P5-1

Active Magnetic Shield controlled by algorithms without Cross-interference

T. Ueda[1], K. Yamazaki[2], M. Takenaka[1], T. Sato[3], A. Haga[3]

KRI, Inc.[1], Takenaka Corp.[2], Tohoku Gakuin University[3], Japan

ABSTRACT

We propose new methods to control the active magnetic shield system composed of plural compensation coils, plural broadband magnetometric sensors, and a control unit. The conventional active magnetic shield system suffers from the oscillation problem because a magnetometric sensor detect environmental magnetic noise and compensating magnetic fields generated by the currents flowing in not only the nearest coil but also other coils. To prevent this oscillation problem, we propose two methods (Base Transition Method and Genaral Inverse Matrix Method) using the sensitivity co-efficients. In both proposed methods, the stability of controlling the prototype system has been confirmed in the experiments.

KEY WORDS

Active magnetic shield, Magnetic field compensation, Base transition method, Oscillation, MCG, MEG, Magnetization of biomagnetite, Magnetization of ferumoxides.

INTRODUCTION

Environmental magnetic noises adversely affect measuring equipments in fields such as biomagnetism measurement, localization of magnetic fluid marker in vivo, study on characteristics of magnetic materials and so on. The earth magnetism is always varying because of the affections of the solar storm and the core activities in the earth. The magnetic fluxs concentrate to automobiles, elevators, steel doors and other structures made of magnetic materials. Therefore the spatial movement of them causes environmental magnetic noises. Electric currents flowing in near catenary cables of DC electric railcar or supply cables for power-electronics apparatus around and spinning fans for air-conditioning also cause noises. These environmental magnetic noises generally have spatial inclination. AMS (active magnetic shield) system with plural coils and plural sensors is thought to be a better technical method to reduce environmental magnetic noises than heavy MSR (magnetic shield room) made from expensive materials such as Permalloy because AMS could generate homogeneous zero magnetic fields by using plural coils. However conventional AMS system has the oscillation problem because magnetic fields are piled up at each sensor position to compensate environmental noises by plural coils. Here we propose new control methods to prevent this oscillation problem.

METHODS

[Base Transition Method]

In AMS system with m compensation coils and n magnetometric sensors, the output B_j of sensor j is predicated as residual environmental magnetic noise.

$$B_j = S_j - O_j \quad (1)$$

where S_j is true environmental magnetic noise at sensor position j and O_j is estimated compensation magnetic field value given by eq. (2)

$$O_j = \sum_{i=1}^{m} \alpha_{ij} u_i \quad (2)$$

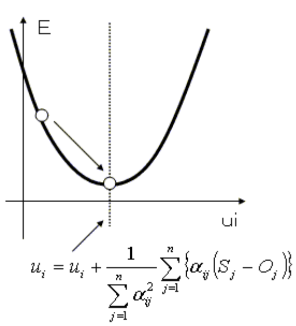


Figure 1. Explanation of Base Transition Method

where a sensitivity co-efficient α_{ij} is defined as the output value of sensor j when unit current is supplied to only compensation coil i, and u_i is electric current flowing in coil i to compensate environmental noises.

Evaluation function E given by eq. (3) can be translated such as (4),(4'), and (4'').

$$E = \sum_{j=1}^{n} \left(S_j - O_j \right)^2 \quad (3)$$

$$E = \sum_{j=1}^{n} \left\{ \left(S_j - O_j + \alpha_{ij} u_i \right) - \alpha_{ij} u_i \right\}^2 \quad (4)$$

$$E = \sum_{j=1}^{n} \left(S_j - O_j + \alpha_{ij} u_i \right)^2 - 2u_i \sum_{j=1}^{n} \left\{ \alpha_{ij} \left(S_j - O_j + \alpha_{ij} u_i \right) \right\} + u_i^2 \sum_{j=1}^{n} \alpha_{ij}^2 \quad (4')$$

$$E = \left(A_i u_i - B_i \right)^2 + C_i - B_i^2 \quad (4'')$$

Here $A_i^2 = \sum_{j=1}^{n} \alpha_{ij}^2$, $A_i B_i = \sum_{j=1}^{n} \left\{ \alpha_{ij} \left(S_j - O_j + \alpha_{ij} u_i \right) \right\}$, $C_i = \sum_{j=1}^{n} \left(S_j - O_j + \alpha_{ij} u_i \right)^2$

As evaluation function E is always a parabolic function concerning as a unknown value u_i, we use the following recurrence formula eq.(5) in order to minimize evaluation function E eq.(3). K_i is a constant co-efficient previously calculated by using m×n sensitivity co-efficients.

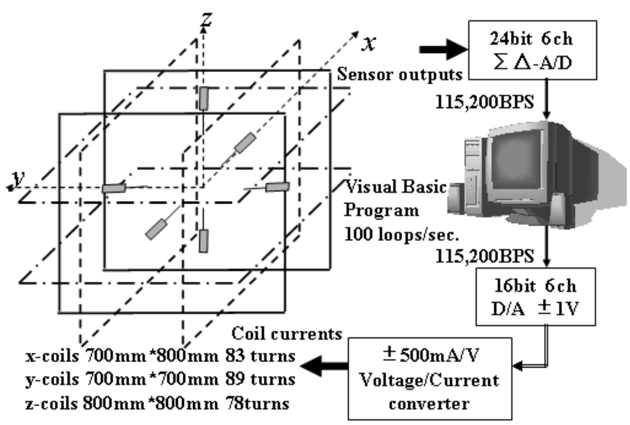
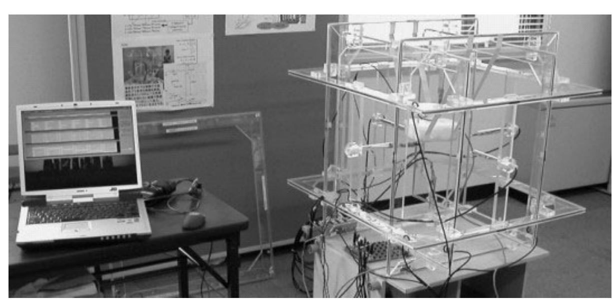
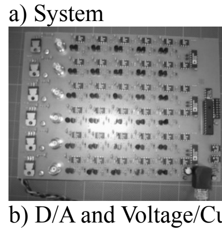


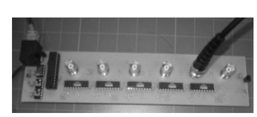
Figure 2. Construction of Experimental System



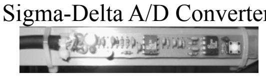
a) System



b) D/A and Voltage/Current converter



c) Sigma-Delta A/D Converter



d) MR Sensor

Figure 3. Photograph of Experimental System and Boards

$$u_i = u_i + K_i \sum_{j=1}^{n} \alpha_{ij} B_j \quad (5) \qquad \text{Here} \quad K_i = \frac{1}{\sum_{j=1}^{n} \alpha_{ij}^2} \quad (6)$$

Here eq.(5) is given by the fact that the axis of parabolic function E is given by eq.(7).

$$u_i = \frac{B_i}{A_i} = \frac{A_i B_i}{A_i^2} \quad (7)$$

However each sensor must be assigned to the most appropriate position to generate a homogeneous zero magnetic field space.

It is very interesting that if m is equal to n and all α_{ij} is zero when i is not equal to j, equation (5) reduces to Gauss-Seidel Method, and that K_i is equal to the best step co-efficient ε of adaptive digital filter algorithm called as LMS (least square mean).

【Sensitivity Co-efficients α_{ij}】

	Coil(x1)	Coil(x2)	Coil(y1)	Coil(y2)	Coil(z1)	Coil(z2)
Sensor(x1)	10.6670308333333	4.34675916666667	3.7816575	4.23936166666667	−4.51905083333333	−5.25111916666667
Sensor(x2)	6.79527	26.2884033333333	−7.31756916666667	−7.89049166666667	10.8560683333333	15.2418041666667
Sensor(y1)	6.44452666666667	−7.41953416666667	21.166505	−7.15070166666667	6.57862666666667	8.751045
Sensor(y2)	8.03745666666667	−6.789215	−7.90115583333333	22.1327316666667	6.6624775	9.5334275
Sensor(z1)	−4.90601916666667	5.08657083333333	4.28881333333333	4.50809083333333	19.1646591666667	−5.41455416666667
Sensor(z2)	−5.03207333333333	4.78019333333333	4.90943	5.65512083333333	−6.35239	18.6120725

【Inverse Matrix A^{-1}】

	Sensor(x1)	Sensor(x2)	Sensor(y1)	Sensor(y2)	Sensor(z1)	Sensor(z2)
Coil(x1)	3.07323392627652E-02	1.60332668846225E-02	1.96340260965531E-02	1.93060799631658E-02	-2.55682475044737E-02	-3.10179728167283E-02
Coil(x2)	3.67177591126987E-02	1.37748006995124E-02	-1.82871419986436E-02	-1.82691271038966E-02	2.11717529193757E-02	2.31941455314531E-02
Coil(y1)	3.30559276801758E-02	-1.37272317210301E-02	1.93881705323824E-02	-0.016619593976946	2.35847349622642E-02	2.68258228350158E-02
Coil(y2)	3.11586738151425E-02	-1.51636776528207E-02	-0.015998567208725	1.65855031520966E-02	2.47575827471933E-02	0.02743802320012
Coil(z1)	-2.44143840543992E-02	0.010665679986231	1.33465353152219E-02	1.35286840451172E-02	0.023839686671278	-0.02189206121774
Coil(z2)	-2.76407756328914E-02	1.26655554229573E-02	1.43072350246801E-02	1.38737239409838E-02	-1.79572752435907E-02	1.65006363213293E-02

Figure 4. Example of Measured Sensitivity Co-efficients by Experiment and Calculated Inverse Matrix $\mathbf{A}^{-}$

[General Inverse Matrix Method]

It is defined that **A** is sensitivity matrix with m×n sensitivity co-efficients α_{ij} as elements, **U** is coil current matrix, **S** is true environmental noise, **O** is compensating magnetic field matrix, and **B** is sensor output matrix. The condition is given by eq.(15) to minimize evaluation function E eq.(14). We propose algorithm eq.(17). Here $\mathbf{A}^{-}$ is general inverse matrix of **A**.

$$\mathbf{A} = \begin{bmatrix} \alpha_{11} & \alpha_{21} & \cdots & \alpha_{m1} \\ \alpha_{12} & \alpha_{22} & \cdots & \alpha_{m2} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{1n} & \alpha_{2n} & \cdots & \alpha_{mn} \end{bmatrix} \quad (8), \qquad u = [u_1, u_2, u_3, \cdots, u_i, \cdots, u_m]^T \quad (9)$$

$$\mathbf{S} = [S_1, S_2, S_3, \cdots, S_j, \cdots, S_n]^T \quad (10), \qquad \mathbf{O} = [O_1, O_2, O_3, \cdots, O_j, \cdots, O_n]^T \quad (11)$$

$$\mathbf{B} = [S_1 - O_1, S_2 - O_2, S_3 - O_3, \cdots, S_j - O_j, \cdots, S_n - O_n]^T \quad (12), \qquad \mathbf{O} = \mathbf{Au} \quad (13)$$

$$E = \sum_{j=1}^{n} (S_j - O_j)^2 = (\mathbf{S} - \mathbf{Au})^T (\mathbf{S} - \mathbf{Au}) = \mathbf{S}^T\mathbf{S} - 2\mathbf{u}^T\mathbf{A}^T\mathbf{S} + \mathbf{u}^T\mathbf{A}^T\mathbf{Au} \quad (14)$$

$$\frac{\partial E}{\partial \mathbf{u}} = \mathbf{0} \quad (15), \qquad \mathbf{u} = \mathbf{A}^{-}\mathbf{S} \quad (16), \qquad \mathbf{U} = \mathbf{U} + \varepsilon \mathbf{A}^{-}\mathbf{B} \quad \text{where } 0 < \varepsilon \leqq 1 \quad (17)$$

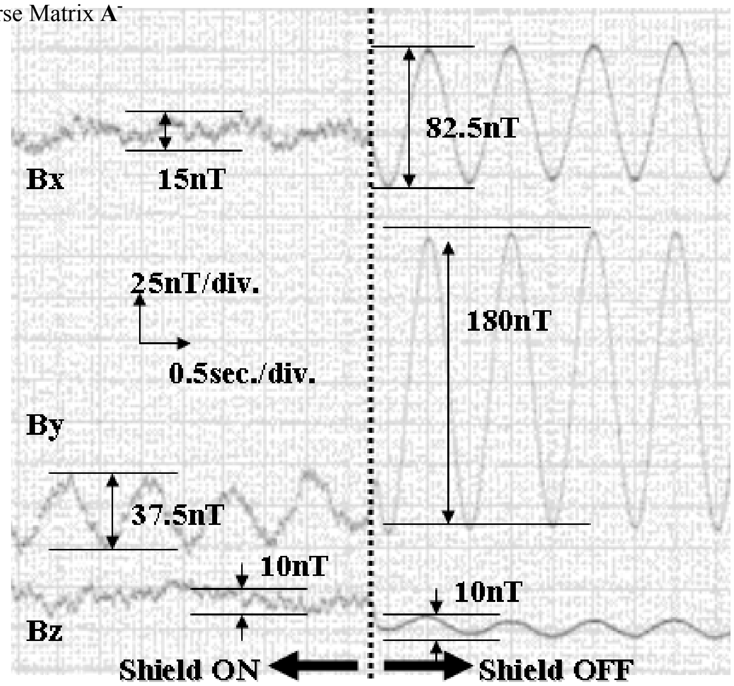


Figure 5. Result of Experiment by using General Inverse Matrix Method

RESULTS

As shown in figure 2 and 3, our prototype apparatus of active magnetic shield system was composed of 6 coils, 6 MR sensors, sigma-delta A/D board with 6 input channels, a computer, and D/A and Voltage/Current converter board with 6 output channels. As shown in figure 4, sensitivity co-efficients of which total number is 36 could be measured by our prototype system and inverse matrix of them were calculated. The coil configuration had strong cross-interference condition because of short distance between coils. However it seems that our proposed active magnetic shield with new control method is very effective as show in figure 5.

DISCUSSION

It has been demonstrated that our proposed control method is effective and that it is possible to achieve active magnetic shield control stably even on the unstable oscillation condition with strong cross-interference. However the base transition method seems more effective than the inverse matrix method because of flushing errors to a particular co-efficient at calculating inverse matrix.

In the case of system with Base Transition method, true environmental magnetic noise can be easily known by adding compensation field value to measured sensor output value. So artificial magnetic field with arbitrary vector can be generated in the active magnetic shield space. $f_i(t)$ is a coil current to generate artificial magnetic field. The true residual environmental magnetic noise is given by eq.(18) and coil current i for generating arbitrary artificial magnetic fields is given by eq.(19).

$$B_j = B_j - \sum_{i=1}^{m} \alpha_{ij} f_i(t) \quad (18), \qquad u_i = u_i + K_i \sum_{j=1}^{n} \alpha_{ij} B_j + f_i(t) \quad (19)$$

This function is important in order to magnetize or de-magnetize magnetic materials or particles such as ferumoxides or biomagnetites in active magnetic shield space by using same coils generating compensation field because Permalloy shield distorts magnetic field.

REFERENCES

Ueda T, Kasai N, Sagane M, Chinone K, Awano N. Visualization for Electric Activities in a Human Heart. Biomag96; 1996, p. 569-572.