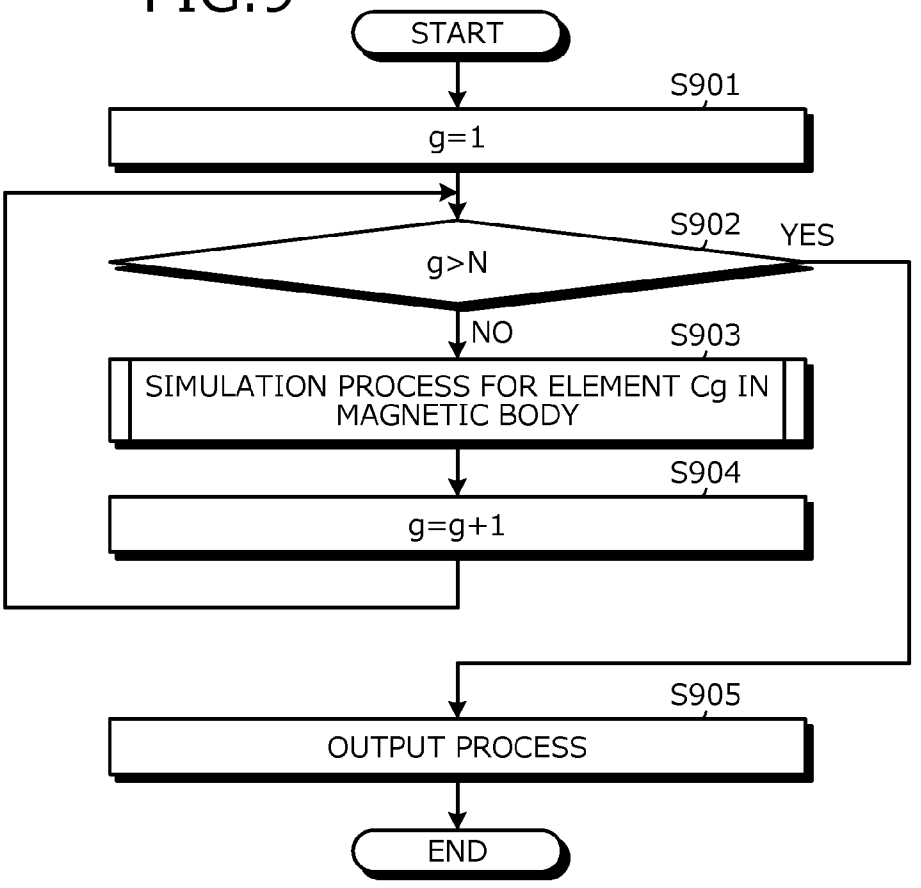

START
S901
g=1
S902
g>N
YES
NO
S903
SIMULATION PROCESS FOR ELEMENT Cg IN MAGNETIC BODY
S904
g=g+1
S905
OUTPUT PROCESS
END

FIG.10

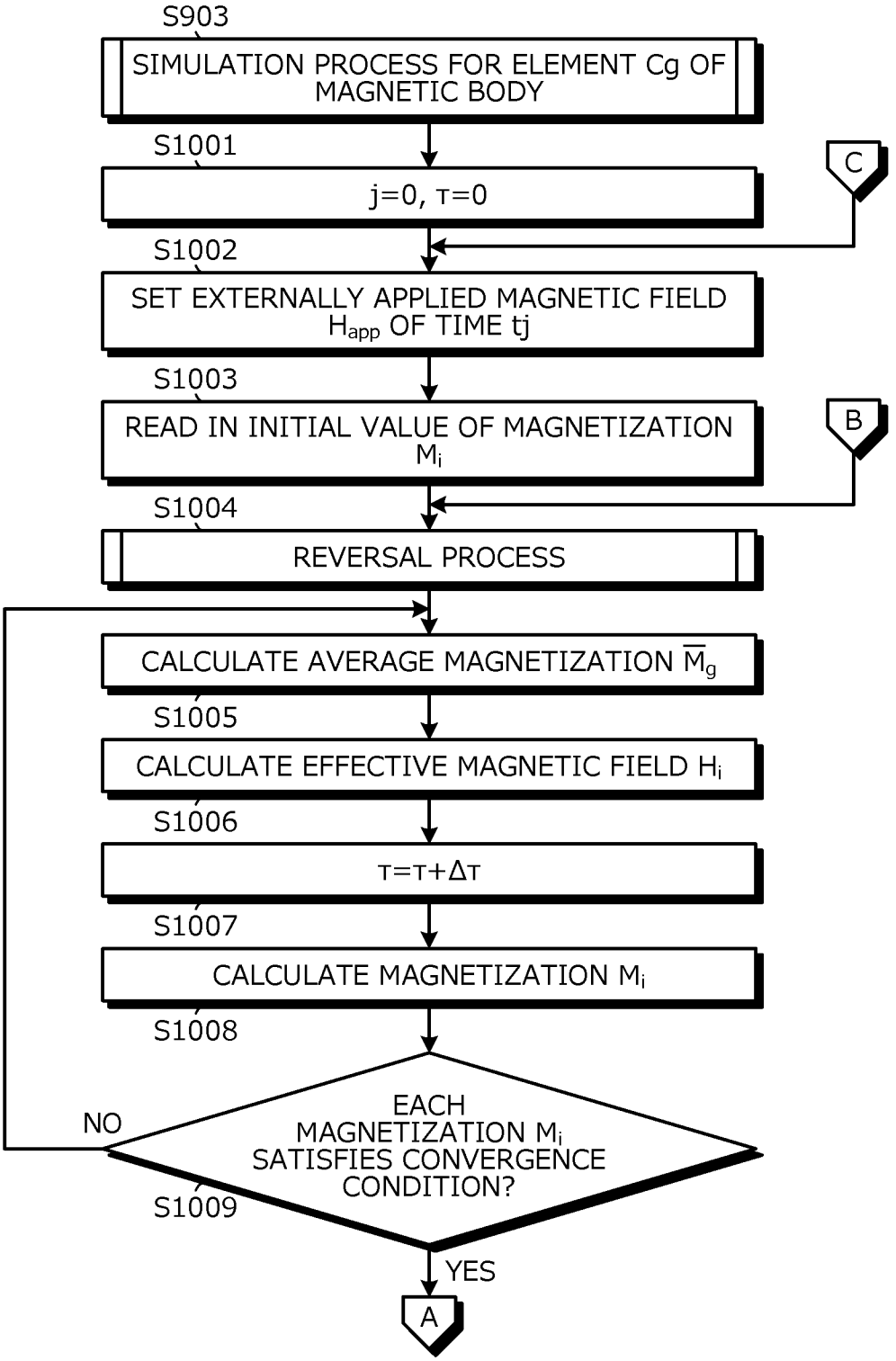

S903
SIMULATION PROCESS FOR ELEMENT Cg OF MAGNETIC BODY
S1001
j=0, τ=0
C
S1002
SET EXTERNALLY APPLIED MAGNETIC FIELD H_{app} OF TIME tj
S1003
READ IN INITIAL VALUE OF MAGNETIZATION M_i
B
S1004
REVERSAL PROCESS
CALCULATE AVERAGE MAGNETIZATION $\overline{M}_g$
S1005
CALCULATE EFFECTIVE MAGNETIC FIELD H_i
S1006
τ=τ+Δτ
S1007
CALCULATE MAGNETIZATION M_i
S1008
EACH MAGNETIZATION M_i SATISFIES CONVERGENCE CONDITION?
NO
S1009
YES
A

FIG.11

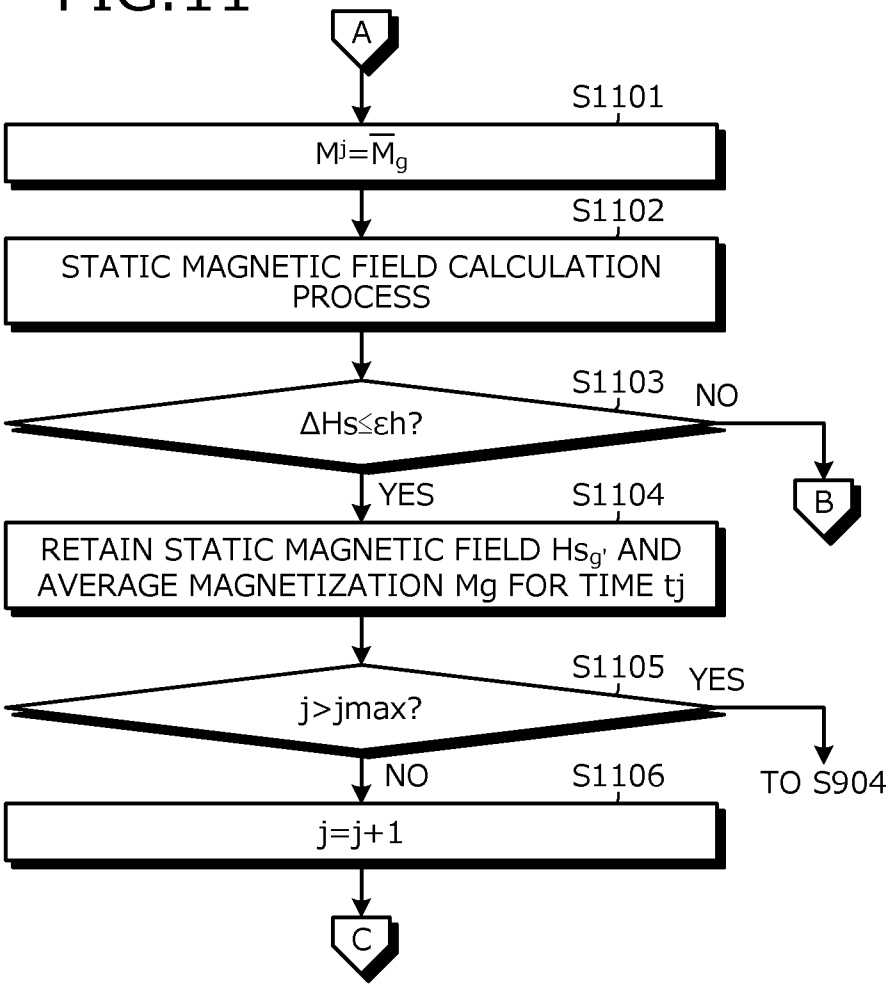

A
S1101
$M^j=\overline{M}_g$
S1102
STATIC MAGNETIC FIELD CALCULATION PROCESS
S1103
$\Delta Hs \leq \varepsilon h$?
NO
B
YES
S1104
RETAIN STATIC MAGNETIC FIELD $Hs_{g'}$ AND AVERAGE MAGNETIZATION Mg FOR TIME tj
S1105
j>jmax?
YES
TO S904
NO
S1106
j=j+1
C

FIG.12

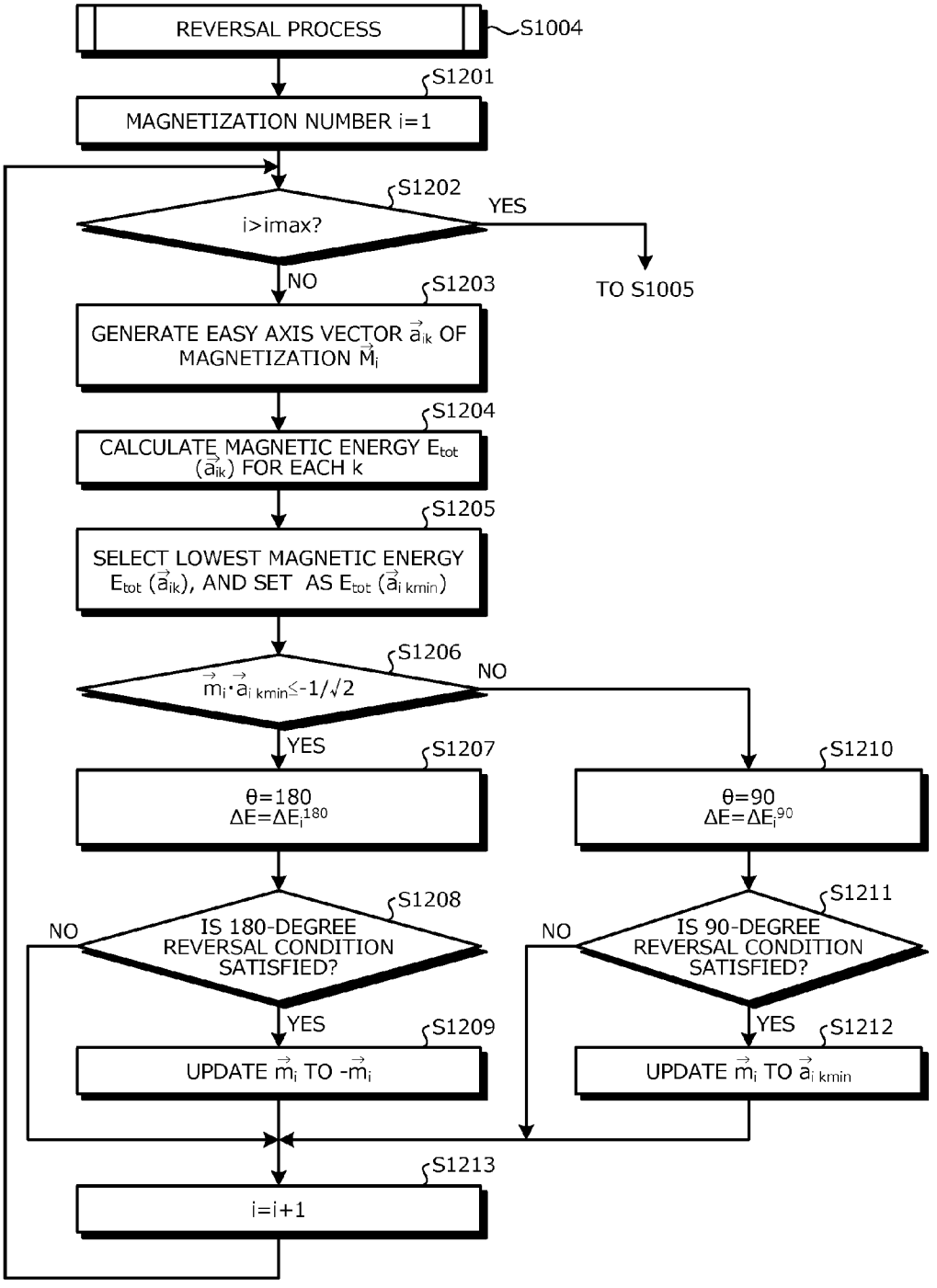
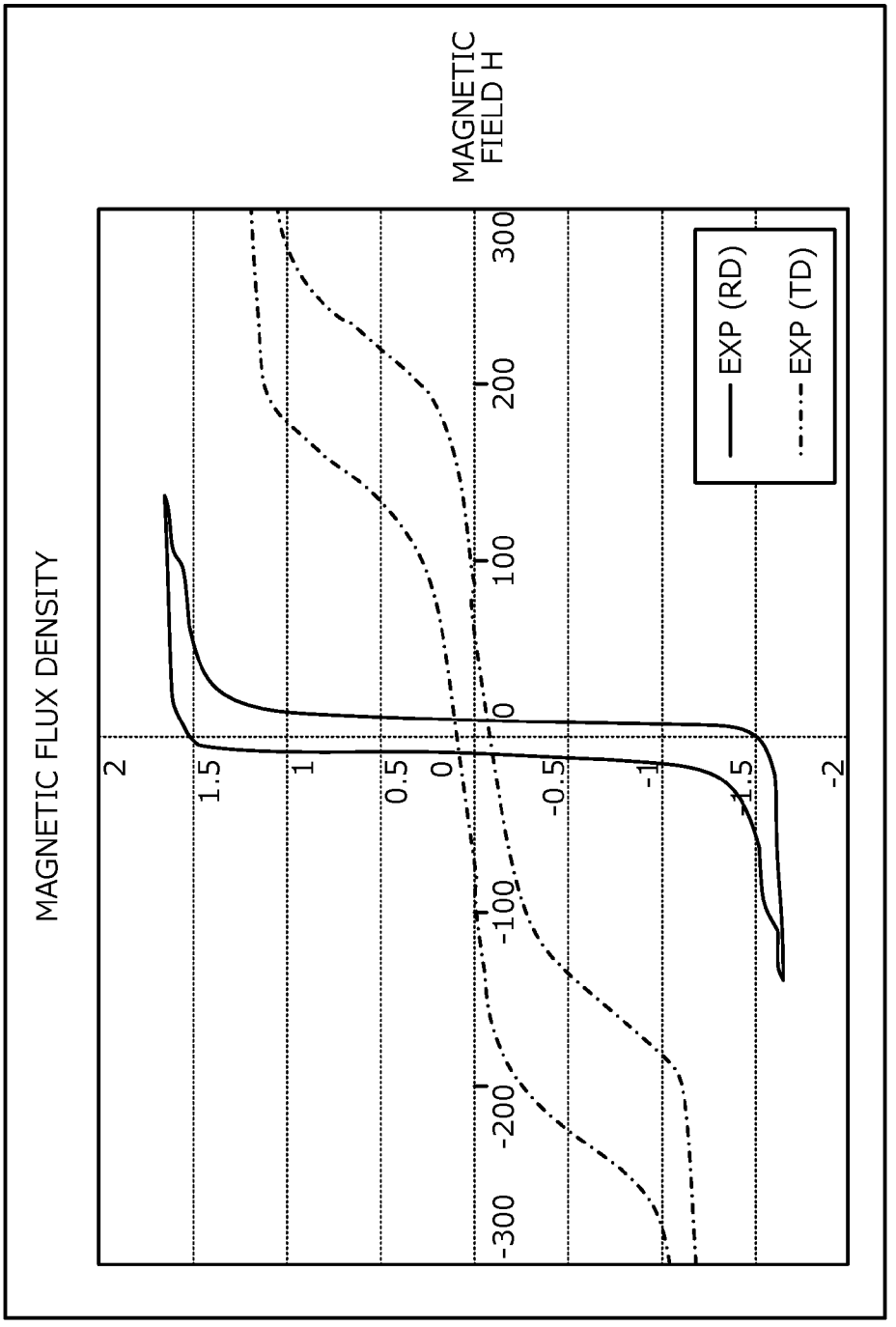

REVERSAL PROCESS
S1004
S1201
MAGNETIZATION NUMBER i=1
S1202
i>imax?
YES
TO S1005
NO
S1203
GENERATE EASY AXIS VECTOR $\vec{a}_{ik}$ OF MAGNETIZATION $\vec{M}_i$
S1204
CALCULATE MAGNETIC ENERGY E_{tot} ($\vec{a}_{ik}$) FOR EACH k
S1205
SELECT LOWEST MAGNETIC ENERGY E_{tot} ($\vec{a}_{ik}$), AND SET AS E_{tot} ($\vec{a}_{i\,kmin}$)
S1206
$\vec{m}_i \cdot \vec{a}_{i\,kmin} \leq -1/\sqrt{2}$
NO
YES
S1207
θ=180
$\Delta E=\Delta E_i^{180}$
S1210
θ=90
$\Delta E=\Delta E_i^{90}$
S1208
IS 180-DEGREE REVERSAL CONDITION SATISFIED?
NO
YES
S1209
UPDATE $\vec{m}_i$ TO $-\vec{m}_i$
S1211
IS 90-DEGREE REVERSAL CONDITION SATISFIED?
NO
YES
S1212
UPDATE $\vec{m}_i$ TO $\vec{a}_{i\,kmin}$
S1213
i=i+1

FIG.13


MAGNETIC FLUX DENSITY
MAGNETIC FIELD H
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
300
200
100
0
-100
-200
-300
EXP (RD)
EXP (TD)

MAGNETIC BODY SIMULATION COMPUTER PRODUCT, SIMULATION APPARATUS, AND SIMULATION METHOD

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation application of International Application PCT/JP2012/072083, filed on Aug. 30, 2012 and designating the U.S., the entire contents of which are incorporated herein by reference.

FIELD

[0002] The embodiments discussed herein are related to a magnetic body simulation computer product, simulation apparatus, and simulation method.

BACKGROUND

[0003] The simulation of electronic devices, such as motors and power generators, that use magnetic material has become widely performed in various contexts consequent to improved computer performance and advances in electromagnetic analysis techniques. The finite difference method and finite element method are generally used as electromagnetic analysis techniques. Recently, electronic device efficiency has become extremely important as a means to curb CO_2 and prevent global warming and therefore, expectations for simulation have become high.

[0004] The most commonly used material in devices, such as motors and transformers, to which a low-frequency alternating current is input is electrical steel sheeting. Electrical steel sheeting is steel whose conversion efficiency of electrical energy and magnetic energy has been increased. Magnetic anisotropy is a problem that arises when the hysteresis of electrical steel sheeting is represented. Electrical steel sheeting includes two types: grain-oriented electrical steel sheeting for which magnetic characteristics are good with respect to a specific direction, and non-oriented electrical steel sheeting for which magnetic characteristics are good to a certain extent with respect any direction. In particular, with grain-oriented electrical steel sheeting, the magnetization curve varies drastically consequent to the magnetic field application direction.

[0005] FIG. **13** is a graph depicting one example of a magnetization curve for grain-oriented electrical steel sheeting. A stop model is one method of coping with such a hysteresis curve by numerical computation. This method is used as a method of expressing arbitrary hysteresis characteristics from a mathematical perspective (for example, refer to Tetsuji Matsuo, Masaaki Shimasaki, "Representation Theorems for Stop and Play Models With Input-Dependent Shape Functions", IEEE TRANSACTIONS ON MAGNETICS, VOL. 41, NO. 5, May 2005, Pages 1548-1551).

[0006] Further, a technique based on micromagnetics has been disclosed as a technique to model from a microscopic perspective (for example, refer to Published Japanese-Translation of PCT Application, Publication No. 2011/114492). The conventional technique of Published Japanese-Translation of PCT Application, Publication No. 2011/114492 addresses domain wall displacement in a simplified manner.

[0007] Nonetheless, with the conventional technique of Tetsuji Matsuo, Masaaki Shimasaki, "Representation Theorems for Stop and Play Models With Input-Dependent Shape Functions", a problem arises in that when the hysteresis curve is numerically computed, the hysteron distribution has to be obtained and numerous measurements are required to identify the hysteron distribution. Further, concerning the magnetic characteristics of a magnetic body to be measured, although attributable to the microscopic crystalline structure of the material, the characteristics in a case where the crystalline structure has changed cannot be measured.

[0008] Further, with the conventional technique of Published Japanese-Translation of PCT Application, Publication No. 2011/114492, the orientation dependency of magnetic characteristics seen with grain-oriented electrical steel sheeting and non-oriented electrical steel sheeting cannot be reproduced. Therefore, in the conventional technique of Tetsuji Matsuo, Masaaki Shimasaki, "Representation Theorems for Stop and Play Models With Input-Dependent Shape Functions", even if the conventional technique of Published Japanese-Translation of PCT Application, Publication No. 2011/114492 is applied, a problem arises in that determining the extent to which the characteristics change consequent to how the crystalline structure varies is difficult.

SUMMARY

[0009] According to an aspect of an embodiment, a non-transitory, computer-readable recording medium stores a magnetic body simulation program that causes a computer to generate an easy axis vector in an area divided from an element of a group of elements forming a magnetic body; calculate magnetic energy of each magnetization of the divided area, select from among the calculated magnetic energies, a magnetic energy that is not the greatest; identify based on the magnetization of an area and a specific easy axis vector in a case of the selected magnetic energy, a reversal angle of magnetization reversal according to a height of an energy barrier that is consequent to pinning in the area; and reverse the magnetization by the identified reversal angle.

[0010] The object and advantages of the invention will be realized and attained by means of the elements and combinations particularly pointed out in the claims.

[0011] It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory and are not restrictive of the invention.

BRIEF DESCRIPTION OF DRAWINGS

[0012] FIG. **1** is a diagram depicting one example of simulation according to a first embodiment;

[0013] FIG. **2** is a block diagram depicting an example of a hardware structure of a simulation apparatus **200** that executes simulation;

[0014] FIG. **3** is a diagram depicting an example of system configuration using the simulation apparatus **200** depicted in FIG. **2**;

[0015] FIG. **4** is a diagram depicting one example of the contents stored in a magnetic body DB;

[0016] FIG. **5** is a block diagram depicting an example of a functional configuration of the simulation apparatus **200** according to the present embodiment;

[0017] FIG. **6** is a graph of a hysteresis curve by direct current to ferrite and the actual measured data, at 1.0 MHz, of the hysteresis curve;

[0018] FIG. **7** is a graph depicting simulation results of the present embodiment;

[0019] FIG. **8** is a block diagram depicting an example of a functional configuration of a reversal processing unit **500** depicted in FIG. **5**;

[0020] FIG. **9** is a flowchart depicting an example of a procedure of a simulation process by the simulation apparatus **200** according to the present embodiment;

[0021] FIG. **10** is a flowchart (part **1**) depicting an example of a detailed process procedure for the simulation process (step S**903**) for an element Cg in a magnetic body and depicted in FIG. **9**;

[0022] FIG. **11** is a flowchart (part **2**) depicting an example of a detailed process procedure of the simulation process (step S**903**) for an element Cg in the magnetic body and depicted in FIG. **9**;

[0023] FIG. **12** is a flowchart depicting an example of a detailed process procedure of reversal processing (step S**1004**) depicted in FIG. **10**; and

[0024] FIG. **13** is a graph depicting one example of a magnetization curve for grain-oriented electrical steel sheeting.

DESCRIPTION OF EMBODIMENTS

[0025] Embodiments of a magnetic body simulation program, simulation apparatus, and simulation method will be described in detail with reference to the accompanying drawings. In the description, vectors expressed in bold text in the drawings and equations are indicated using "[ ]". For example, vector X is [X]. Further, bar notations above vectors in the drawings and equations represent averages. In the description, vectors having such bar notations are indicated using "[av]". For example, vector X having such a bar notation is [Xav].

[0026] FIG. **1** is a diagram depicting one example of simulation according to a first embodiment. A magnetic body model **100** is digital data of a grain-oriented electrical steel sheet that is one example of a magnetic body and that has been modeled. The grain-oriented electrical steel sheet, for example, is a magnetic body for which the alternating current magnetic field is of a frequency f of 1.0 MHz or greater.

[0027] (A) depicts the magnetic body model **100** of the grain-oriented electrical steel sheet. In (A), RD is the rolling direction at the time of processing and TD is a direction orthogonal to the rolling direction. Characteristics of the magnetic body of the grain-oriented electrical steel sheet differ for the rolling direction RD and the orthogonal direction TD. The permeability for the rolling direction RD is high as compared to the orthogonal direction TD and the hysteresis loss for the rolling direction RD small as compared to the orthogonal direction TD. In the present embodiment, simulation is executed such that differences in the characteristics for the rolling direction RD and the orthogonal direction TD can be reproduced. The magnetic body model **100** is respectively assigned to N elements C**1** to CN (N≥2).

[0028] (B) is an enlarged view of an element Cg of the magnetic body model **100**. In (A), the magnetic body model **100** is expressed 3-dimensionally, but is expressed 2-dimensionally in (B) as a matter of convenience. The element Cg (1≤g≤N) has n (n≥2) areas **c1** to cn. The n (n≥2) areas **c1** to cn, for example, represent the micromagnetics distribution of magnetization. In micromagnetics, the magnetic energy of a magnetic body is expressed by magnetic anisotropic energy E_{ani}, magnetostatic energy E_{mag}, exchange interaction energy E_{exc}, and the Zeeman energy E_{ext} of equations (1) to (7).

$$E_{ani} = K[1-(k_i \cdot m_i)^2] \quad \text{(uniaxial anisotropy)} \tag{1}$$

$$E_{ani}(\vec{m_i}) = K_1(\alpha_{1,i}^2\alpha_{2,i}^2 + \alpha_{2,i}^2\alpha_{3,i}^2 + \alpha_{3,i}^2\alpha_{1,i}^2) \quad \text{(cubic anisotropy)} \tag{2}$$

$$E_{mag} = -M_i \cdot \left[\sum_{j \neq i} D_{ij} \cdot M_j + \frac{1}{2} D_{ij} \cdot M_j\right] \quad i = 1, 2, \ldots, n \tag{3}$$

$$D_{ij} = \frac{1}{v_i}\int_{v_i} dr^3 \int_{s_j} dr'^2 \frac{(r-r')\hat{n}'}{|r-r'|^3} \tag{4}$$

$$E_{exc} = -\frac{2A^*}{M^2a^2} M_i \cdot \sum_{n,n} M_j, \quad i = 1, 2, \ldots, n \tag{5}$$

$$E_{ext} = -H_{app} \cdot M_i, \quad i = 1, 2, \ldots, n \tag{6}$$

$$E_\sigma(\vec{m_i}) = -\frac{3}{2}\lambda_{100}\sigma\left(\alpha_{1,i}^2\gamma_{1,i}^2 + \alpha_{2,i}^2\gamma_{2,i}^2 + \alpha_{3,i}^2\gamma_{3,i}^2 - \frac{1}{3}\right) - 3\lambda_{111}\sigma(\alpha_{1,i}\alpha_{2,i}\gamma_{1,i}\gamma_{2,i} + \alpha_{2,i}\alpha_{3,i}\gamma_{2,i}\gamma_{3,i} + \alpha_{3,i}\alpha_{1,i}\gamma_{3,i}\gamma_{1,i}) \tag{7}$$

[0029] Where, K: magnetic anisotropy coefficient, [k]: unit vector of direction of easy magnetization axis, [m]: unit vector of magnetization direction, [M]: magnetization of area ci, M: extent of magnetization [M], D_{ij}: demagnetization field determined from geometric configuration of area ci, [r]: position vector of area ci, [r']: position vector of area cj, A*: stiffness constant, a: area interval, $[H_{app}]$: externally applied magnetic field, n: area count. Σ[M_j] is equation (5) is the sum of the magnetization of the areas adjacent to area [M_i].

[0030] λ_{100} and λ_{111} are magnetostriction constants. A magnetostriction constant has a value that differs according to the crystal axis. λ_{100} is the magnetostriction constant of the (100) direction and λ_{111} is the magnetostriction constant of the (111) direction. Further, α and γ are given by equations (8), (9).

$$\alpha_{1,i}^2 = (\vec{m_i} \cdot \vec{a}_{1,i})^2 \tag{8}$$

$$\gamma_{1,i}^2 = (\vec{\sigma} \cdot \vec{a}_{1,i})^2 \tag{9}$$

[0031] Where, $[a_{1,i}]$, $[a_{2,i}]$, and $[a_{3,i}]$ are the crystalline easy axes corresponding to an i-th magnetization and in the case of a cubic crystal, are vectors having axial directions a, b, and c indicating crystal orientation and having a length of 1. [σ] is a unit vector of the application direction of stress. The easy axis, in a grain-oriented electrical steel sheet and when the rolling direction RD is assumed to be the x axis, has the value $[a_{1,i}]=(1,0,0)$. Assuming the orthogonal direction TD, which is orthogonal to the rolling direction RD of the electrical steel sheet, to be the y axis, the easy axis is $[a_{2,i}]=(0,1/\sqrt{2},1/\sqrt{2})$. $[a_{3,i}]$ is set in a direction orthogonal to $[a_{1,i}]$ and $[a_{2,i}]$.

[0032] In FIG. **1**, arrows in the areas ci (1≤i≤n) indicate magnetization [M_i]. The magnetization [M_i] varies at each very small period Δτ. By dividing the sum of the magnetization [M_i] of the areas ci by the area count n, the average magnetization [Mav] is obtained. The unit vector [m_i] of the magnetization direction in an area ci is represented by $[m_i]=[M_i]/M_i$.

[0033] Overall magnetic energy E_{tot} in the element Cg of the magnetic body is represented by the sum of the magnetic anisotropic energy E_{ani}, the magnetostatic energy E_{mag}, the exchange energy E_{exc}, the Zeeman energy E_{ext}, and the mag-

netoelastic energy Eσ([m_i]) caused by stress, as indicated by equation (10).

$$E_{tot}(\vec{m}_i)=E_{ani}(\vec{m}_i)+E_{mag}(\vec{m}_i)+E_{exc}(\vec{m}_i)+E_{ext}(\vec{m}_i)+E_{\sigma}(\vec{m}_i) \quad (10)$$

[0034] These energies differ according to what is being calculated and are calculated as combinations of the above energies having one or more items. Here, when the magnetic state is calculated, two types of processes, magnetic rotation and magnetization reversal, are calculated. The first is a method according to the Landau-Lifshitz-Gilbert equation (hereinafter, "LLG equation"). Here, magnetic rotational motion according to the effective magnetic field is calculated.

[0035] (C) depicts a concept of magnetic rotational motion. With magnetic rotational motion, the respective magnetizations vary according to the LLG equation. In this case, the magnetization rotates in the direction of lower energy and therefore, as indicated by u**1**, continuously changes in the magnetization direction of lower energy. On the other hand, with magnetization reversal, as indicated by u**2**, domain wall pinning P, which is a magnetization energy barrier, is overcome and discontinuous variation toward a position of energy corresponding to 180 degrees or 90 degrees occurs. In the present embodiment, by reproducing (C) for each area ci by simulation, a state after magnetic rotation or magnetization reversal such as that depicted in (D) is obtained.

[0036] Thus, from a macroscopic view such as that of (A), although the direction of magnetization of the magnetic body is the rolling direction RD, from a microscopic view such as that of (D), the direction of the magnetization [M_i] of an area ci in the element Cg is not uniform. This contrast occurs because simulation is executed taking the presence of impurities in the magnetic body into consideration. Since the simulation apparatus executes such simulation, in the magnetic body, orientation dependency in which the direction of magnetization is dependent on the direction of a specific crystal axis and reverses can be reproduced with high accuracy.

[0037] Here, calculation of the magnetic rotational motion indicated by u**1** of (C) will be described. The magnetic rotational motion is calculated from the effective magnetic field, which is calculated based on the energy. The effective magnetic field is calculated as indicated by equation (11).

$$H_i = -\frac{\partial E_{tot}(\vec{m}_i)}{\partial M_i} \quad (11)$$

[0038] Equation (11) is the magnetic field by magnetic energy for the magnetization [M_i] in an area ci. The effective magnetic field [H_i] is used to obtain temporal variation of the magnetization [M_i] of the next time. Normalization of equation (11) by the magnetic anisotropy H_k=2K/M yields equation (12).

$$h_i = \frac{H_i}{H_k} = (k_i \cdot m_i)k_i + h_m\sum_{j=1}^{N} D_{ij}\cdot m_j + h_e\sum_{n,n} m_j + h_a + \frac{3\lambda_{100}\sigma}{H_k}(\vec{a}_{1,i}\alpha_{1,i}\gamma_{1,i}^2 + \vec{a}_{2,i}\alpha_{2,i}\gamma_{2,i}^2 + \vec{a}_{3,i}\alpha_{3,i}\gamma_{3,i}^2) + 3\lambda_{111}\sigma(\vec{a}_{1,i}(\alpha_{2,i}\gamma_{1,i}\gamma_{2,i} + \alpha_{3,i}\gamma_{3,i}\gamma_{1,i}) + \vec{a}_{2,i}(\alpha_{1,i}\gamma_{1,i}\gamma_{2,i} + \alpha_{3,i}\gamma_{2,i}\gamma_{3,i})) + 3\lambda_{111}\sigma\cdot\vec{a}_{3,i}(\alpha_{2,i}\gamma_{2,i}\gamma_{3,i} + \alpha_{1,i}\gamma_{3,i}\gamma_{1,i}) \quad (12)$$

[0039] Where, h_m, h_e are respectively a static magnetic field coefficient and an exchange interaction coefficient normalized by the magnetic anisotropy H_k as indicated by equations (13), (14). Further, h_k is the externally applied magnetic field H_{app}/H_k normalized by the magnetic anisotropy H_k.

$$h_m = \frac{M}{H_k} \quad (13)$$

$$h_e = \frac{A^*}{Ka^2} \quad (14)$$

[0040] The motion of the magnetization of the magnetic body is determined by the LLG equation indicated by equation (15).

$$\frac{dm_i}{d\tau} = m_i \times h_i - \alpha m_i \times (m_i \times h_i), \quad i = 1, 2, \ldots, n \quad (15)$$

[0041] Where, α is a damping constant. The damping constant α is a magnetic-body-specific constant representing the speed of a process of damping. The first term on the right side of equation (15) is a precessional motion term and the second term is a damping term. In the case of ferrite, for example, α=0.1 is used. τ is a time variable for executing the calculation of the LLG equation.

[0042] Here, a distribution calculation method of the LLG equation will be described using equation (16). In the calculation of equation (16), Δτ is a calculation time step length of the LLG equation. Here, the step length of each step is uniform.

$$m_i^{new}=m_i^{old}+\{m_i^{old}\times h_i-\alpha m_i^{old}\times(m_i^{old}\times h_i)\}\Delta\tau, i=1, 2, \ldots n \quad (16)$$

[0043] $[m_i]^{old}$ is the [m_i] at the current time step τ and $[m_i]^{new}$ is the [m_i] at the next time step (τ+Δτ).

[0044] For each time step, equations (17), (18) are evaluated.

$$\left(\frac{\partial \overline{M}}{\partial t}\right) = \frac{\overline{M}^j - \overline{M}^{j-1}}{\Delta t} \quad (17)$$

$$\left(\frac{\partial^2 \overline{M}}{\partial t^2}\right) = \frac{\overline{M}^j - 2\overline{M}^{j-1} + \overline{M}^{j-2}}{\Delta t^2} \quad (18)$$

[0045] Where, $[Mav]^j$ is the average magnetization in the element Cg at (time t_j) when all of the magnetization [M_i] in the element Cg is converged. $[Mav]^{j-1}$ is the average magnetization immediately before $[Mav]^j$ when all of the magnetization [M_i] in the element Cg is converged. Further, $[Mav]^{j-2}$ is the average magnetization immediately before $[Mav]^{j-1}$ when all of the magnetization [M_i] in the element Cg is converged.

[0046] Convergence determination of the magnetization above, for example, is executed by equation (19).

$$\Delta m=(m_i^{new}-m_i^{old})^2<\epsilon_m \quad (19)$$

[0047] The simulation apparatus determines convergence if for all of $[m_i]$, the magnetization has become less than a minute amount ϵ_m. Here, 1.e-6 is used for ϵ_m.

[0048] Magnetization reversal motion will be described. The magnetization reversal process corresponds to rapidly changing the direction of the magnetization to the easy axis along which energy becomes low. This corresponds to the phenomenon of magnetic domains of low energy consequent to domain wall displacement increasing, rather than the magnetization in a very small area and consequent to domain wall displacement, rotating as a whole. However, in general, domain wall displacement does not always move smoothly and the suppression of domain wall displacement called pinning and consequent to impurities occurs. Since domain wall pinning occurs, the magnetization cannot be further transitioned to a lower energy state. With magnetization reversal, discontinuous magnetization variations corresponding to 180 degrees and 90 degrees are possible, in which case, reversal is calculated from the magnitude relation of the energy. The 180-degree reversing process corresponding to 180-degree domain wall displacement is calculated by expression (20).

$$\vec{m}_i(r_i)\Rightarrow -\vec{m}_i \text{ if } (E_{tot}(\vec{m}_i)-E_{tot}(-\vec{m}_i))\geq\Delta E_i^{180} \quad (20)$$

[0049] Where, ΔE_i^{180} is a parameter corresponding to the height of the energy barrier that is consequent to pinning. The electrical steel sheet has anisotropy mainly consequent to a cubical crystal. In other words, in the direction of a axis, b axis, and c axis, which are crystal axes, the magnetic anisotropic energy becomes smaller. Therefore, not only 180-degree reversing, but also 90-degree reversing is present. The 90-degree reversing process is calculated by expression (21).

$$\vec{m}_i\Rightarrow \vec{a}_{ik} \text{ if } (E_{tot}(\vec{m})-E_{tot}(\vec{a}_{ik}))\geq\Delta E_i^{90} \quad (21)$$

[0050] In expression (21), $[a_j]$ is an easy axis vector. Further, $E_{tot}([a_j])$ in expression (21) is calculated by substituting in equation (10), $[a_j]$ into $E_{tot}(\ )$ instead of $[m_i]$. The unit vector $[m_i]$ of the magnetization $[M_i]$ has a property of easily becoming parallel to any one of the crystal axes, a axis, b axis, and c axis. Therefore, the unit vector $[m_i]$ of the magnetization $[M_i]$ before reversal is reversed to a crystal axis of low energy by 90-degree reversing. For example, if the direction of the unit vector $[m_i]$ of the magnetization $[M_i]$ before reversal is the direction of a axis, the direction of the unit vector $[m_i]$ of the magnetization $[M_i]$ after reversal is any one of the directions of b axis and c axis, these directions being of a lower magnetic energy than the direction of a axis. More specifically, the direction of the unit vector $[m_i]$ of the magnetization $[M_i]$ after reversal is the direction for which the energy is lower among the directions of b axis and c axis.

[0051] To reproduce this property, in the present embodiment, if the inequality of expression (21) is satisfied in the 90-degree reversing, the unit vector $[m_i]$ of the magnetization $[M_i]$ before reversal is updated to the easy axis vector $[a_j]$ having a lower magnetic energy than the unit vector $[m_i]$ of the magnetization $[M_i]$ before reversal. The unit vector $[m_i]$ of the magnetization $[M_i]$ before reversal and the easy axis vector $[a_j]$ are orthogonal and therefore, the 90-degree reversing can be reproduced by a simple calculation.

[0052] As depicted by u**2** of (C) in FIG. **1**, with magnetization reversal, both the 180-degree reversing of expression (20) and the 90-degree reversing of expression (21) may occur. In this case, since transition to a state in which the energy difference is greatest conceivable, the simulation apparatus reverses the magnetization to a state in which the energy becomes the least.

[0053] Thereafter, if each of the magnetizations $[M_i]$ satisfies the convergence determination of equation (19), for the element Cg, static magnetic field calculation using the average magnetization [Mav] is executed. In the static magnetic field calculation, the static magnetic field Hs_g is obtained using equation (22). υ is the inverse of the permeability μ.

$$rot(\upsilon rotA)=J_0-\sigma\frac{\partial A}{\partial t}-\sigma\cdot grad\phi \quad (22)$$

[0054] The static magnetic field calculation in the finite element method is performed using equation (16), which is from a derivation of Maxwell's equation, a basic equation of electromagnetics. Where, A is the magnetic vector potential and J_0 is the current flowing in the magnetic body subject to calculation.

[0055] In the present embodiment, the magnetic body is of high resistivity and therefore, the current flowing in the magnetic body becomes $J_0=0$. Further, if an external current is present, the effects of the external current have to be considered and therefore, J_0 is given the value of the external current. By providing positional coordinates of the element Cg to the magnetic vector potential A of equation (22), the magnetic vector potential A is obtained. The magnetic vector potential A is defined to be [B]=rot(A), when the magnetic flux density [B]=μ[H]+[M]. Therefore, if the magnetic vector potential A is obtained, the magnetic flux density [B] is also obtained. If the magnetic flux density [B] is obtained, by providing the magnetization [M], the static magnetic field [H] is obtained.

[0056] In the present example, by providing [Mav] to M, the static magnetic field $[Hs_g]$ is obtained by the static magnetic field calculation. Each time the static magnetic field $[Hs_g]$ converges magnetization, a combination of the average magnetization [Mav] and static magnetic field $[Hs_g]$ at that time are saved. The average magnetization [Mav] and the static magnetic field $[Hs_g]$ can provide multiple combinations and therefore, a hysteresis curve HLg is created by plotting to a graph. The area Sg in the hysteresis curve HLg is the hysteresis loss for the element Cg.

[0057] Thus, even for the magnetic body of a high resistivity magnetic material, magnetization variations consequent to resonance phenomenon can be reproduced with high accuracy and therefore, hysteresis loss due to the resonance phenomenon of the magnetic body of a high resistivity magnetic material can be obtained with high accuracy.

[0058] FIG. **2** is a block diagram depicting an example of a hardware structure of a simulation apparatus **200** that executes simulation. In FIG. **2**, the simulation apparatus **200** is a computer that is configured by a processor **201**, a memory apparatus **202**, an input apparatus **203**, an output apparatus **204**, and a communications apparatus **205** connected by a bus **206**.

[0059] The processor **201** governs overall control of the simulation apparatus **200**. The processor **201** executes various programs (operating system (OS), the program of the present embodiment, etc.) stored in the memory apparatus

202 whereby, data in the memory apparatus **202** is read out, data resulting from the execution of programs is written to the memory apparatus **202**, etc.

[0060] The memory apparatus **202** is configured by read-only memory (ROM), random access memory (RAM), flash memory, a magnetic disk drive, etc., is used as a work area of the processor **201**, and stores various programs (the OS, the program of the present embodiment, etc.), various types of data (including data obtained by an execution of the various programs), etc.

[0061] The input apparatus **203** is an interface that performs the input of various types of data by user operation of a keyboard, a mouse, touch panel, etc. The output apparatus **204** is an interface that outputs data by an instruction of the processor **201**. The output apparatus **204** may be a display, a printer, and the like. The communications apparatus **205** is an interface that receives data from external sources via a network, outputs data to external destinations, etc.

[0062] FIG. **3** is a diagram depicting an example of system configuration using the simulation apparatus **200** depicted in FIG. **2**. In FIG. **3**, a network NW is a network communicable with servers **301**, **302** and clients **331** to **334** and for example, is configured by a local area network (LAN), a wide area network (WAN), the internet, a mobile telephone network, etc.

[0063] The server **302** is a management server of a server group (servers **321** to **325**) configuring a cloud **320**. Among the clients **331** to **334**, the client **331** is a notebook personal computer, the client **332** is a desktop personal computer, the client **333** is a mobile telephone (may be a smartphone, personal handyphone system (PHS), etc.), and the client **334** is a tablet terminal. The servers **301**, **302**, **321** to **325**, and the clients **331** to **334** of FIG. **3**, for example, are realized by the simulation apparatus **200** depicted in FIG. **2**. The clients **331** to **334** do not always have to be connected to the network NW.

[0064] FIG. **4** is a diagram depicting one example of the contents stored in a magnetic body DB. In FIG. **4**, a magnetic body DB **400** stores for each magnetic body, a magnetic body ID, a damping constant α, a friction factor β, an inertial factor γ, the electrical conductivity σ, the anisotropic magnetic field Hk, and an easy axis type AE.

[0065] The electrical conductivity σ and the anisotropic magnetic field Hk are used in the static magnetic field calculation for the element Cg. The easy axis type AE represents the easy axis of magnetization (hereinafter, simply "easy axis") applied to the magnetic body. An easy axis is a crystal orientation that is easily magnetized. For example, in the case of iron, six easy axes are present. The easy axis type includes two types, uniaxial anisotropy and cubic anisotropy. In the case of uniaxial anisotropy, there are two easy axes that are in opposite directions of each other. In the case of cubic anisotropy, there are six easy axes, including the three axes: a axis, b axis, and c axis, plus three axes of opposite directions thereof. The easy axis type AE of iron is cubic anisotropy and therefore, there are six easy axes of iron. When the magnetic body ID is specified by the computer, the values in the record of the specified magnetic body ID are read out from the magnetic body DB **400**. More specifically, for example, a function of the magnetic body DB **400** is realized by the memory apparatus **202** depicted in FIG. **2**.

[0066] FIG. **5** is a block diagram depicting an example of a functional configuration of the simulation apparatus **200** according to the present embodiment. The simulation apparatus **200** has the magnetic body DB **400** and a storage area **511**. Further, the simulation apparatus **200** has a reversal processing unit **500**, an average magnetization calculating unit **501**, a magnetic field calculating unit **502**, a magnetization calculating unit **503**, a judging unit **504**, a static magnetic field calculating unit **505**, a determining unit **506**, a storing unit **507**, a creating unit **508**, a loss calculating unit **509**, and an output unit **510**. More specifically, for example, functions of the reversal processing unit **500** to the output unit **510** are realized by causing the processor **201** to execute the simulation program stored in the memory apparatus **202** depicted in FIG. **2**. Further, a function of the storage area **511** is realized by the memory apparatus **202** depicted in FIG. **2**.

[0067] The reversal processing unit **500** executes reversal processing for the magnetization $[M_1]$ to $[M_n]$ of the areas **c1** to cn in the element Cg. Details of the reversal processing unit **500** will be described with reference to FIG. **8**.

[0068] The average magnetization calculating unit **501** calculates the average magnetization [Mav] of the magnetization $[M_1]$ to $[M_n]$ of the areas **c1** to cn in the element Cg, each time the time τ changes by $\Delta\tau$. More specifically, for example, the average magnetization [Mav] is calculated by equation (23).

$$\overline{M} = \frac{\sum M_i}{n} \tag{23}$$

[0069] When the magnetization of each area among a group of areas into which an element of an element group forming the magnetic body is divided is updated, the magnetic field calculating unit **502** calculates for each area, the effective magnetic field generated by the magnetic energy in the area. Here, "the magnetic field generated by the magnetic energy in the area" is the magnetic field generated by the magnetic energy in the area ci and corresponds to the right term of equation (11).

[0070] Further, the magnetic field calculating unit **502** may calculate the effective magnetic field by taking into consideration the rate of magnetization variation working in a direction that prevents variation of the average magnetization of the updated areas, and the inertia that brings into action, a magnetic field in a direction that keeps the rate of magnetization variation constant. In this case, equation (24) is used in place of equation (11).

$$H_i = -\frac{\partial E_{tot}(r)}{\partial M_i} - m\frac{\partial^2 \overline{M}}{\partial t^2} - \beta\frac{\partial \overline{M}}{\partial t} \tag{24}$$

[0071] "The rate of magnetization variation working in a direction that prevents variation of the average magnetization of the updated areas" is the rate of magnetization variation working in a direction that prevents variation of the average magnetization [Mav] and corresponds to the friction term, which is the third term on the right side of equation (24). Further, "the inertia that brings into action, the magnetic field in a direction that keeps the rate of magnetization variation constant" is the inertia that brings into action, a magnetic field in a direction that keeps the rate of magnetization variation expressed by the friction term of equation (24) constant and corresponds to the inertia term, which is the second term on the right side of equation (24). In equation (24), the first term

on the right side is the magnetic field generated by the magnetic energy in the area ci and corresponds to the right side of equation (11).

[0072] The magnetic field calculating unit **502** calculates the effective magnetic field $[H_i]$ of the area ci by equation (11) or equation (24), each time the time τ changes by $\Delta\tau$. The inertia term may be omitted from the right side of equation (24). The effective magnetic field $[H_i]$ is used in obtaining the magnetization $[M_i]$ of the next time.

[0073] Thus, by obtaining the effective magnetic field $[H_i]$ using the friction term, in the area ci, the amount of change $\Delta[M_i]$ from the magnetization $[M_i]$ of the time $(\tau-\Delta\tau)$ to the magnetization $[M_i]$ of the time τ can be obtained taking the friction of the magnetization $[M_i]$ of the time $(\tau-\Delta\tau)$ and the friction of the magnetization $[M_i]$ of the time τ into consideration. Therefore, the behavior that prevents variation of the magnetization $[M_i]$, which varies over time consequent to the resonance phenomenon, can be reproduced.

[0074] Further, if both the friction term and the inertia term are included, by obtaining the effective magnetic field $[H_i]$ using the friction term and the inertia term, in the area ci, the amount of change $\Delta[M_i]$ from the magnetization $[M_i]$ of the time $(\tau-\Delta\tau)$ to the magnetization $[M_i]$ of the time τ can be obtained taking the friction and the inertia of the magnetization $[M_i]$ of the time $(\tau-\Delta\tau)$ and of the magnetization $[M_i]$ of the time τ into consideration. Therefore, the behavior that prevents variation of the magnetization $[M_i]$, which varies over time consequent to the resonance phenomenon, and the behavior that keeps the rate of magnetization variation constant can be reproduce.

[0075] The magnetization calculating unit **503** calculates the magnetization of each area, by obtaining the amount of magnetization variation for each area, based on the effective magnetic field calculated for each area and the magnetization of each area. At the magnetization calculating unit **503**, the amount of magnetization variation is calculated before the magnetization calculation. The amount of magnetization variation is the amount of change of the unit vector $[m_i]$ of the magnetization $[M_i]$ when the time has changed from τ to $\tau+\Delta\tau$ and more specifically, is expressed by the second term on the right side of equation (16). When the unit vector of equation (16) is updated from $[m_i]^{old}$ to $[m_i]^{new}$, $[m_i]^{new}$ after the update is multiplied by the extent M_i of the magnetization $[M_i]$ whereby, the magnetization $[M_i]$ after the updating is calculated. The calculated magnetization $[M_i]$ is provided to the magnetic field calculating unit **502** and the effective magnetic field $[H_i]$ of the next time is calculated.

[0076] The judging unit **504**, based on the magnetization before variation and the magnetization after variation respectively calculated for each area by the magnetization calculating unit **503**, makes a judgment about magnetization convergence at an element. More specifically, for example, the judging unit **504** uses the pre-updating $[m_i]^{old}$ and the post-updating $[m_i]^{new}$ in the element Cg to make the judgment by equation (19).

[0077] The static magnetic field calculating unit **505** uses equation (22) to calculate the static magnetic field Hs_g of the element Cg. More specifically, for example, the static magnetic field calculating unit **505** calculates the static magnetic field Hs_g of the element Cg, if at the same time τ at the judging unit **504** each of the magnetizations $[M_i]$ satisfies the magnetization convergence condition of equation (19). For example, vacuum permeability is used as the permeability μ in the static magnetic field calculation.

[0078] The determining unit **506** determines whether the static magnetic field satisfies a magnetic field convergence condition. More specifically, for example, the determining unit **506** determines magnetic field convergence if the difference ΔHs of the current static magnetic field $[Hs_g]^{new}$ and the previous static magnetic field $[Hs_g]^{old}$ is within a threshold ξh.

[0079] The storing unit **507** stores to the storage area **511**, a combination of the average magnetization $[M_i]$ of the time tj when the magnetization convergence condition of equation (19) was satisfied and the static magnetic field Hs_g that satisfied the magnetic field convergence condition by the determining unit **506**. The stored combinations of the average magnetization $[M_i]$ and the static magnetic field Hs_g are the source of the hysteresis curve.

[0080] The creating unit **508** plots the stored combinations of the average magnetization $[M_i]$ and the static magnetic field $[Hs_g]$ to a graph where the horizontal axis is the magnetic field and the vertical axis is the magnetic flux density and thereby, creates a hysteresis curve. At the creating unit **508**, by providing the average magnetization [Mav] and static magnetic field $[Hs_g]$ to the magnetic flux density$[B]=\mu[H]+[M]$, the magnetic flux density [B] for each time tj is obtained. As a result, the hysteresis curve can be created.

[0081] The loss calculating unit **509** calculates hysteresis loss by calculating the area in the hysteresis curve created by the creating unit **508**. In the case of application of equation (24), hysteresis loss that takes into account the friction term and the inertia term of equation (24) can be obtained.

[0082] The output unit **510** outputs the hysteresis loss calculated by the loss calculating unit **509**. The output unit **510** may display the hysteresis loss on a display or print out the hysteresis loss by a printer. Further, the output unit **510** may transmit the hysteresis loss to an external apparatus or store the hysteresis loss to the memory apparatus **202**. The output unit **510** may further output the hysteresis curve created by the creating unit **508**. Here, an example of a hysteresis curve will be described.

[0083] FIG. **6** is a graph of a hysteresis curve by direct current to ferrite and the actual measured data, at 1.0 MHz, of the hysteresis curve. (b) is an enlarged graph of (a). The area inside the loop of the hysteresis curve is known to be the energy loss per one cycle, consumed in the magnetic body.

[0084] FIG. **7** is a graph depicting simulation results of the present embodiment. The hysteresis curve calculated using equation (11) is indicated by a dotted line **701**. Further, the hysteresis curve calculated with only the inertia term as 0 is indicated by a dotted/dashed line **702**. The hysteresis curve calculated by equation (24) to include the inertia term and the friction term is indicated by a solid line **703**. The hysteresis curve of the solid line **703** is an ellipse; the hysteresis curve by actual measurement is reproduced. In the hysteresis curves of the dotted line **701** and the dotted/dashed line **702**, reproduction by an ellipse is not achieved. In FIG. **7**, frequency f=1.0 MHz, $\gamma=0.75\times10^{-11}$, $\beta=4.0\times10^{-5}$ are assumed.

[0085] FIG. **8** is a block diagram depicting an example of a functional configuration of the reversal processing unit **500** depicted in FIG. **5**. The reversal processing unit **500** has a generating unit **801**, a selecting unit **802**, an identifying unit **803**, a reversal judging unit **804**, and a reversing unit **805**.

[0086] The generating unit **801** generates easy axis vectors of areas into which an element of the element group is divided. More specifically, for example, the generating unit **801** refers to the magnetic body DB **400** and identifies an easy

axis type of the magnetic body subject to analysis. The generating unit **801** generates an easy axis vector according to the easy axis type. For example, in a case where the easy axis type is cubic anisotropy, six unit vectors in the positive direction of a axis to axis c are generated as easy axis vectors. Further, in a case where the easy axis type is uniaxial anisotropy, for example, two unit vectors in the positive direction of a axis are generated as easy axis vectors. More specifically, the generating unit **801** generates the easy axis vectors such that the rolling direction RD is (100), and the orthogonal direction TD thereof is (011).

[0087] The selecting unit **802** calculates the magnetic energy of each magnetization of a divided area and selects from a group of calculated magnetic energies, a magnetic energy that is not the greatest. More specifically, for example, the selecting unit **802**, for each magnetization of the divided area, calculates the magnetic energy E_{tot} such as that indicated by equation (10). The selecting unit **802**, in equation (10), provides as a parameter, an easy axis vector in place of the magnetization vector $[m_i]$. As result, for each magnetization of the divided area, the magnetic energy E_{tot} is calculated.

[0088] The selecting unit **802** selects from among the magnetic energies E_{tot} calculated for each magnetization of the divided area, a magnetic energy that is not the greatest or selects the lowest magnetic energy. In the magnetization reversal process, the direction of magnetization rapidly changes to an easy axis for which the energy becomes low. Therefore, the selecting unit **802**, by selecting a magnetic energy that is not the greatest from among the magnetic energies E_{tot}, can reproduce variations of the easy axis vector that is the calculation basis of the selected magnetic energy E_{tot}. As result, the phenomenon of magnetic domains of low energy consequent to domain wall displacement increasing, rather than the magnetization in a very small area and consequent to domain wall displacement, rotating as a whole can be reproduced.

[0089] The identifying unit **803** identifies based on the magnetization of the area and the identified easy axis vector in the case of selected magnetic energy, a reversal angle of the magnetization reversal according to the height of the energy barrier that is consequent to pinning in the area. More specifically, for example, the identifying unit **803** judges whether expression (25) is satisfied. The identified easy axis vector is the easy axis vector used in the calculation of the magnetic energy selected by the selecting unit **802**. Here, $[a_{i\ kmin}]$ is assumed.

$$\vec{m}_i \cdot \vec{a}_{i\ k\ min} \leq -\frac{1}{\sqrt{2}} \tag{25}$$

[0090] Expression (25) is the inner product of the magnetization vector $[m_i]$ and the identified easy axis vector $[a_{i\ kmin}]$. In other words, if the angle formed by the magnetization vector $[m_i]$ and the identified easy axis vector $[a_{i\ kmin}]$ is between 135 degrees and 225 degrees, the identifying unit **803** assumes the reversal angle of the magnetization vector $[m_i]$ to be 180 degrees. In other cases, the identifying unit **803** assumes the reversal angle of the magnetization vector $[m_i]$ to be 90 degrees. Here, although the range of the angle formed by the magnetization vector $[m_i]$ and the identified easy axis vector $[a_{i\ kmin}]$ is regarded to be 135 degrees to 225 degrees, the range can be arbitrarily set from 90 degrees to 270 degrees.

[0091] The reversing unit **805** reverses the magnetization by the identified reversal angle. More specifically, for example, if the reversal angle is 180 degrees, the reversing unit **805** updates the unit vector $[m_i]$ of the magnetization $[M_i]$ to $-[m_i]$. As a result, the unit vector $[m_i]$ of the magnetization $[M_i]$ becomes in a state of being reversed by 180 degrees. Further, if the reversal angle is 90 degrees, the reversing unit **805** updates the unit vector $[m_i]$ of the magnetization $[M_i]$ to the identified easy axis vector $[a_{i\ kmin}]$. As a result, the unit vector $[m_i]$ of the magnetization $[M_i]$ becomes in a state of being reversed by 90 degrees.

[0092] Further, the identifying unit **803** identifies based on the magnetization and the identified easy axis, a parameter ΔE that corresponds to the height of the energy barrier that is consequent to pinning. As described, in the magnetization reversal process, the magnetic domains of low energy consequent to domain wall displacement increase rather than the magnetization in a very small area and consequent to domain wall displacement, rotating as a whole and therefore, the direction of magnetization rapidly changes to the easy axis for which the energy is low. However, in general, domain wall displacement does not always move smoothly and as depicted by (C) of FIG. **1**, pinning occurs consequent to impurities, etc.

[0093] Therefore, concerning the discontinuous magnetization variation corresponding to 180-degree or 90-degree magnetization reversal, at the identifying unit **803**, a parameter for calculating reversal from a magnitude relation of the magnetic energy is identified. More specifically, in the case of 180-degree reversal, the identifying unit **803** sets the parameter ΔE that corresponds to the height of the energy barrier caused by pinning to be ΔE_i^{180}. In the case of 90-degree reversal, the identifying unit **803** sets the parameter ΔE that corresponds to the height of the energy barrier caused by pinning to be ΔE_i^{90}. Although the parameter that corresponds to the height of the energy barrier may be a value fixed for each reversal angle, here, Lorentz distribution is assumed and therefore, a value that differs according to the magnetization $[M_i]$ by a random number is used. For example, ΔE_i^{180} is 10 ± 15 [J/m^3]; ΔE_i^{90} is 40 ± 20 [J/m^3].

[0094] The reversal judging unit **804**, based on the magnetic energy in the area related to the magnetization and the parameter that corresponds to the height of the energy barrier that is consequent to pinning, judges whether the magnetization is to be reversed by the reversal angle. More specifically, for example, in the case of 180-degree reversal, the reversal judging unit **804** judges whether the 180-degree reversal condition represented by expression (20) is satisfied. If the 180-degree reversal condition is satisfied, the reversing unit **805** updates the unit vector $[m_i]$ of the magnetization $[M_i]$ to $-[m_1]$ whereby, the unit vector $[m_i]$ of the magnetization $[M_i]$ is in a state of being reversed by 180 degrees.

[0095] Similarly, in the case of 90-degree reversal, the reversal judging unit **804** judges whether the 90-degree reversal condition represented by the expression (21) is satisfied. If the 90-degree reversal condition is satisfied, the reversing unit **805** updates the unit vector $[m_i]$ of the magnetization $[M_i]$ to the identified easy axis vector $[a_{i\ kmin}]$. If the 90-degree reversal condition of expression (21) is satisfied, the angle formed by the unit vector $[m_i]$ of the magnetization $[M_i]$ and the identified easy axis vector $[a_{i\ kmin}]$ is 90 degrees and therefore, the unit vector $[m_i]$ of the magnetization $[M_i]$ becomes in a

state of being reversed by 90 degrees. With either judgment, if the reversal condition is not satisfied, the reversing unit **805** does not update the unit vector $[m_i]$ of the magnetization $[M_i]$.

[0096] FIG. **9** is a flowchart depicting an example of a procedure of a simulation process by the simulation apparatus **200** according to the present embodiment. The simulation apparatus **200** sets a variable g, which identifies an element, to be g=1 (step S**901**), and judges whether g>N is true (step S**902**). N is the total number of elements. If g>N is not true (step S**902**: NO), the simulation apparatus **200** executes the simulation process for the element Cg in the magnetic body (step S**903**).

[0097] The simulation apparatus **200** increments g (step S**904**), and returns to step S**902**. At step S**902**, if g>N is true (step S**902**: YES), there is no element Cg to be simulated and the simulation apparatus **200** executes an output process by the output unit **510** (step S**905**), and ends a series of the simulation process. In FIG. **9**, although the simulation process (step S**903**) is executed sequentially for each element Cg, the simulation process may be executed in parallel.

[0098] FIG. **10** is a flowchart (part **1**) depicting an example of a detailed process procedure for the simulation process (step S**903**) for an element Cg in the magnetic body and depicted in FIG. **9**. The simulation apparatus **200** sets a time variable j and an update time τ to be j=0, τ=0, respectively (step S**1001**). The simulation apparatus **200** sets the externally applied magnetic field $[H_{app}]$ of the time tj (step S**1002**). The externally applied magnetic field $[H_{app}]$ is a magnetic field determined by the frequency f and the time tj. The frequency f is assumed to be provided in advance. The externally applied magnetic field $[H_{app}]$ is used in equation (6).

[0099] The simulation apparatus **200** reads in the initial value of the magnetization $[M_i]$ from the memory apparatus **202** (step S**1003**). The initial value of the magnetization $[M_i]$ is, for example, assumed to be pre-stored in the memory apparatus **202** and read in from the memory apparatus **202** at the start of simulation.

[0100] The simulation apparatus **200** executes reversal processing of the magnetization $[M_i]$ via the reversal processing unit **500** (step S**1004**). Details of the reversal processing (step S**1004**) will be described with reference to FIG. **12**.

[0101] The simulation apparatus **200** calculates the average magnetization $[M_g av]$ for the time τ via the average magnetization calculating unit **501** (step S**1005**). The simulation apparatus **200** calculates the effective magnetic field $[H_i]$ for the time τ via the magnetic field calculating unit **502** (step S**1006**).

[0102] The simulation apparatus **200** advances the time τ by a given time length $\Delta\tau$ (step S**1007**), uses the LLG equation of equation (15), and calculates the amount of change of the unit vector $[m_i]$ of the magnetization $[M_i]$ and thereby calculates the magnetization $[M_i]$ using equation (16), via the magnetization calculating unit **503** (step S**1008**). The simulation apparatus **200** uses the magnetization $[M_i]$ before and after variation to judge, via the judging unit **504** and for each area ci, whether the magnetization convergence condition is satisfied (step S**1009**).

[0103] If even any one area ci does not satisfy the magnetization convergence condition (step S**1009**: NO), the simulation apparatus **200** returns to step S**1005**, and calculates the average magnetization [Mav] by the updated magnetization $[M_i]$ at step S**1008**. On the other hand, if each of area ci satisfies the magnetization convergence condition (step S**1009**: YES), the simulation apparatus **200** transitions to step S**1101** in FIG. **11**.

[0104] FIG. **11** is a flowchart (part **2**) depicting an example of a detailed process procedure of the simulation process (step S**903**) for an element Cg in the magnetic body and depicted in FIG. **9**. After step S**1009**: YES in FIG. **10**, the simulation apparatus **200** sets $[M]^j$ to the latest average magnetization [Mav] obtained at step S**1005** (step S**1101**). $[M]^j$ is a value used by the friction term of equation (17) and the inertial term of equation (18). At a subsequent step S**1106**, j is incremented and therefore, in the calculation of the effective magnetic field (step S**1006**) thereafter, $[M_g]^{j-1}$ is used.

[0105] The simulation apparatus **200** uses equation (22) and executes a static magnetic field calculation process via the static magnetic field calculating unit **505** (step S**1102**). The simulation apparatus **200** determines, via the determining unit **506**, whether the static magnetic field $[Hs_g]$ satisfies the magnetic field convergence condition (step S**1103**). If not (step S**1103**: NO), the simulation apparatus **200** returns to step S**1004** in FIG. **10**. The combination of the static magnetic field $[Hs_g]$ and the average magnetization [Mav] in this case are not stored to the storage area **511** and are not reflected in the hysteresis curve.

[0106] On the other hand, if the magnetic field convergence condition is satisfied (step S**1103**: YES), the simulation apparatus **200** retains in the storage area **511**, the static magnetic field $[Hs_g]^j$ and the average magnetization $[Mav]^j$ for the time tj (step S**1104**) and judges whether j>jmax is true (step S**1105**). jmax is the maximum value of the variable j and tjmax is the simulation time. If j>jmax is not true (step S**1105**: NO), the simulation apparatus **200** increments j (step S**1106**), returns to step S**1002** in FIG. **10**, and resets the externally applied magnetic field $[H_{app}]$ for the incremented time tj.

[0107] Further, consequent to the incrementing of j, the latest average magnetization $[Mav]^j$ at step S**1001** is the average magnetization [Mav], and the average magnetization $[Mav]^{j-1}$ is the average magnetization $[Mav]^{j-2}$. As a result, the calculation of the friction term (equation (17)) and the inertia term (equation (18)) can be performed. On the other hand, if j>jmax is true (step S**1105**: YES), the simulation process for the element Cg ends and therefore, the simulation apparatus **200** transitions to step S**904** in FIG. **9**.

[0108] FIG. **12** is a flowchart depicting an example of a detailed process procedure of the reversal processing (step S**1004**) depicted in FIG. **10**. The simulation apparatus **200** sets a magnetization number i=1 (step S**1201**), and determines whether i>imax is true (step S**1202**). imax is the maximum value of the magnetization number i. If i>imax is not true (step S**1202**: NO), the simulation apparatus **200** generates, via the generating unit **801**, the easy axis vector $[a_{ik}]$ of the magnetization $[M_i]$ (step S**1203**). k is the number of the easy axis vector and in the case of uniaxial anisotropy, k=1, 2; and in the case of cubic anisotropy, k=1, 2, 3, 4, 5, 6.

[0109] The simulation apparatus **200** calculates, via the selecting unit **802** and for each k, the magnetic energy $E_{tot}(a_{ik})$ (step S**1204**). The simulation apparatus **200**, via the selecting unit **802**, selects the lowest magnetic energy $E_{tot}([a_{ik}])$, and sets the selected magnetic energy $E_{tot}(a_{ik})$ as $E_{tot}([a_{i\ kmin}])$ (step S**1205**). The easy axis vector $[a_{i\ kmin}]$ is the identified easy axis vector.

[0110] The simulation apparatus **200** judges, via the identifying unit **803**, whether expression (25) is satisfied (step S**1206**). If so (step S**1206**: YES), the simulation apparatus

200, via the identifying unit **803**, sets the reversal angle θ to θ=180, and sets the parameter ΔE that corresponds to the height of the energy barrier that is consequent to pinning to be ΔE_i^{180} (step S**1207**). The simulation apparatus **200** judges, via the reversal judging unit **804**, whether the 180-degree reversal condition represented by expression (20) is satisfied (step S**1208**). If the 180-degree reversal condition represented by expression (20) is satisfied (step S**1208**: YES), the simulation apparatus **200** updates, via the reversing unit **805**, the unit vector $[m_i]$ of the magnetization $[M_i]$ to $-[m_i]$ (step S**1209**), and transitions to step S**1213**. On the other hand, if the 180-degree reversal condition represented by expression (20) is not satisfied (step S**1208**: NO), the simulation apparatus **200** transitions to step S**1213** without updating the unit vector $[m_i]$ of the magnetization $[M_i]$.

[0111] At step S**1206**, if expression (25) is not satisfied (step S**1206**: NO), the simulation apparatus **200**, via the identifying unit **803**, sets the reversal angle θ to θ=90, and sets the parameter ΔE that corresponds to the height of the energy barrier that is consequent to pinning to be ΔE_i^{90} (step S**1210**). The simulation apparatus **200** judges, via the reversal judging unit **804**, whether the 90-degree reversal condition represented by expression (21) is satisfied (step S**1211**). If the 90-degree reversal condition represented by expression (21) is satisfied (step S**1211**: YES), the simulation apparatus **200**, via the reversing unit **805**, updates the unit vector $[m_i]$ of the magnetization $[M_i]$ to the identified easy axis vector $[a_{i\ kmin}]$ (step S**1212**), and transitions to step S**1213**. On the other hand, if the 90-degree reversal condition represented by expression (21) is not satisfied (step S**1211**: NO), the simulation apparatus **200** transitions to step S**1213** without updating the unit vector $[m_i]$ of the magnetization $[M_i]$.

[0112] At step S**1213**, the simulation apparatus **200** increments i (step S**1213**), and returns to step S**1202**. At step S**1202**, if i>imax is true (step S**1202**: YES), the simulation apparatus **200** ends the reversal processing (step S**1004**), and transitions to step S**1005**.

[0113] Thus, according to the present embodiment, the orientation dependency of magnetic characteristics seen with grain-oriented electrical steel sheeting and non-oriented electrical steel sheeting can be reproduce. Further, in the present embodiment, not only can the magnetic characteristics for the rolling direction RD of grain-oriented electrical steel sheeting be reproduced, but the magnetic characteristics for the orthogonal direction TD can also be reproduced. As indicated by expression (20) and expression (21), since the orientation dependency can be reproduced by a simple computation, increases in the calculation volume with the reproduction of the orientation dependency can be suppressed. Further, since magnetization convergence is judged and the static magnetic field is calculated from a state after the reversal processing, the hysteresis loss that occurs in the electrical steel sheeting of motors, transformers, etc. can be calculated.

[0114] According to the present embodiment, since the effective magnetic field $[H_i]$ is obtained taking friction into consideration, a behavior that prevents variation in the magnetization $[M_i]$ that varies over time consequent to the resonance phenomenon can be reproduced. Therefore, a hysteresis curve reflecting the effects of such behavior is obtained, and hysteresis loss can be obtained with high accuracy with respect to magnetic bodies of high resistivity magnetic material with a high frequency.

[0115] If the friction term and the inertia are included, the effective magnetic field $[H_i]$ can be obtained taking into consideration friction and inertia; and therefore, a behavior that prevents variation of the magnetization $[M_i]$, which varies over time consequent to the resonance phenomenon, and a behavior that keeps the rate of magnetization variation constant can be reproduced. Therefore, a hysteresis curve reflecting the effects of such behaviors is obtained, and hysteresis loss can be obtained with high accuracy with respect to magnetic bodies of high resistivity magnetic material with a high frequency.

[0116] According to the present embodiment, in the simulation apparatus **200**, although the creating unit **508** creates the hysteresis curve and the loss calculating unit **509** calculates the hysteresis loss, the creating unit **508** and the loss calculating unit **509** may be executed by another apparatus other than the simulation apparatus **200**. For example, configuration may be such that in the simulation apparatus **200**, the storing unit **507** stores to the storage area **511**, the combination of the static magnetic field $[Hs_g]^j$ and the average magnetization $[Mav]^j$ for the time tj, and transmits the combination to another apparatus having the creating unit **508** and the loss calculating unit **509**.

[0117] According to one aspect, an effect is achieved in that the orientation dependency in a magnetic body can be reproduced with high accuracy.

[0118] All examples and conditional language provided herein are intended for pedagogical purposes of aiding the reader in understanding the invention and the concepts contributed by the inventor to further the art, and are not to be construed as limitations to such specifically recited examples and conditions, nor does the organization of such examples in the specification relate to a showing of the superiority and inferiority of the invention. Although one or more embodiments of the present invention have been described in detail, it should be understood that the various changes, substitutions, and alterations could be made hereto without departing from the spirit and scope of the invention.

What is claimed is:

1. A non-transitory, computer-readable recording medium storing a magnetic body simulation program that causes a computer to:

generate an easy axis vector in an area divided from an element of a group of elements forming a magnetic body;

calculate magnetic energy of each magnetization of the divided area, select from among the calculated magnetic energies, a magnetic energy that is not the greatest;

identify based on the magnetization of an area and a specific easy axis vector in a case of the selected magnetic energy, a reversal angle of magnetization reversal according to a height of an energy barrier that is consequent to pinning in the area; and

reverse the magnetization by the identified reversal angle.

2. The computer-readable recording medium according to claim **1**, wherein

in selecting the magnetic energy, the computer caused to select the magnetic energy that is lowest among the magnetic energies.

3. The computer-readable recording medium according to claim **1**, wherein

the computer is caused to:

identify based on the magnetization and the specific easy axis vector, a parameter that corresponds to the height of the energy barrier that is consequent to pinning; and

judge based on the magnetic energy in the area and related to the magnetization, and the identified parameter, whether to reverse the magnetization by the reversal angle; and

in reversing the magnetization, the computer is caused to reverse the magnetization by the reversal angle, upon judging that the magnetization is to be reversed.

4. The computer-readable recording medium according to claim **3**, wherein

in judging whether the magnetization is to be reversed and when the reversal angle is 180 degrees, the computer is caused to judge whether a difference of the magnetic energy in the area and related to the magnetization minus the magnetic energy of the area and related to magnetization whose direction has been reversed by 180 degrees with respect to the magnetization is at least the parameter, and

in reversing the magnetization and upon judging that the magnetization is to be reversed, the computer is caused to update the magnetization to the magnetization whose direction has been reversed by 180 degrees with respect to the magnetization.

5. The computer-readable recording medium according to claim **3**, wherein

in judging whether the magnetization is to be reversed and when the reversal angle is 90 degrees, the computer is caused to judge whether a difference of the magnetic energy in the area and related to the magnetization minus the magnetic energy in the area and related to the specific easy axis vector is at least the parameter, and

in reversing the magnetization and upon judging that the magnetization is to be reversed, the computer is caused to update the magnetization to the specific easy axis vector.

6. The computer-readable recording medium according to claim **1**, wherein

the computer is caused to:

calculate for each area and after reversing the magnetization, an effective magnetic field based on a magnetic field generated from the magnetic energy of each area divided from an element of the group of elements forming the magnetic body, and a rate of magnetization variation working in a direction that prevents variation of an average magnetization of the magnetization of each area;

obtain based on the effective magnetic field calculated for each area, and the magnetization of each area, an amount of magnetization variation for each area, and calculate for each area, the magnetization after variation;

judge based on based on the magnetization before and after variation for each area, whether the magnetization in the element converges; and

store to a memory apparatus, a combination of the average magnetization in a case where the magnetization in the element is judged to converge, and the static magnetic field based on the average magnetization.

7. The computer-readable recording medium according to claim **6**, wherein

in calculating the effective magnetic field, the computer is caused to calculate for each area and when the magnetization of each area varies, an effective field based on a magnetic field generated by the magnetic energy in the area, the rate of magnetization variation and inertia that brings into action, the magnetic field in a direction that keeps the rate of magnetization variation constant.

8. The computer-readable recording medium according to claim **6**, wherein

the computer is caused to calculate hysteresis loss from an area of a hysteresis curve obtained from a group of combinations of the average magnetization and the static magnetic field stored in the memory apparatus.

9. A magnetic body simulation apparatus comprising:

a processor configured to:

generate an easy axis vector in an area divided from an element of a group elements forming a magnetic body;

calculate magnetic energy for each magnetization of the divided area, and select from the calculated magnetic energies, a magnetic energy that is not the greatest;

identify based on the magnetization of an area and a specific easy axis vector in a case of the selected magnetic energy, a reversal angle of magnetization reversal according to a height of an energy barrier that is consequent to pinning in the area; and

reverse the magnetization by the identified reversal angle.

10. A magnetic body simulation method comprising:

a computer generating an easy axis vector in an area divided from an element of a group of elements forming a magnetic body;

the computer calculating magnetic energy of each magnetization of the divided area, select from among the calculated magnetic energies, a magnetic energy that is not the greatest;

the computer identifying based on the magnetization of an area and a specific easy axis vector in a case of the selected magnetic energy, a reversal angle of magnetization reversal according to a height of an energy barrier that is consequent to pinning in the area; and

the computer reversing the magnetization by the identified reversal angle.

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