Cognition of the Metallic Material Properties and Physical Dimensions by Magnetic Sensor Signal Visualization

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Keywords : magnetic sensor, signal processing, 3D Lissajous diagram, least squares method

Innovative idea underlying modern active magnetic sensors, such as magnetic resistance (MR), flux gate (FG), magneto-impedance (MI), etc., have been changing scenes of industry, as well as medical services. Satisfactory sensitivity and resolution for low field have been realized at room temperature. It is possible to get fine information on magnetic fields under the cheap measurement environment while elaborate methods of signal processing are essentially required because of active sensing. On the other hand, personal computers in recent years with high-speed data acquisition interfaces bring real time observation and calculation, taking advantage of image and signal cognition technologies. Therefore, a database system approach may give one of the effective solutions to treat complicated signals due to magnetization and to reflect skillful experts' experiences. This inspires us to develop a smart magnetic sensing system.

The present paper reports our developed magnetic sensing system in order to provide a smart magnetic sensing function. Our method is composed of three major steps; the first is an active magnetic sensor detecting metallic objects (Fig. 1); the second is proposed as a method of visualization converting from sensor input and output (I/O) signals to image data; the last one is an image cognition methodology using the imaged sensor signals. We apply our system to identify metallic cans commonly utilized for canned drinks. As a result, it is found that our magnetic sensor signals processing ascertain the metallic material properties as well as their physical dimensions.

Concrete exampe is as follows. Figure 2 illustrates the 3-D Lissajous diagrams proposed in this paper for the 2 cans when locating at one of the pickup coils. The period to draw the diagrams is 0.1 s. In Fig. 2, the image size is 64×64 pixels and the dynamic ranges in x- (output) and y- (input) axes are about ±4.0 and ±23.0 V, respectively.

We prepared several aluminum and steel cans with different shapes for experiments. It is obvious that the diameter of cans relates to the width of diagrams since it turns out interaction, i.e., mutual inductance and eddy currents, between the test object and coils. In cases of the steel cans, the distorted diagrams due to magnetization characteristics are obtained. The histograms of steel cans are somewhat averaged because the high frequency components in output signal reduce the low frequency information in output voltage waveforms.

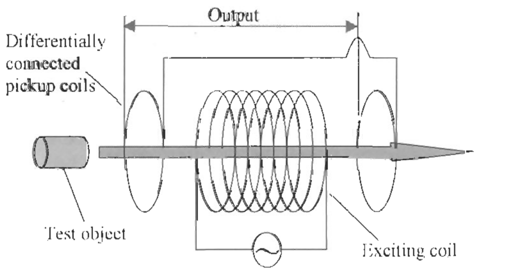
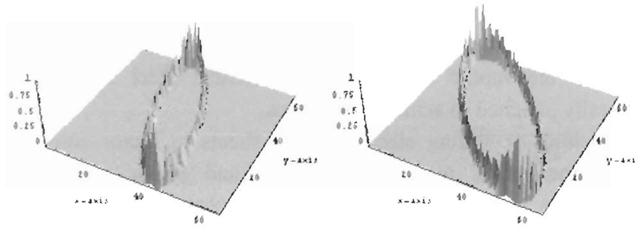
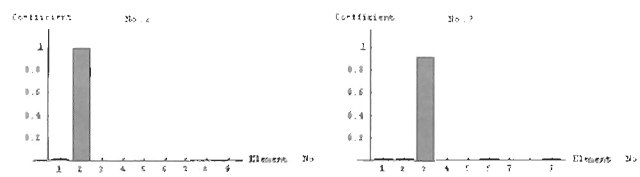


Fig. 1. Schematic diagram of the differential coil sensor system employed in this paper



(a) (b)

Fig. 2. 3-D Lissajous diagrams of the cans in Fig. 4 (400Hz, 64×64 pixels)



(a) (b)

Fig. 3. Elements in solution vector **U** as the identified results

Let us identify the cans by means of the 3-D Lissajous diagrams shown in Fig. 2. We have 4 aluminum and 5 steel cans for constructing the database matrix C. In this case, the dimension of matrix $m \times n$ becomes (64×64)×9. We apply the least squares to solve a system of equations $\mathbf{V}=C\mathbf{U}$ having the column-wise system matrix C. In this sysem of equations, $\mathbf{V}$,$\mathbf{U}$ and C are the input vector with order 9, solution vector with order 64×64 and system matrix with order (64×64) by 9, respectively. The 3-D Lissajous diagram data of Figs. 2 (a) and (b) corresponds to one of the column matrices composing database matrix C, and also an input vector $\mathbf{V}$, respectively.

Figure 3 shows the solution vectors **U** when the diagrams in Fig. 2 are used as the input vectors **V** of the system of equations. The elements taking the maximum value in the solution vectors reveal the cognized cans.

Thus, we have succeeded in identifying the prepared 9 cans by our smart magnetic sensor system.

Paper

Cognition of the Metallic Material Properties and Physical Dimensions by Magnetic Sensor Signal Visualization

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This paper proposes a method of 3-D Lissajous diagram for signal processing of a differential coil type magnetic sensor. Overlapping several Lissajous diagrams between the sensor input and output signals yields a three-dimension or grayscale image whose height or tone reveals a number of overlapped points. This conversion from the time-domain sensor signals to an image provides the differences in frequency, amplitude, phase, distortion, etc. Employing image cognition methodology to this three-dimension image makes it possible to identify each of the signals stored in a database. We demonstrate the renmarkable cognition results by our magnetc sensor signals processing strategy.

Keywords : magnetic sensor, signal processing, 3D Lissajous diagram, least squares method

1. Introduction

Innovative idea underlying modern active magnetic sensors, such as magnetic resistance (MR), flux gate (FG), magneto-impedance (MI), etc., have been changing scenes of industry, as well as medical services[1][2]. Satisfactory sensitivity and resolution for low field have been realized at room temperature. It is possible to get fine information on magnetic fields under the cheap measurement environment while elaborate methods of signal processing are essentially required because of active sensing. On the other hand, personal computers in recent years with high-speed data acquisition interfaces bring real time observation and calculation[3], taking advantage of image and signal cognition technologies. Therefore, a database system approach may give one of the effective solutions to treat complicated signals due to magnetization and to reflect skillful experts' experiences. This inspires us to develop a smart magnetic sensing system[4][5].

The present paper reports our developed magnetic sensing system in order to provide a smart magnetic sensor function. Our method is composed of three major steps; the first is sensing the metallic materials with a magnetic sensor (Fig. 1); the second is visualization converting from sensor input and output (I/O) signals to image data; the last one is an image cognition using the visualized sensor signals[6]. We apply our system to identify metallic cans commonly utilized for canned drinks. As a result, it is found that our magnetic sensor signals processing ascertain the metallic material properties as well as their physical dimensions.

2. 3-D Lissajous Method and Cognition System

2.1 Differential Coil Sensor Figure 1 shows a schematic diagram of the active magnetic sensor employed in this paper. It consists of an exciting coil and a couple of pickup coils differentially connected. The coils are all arranged along with the common axis and a test metallic object passes their inside. When alternating current is applied to the exciting coil and the metallic object locates at any position except the center of exciting coil on the axial line, the difference in linkage flux between the left- and right-sided pickup coils yields a sensor signal. It must be noted that observing both input and output signals, i.e. input voltage of the exciting coil and output voltage of differentially connected pickup coils in Fig.1, is of paramount importance to evaluate the test objects precisely.

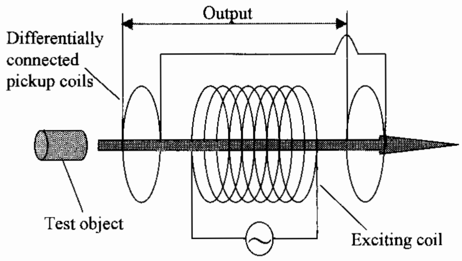

Fig. 1. Schematic diagram of the differential coil sensor system employed in this paper

2.2 3-D Lissajous Diagram The conventional Lissajous diagram simultaneously displays I/O signals on a 2-D plane, representing differences in frequency, amplitude, and phase. In case of contactless magnetic sensor systems, we confront to the serious problems, e.g. signal deflection and distortion due to the targets moving, magnetic hysteresis, and so on. To address this difficulty, we propose a method of 3-D Lissajous diagram. It is a histogram of Lissajous diagrams observed within a regular period. Figure 2, for instance, shows a 3-D Lissajous diagram constructed by input voltage impressed at the exciting coil terminals and output voltage measured at the terminal of differentially connected pickup coils shown in Fig.1. More concretely, let us consider a metallic can identification problem. When some of a metallic can

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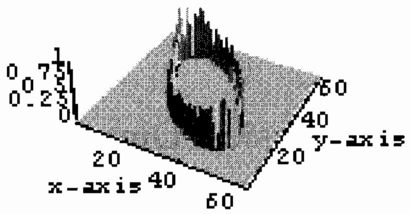
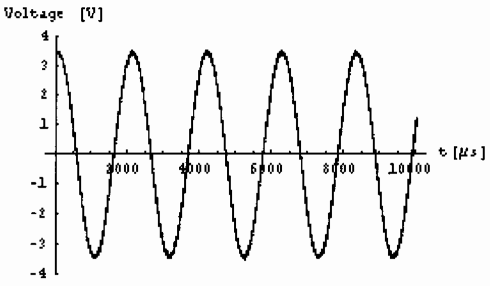
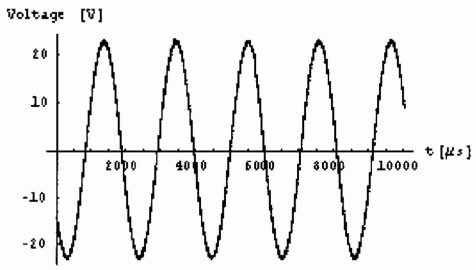


(a) 3-D Lissajous diagram (400Hz 64×64 pixels)



(b) Input voltage as x-axis data



(c) Output voltage as y-axis data

Fig. 2. 3-D Lissajous diagram of the sensor system in Fig.1

is inserted as a test object shown in Fig.1, it is possible to obtain an output voltage signal from the differentially connected pickup coils while an input voltage is impressed to at an exciting coil. Typical examples of input and output voltages are shown in Figs. 2 (b) and (c), respectively. Therefore, the metallic can identification problem is reduced into one of the magnetic sensor signal cognition problems.

Thus, the data x- and y- axes composing a 3-D Lissajous diagram respectively correspond to the values of input (Fig.2 (b)) and output (Fig.2 (c)) signals so that the time is the intervening parameter. Overlapping loci of conventional Lissajous diagram are taken into account as histograms, i.e. counting the rate of overlapping, in the direction of z-axis. This means that the values in x-, y- and z-axes of 3D Lissajous are corresponding to the input voltage at the exciting coil terminals, output voltage obtained at the terminals of differentially connected pickup coils, and the rate of x-y position overlapping. Since this idea contains the information of the time, then it is possible to treat both steady and transient states as grayscale tone image data. Although a linear I/O condition like demonstrated in Fig. 2 is a simple case, the I/O data changing rates can be reflected in the histograms.

2.3 Least Squares To realize the smart magnetic sensing system, we have studied an image cognition methodology using image pixel distribution for the 3-D Lissajous diagrams[7][8] Solving a system of equations in Eq. (1) identifies and evaluates the test objects from magnetic sensor responses.

$$\left.\begin{array}{l} \mathbf{V} = C\mathbf{U}, \\ \mathbf{U} = \begin{bmatrix} u_1 & u_2 & . & u_n \end{bmatrix}^T, \\ C = \begin{bmatrix} \mathbf{C}_1 & \mathbf{C}_2 & . & \mathbf{C}_n \end{bmatrix}. \end{array}\right\} \qquad (1)$$

For the vector expression of the 3-D Lissajous diagram shown in Fig.2 (a), i.e., **V** and $\mathbf{C}_i$, i=1,2,..., n in Eq. (1), assume the 3-D Lissajous diagram as a 2-D digital image G consisting of $k\times l$ pixels,

$$G = g(i,j), \quad i = 1,2,...,k, j = 1,2,...,l, \qquad (2)$$

where $g(i, j)$ refers to the pixel value at the position (i, j). After that the data set of image is rearranged to a 1-D data set as expressed by,

$$\mathbf{V} = [g_v(1,1),..., g_v(1,l), g_v(2,1),..., g_v(2,l),...., g_v(k,1),..., g_v(k,l)]^T, \qquad (3)$$

$$\mathbf{V} = [g_i(1,1),..., g_i(1,l), g_i(2,1),..., g_i(2,l),...., g_i(k,1),..., g_i(k,l)]^T, \qquad (4)$$

where the superscript T refers to transpose of matrix/vector.

The image size $k\times l$ in Eqs. (2),(4) is associated with the voltage resolution and the number of unknowns m. As a matter of reality, the number of pixels is much greater than that of the stored 3-D Lissajous diagrams. The solution, therefore, is obtained by means of least squares[9]

$$\mathbf{U} = \left(C^T C\right)^{-1} C^T \mathbf{V}. \qquad (5)$$

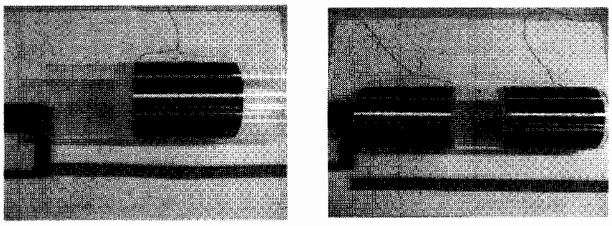
Thus in Eq. (1), **V** represents the 3-D Lissajous diagram corresponding to the information on test object as an input vector with order m; **U** expresses an identified result as a solution vector with order n; moreover C is a $m\times n$ rectangular coefficient matrix storing n 3-D Lissajous diagrams as database. When **V** is identical to the i-th column vector $\mathbf{C}_i$ in the matrix C, the i-th element u_i in the solution vector **U** accordingly takes maximum value. Even though the database does not have the identical data, the linear combination the column vector $\mathbf{C}_i$, $i=1,2,.n$, is capable of extracting similarities between the inputted data and stored database.

3. Identification of Metallic Cans by Means of 3-D Lissajous Diagrams

3.1 Experimental Setup Let us consider a metallic can identification problem to demonstrate the smartness of our magnetic sensor system. Figure 3 shows a differential coil sensor described in Section 2.1. Both exciting and differentially connected pickup coils are assembled in a coaxial way as shown in Fig.1. Table 1 lists the specification of the tested sensor. The metallic cans to be identified are shown in Fig. 4.

3.2 3-D Lissajous Diagram Figure 5 illustrates the 3-D Lissajous diagrams for the 9 cans shown in Fig. 4 when locating at one of the pickup coils. The input voltage of exciting coil is the same as Fig. 2 (c). We measured the input and output signals with 0.1s duration to draw the diagrams. The frequency of the exciting coil is determined by the several previous experimental studied to obtain the reasonable sensibility[(4)-(8)].

In Fig. 5, the image size is 64×64 pixels and the dynamic ranges in x- (output) and y- (input) axes are about ±4.0 and ±23.0 V, respectively. The resolution of diagram depends on the originally



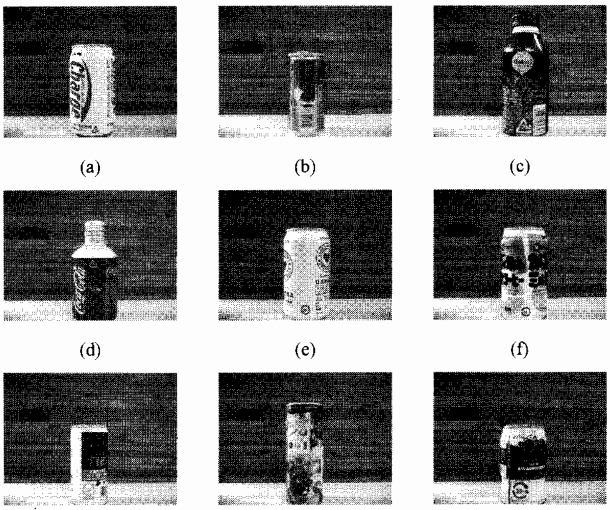
(a) Exciting coil (b) Differentially connected pickup coils

Both coils are assembled in a coaxial way as shown in Fig.1

Fig. 3. Coil elements of the magnetic sensor system illustrated in Fig.1

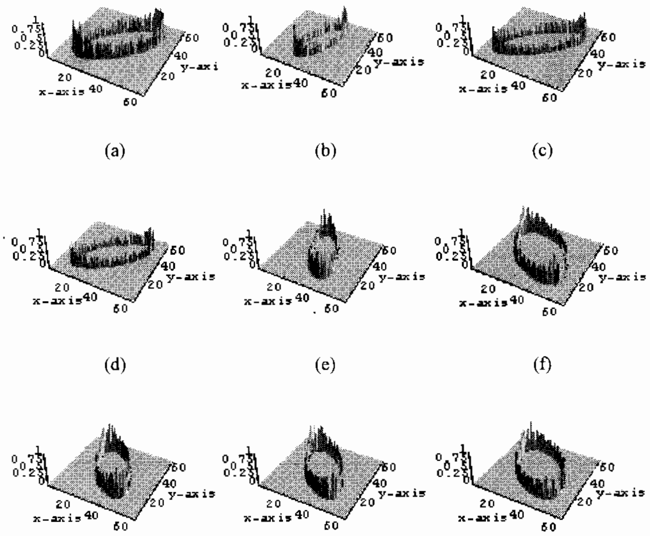
Table 1. Specification of a tested sensor shown in Fig.3

Coil	Number of turns	Diameter (mm)	Length (mm)
Exciting	200	90	115
Pickup	200	80	110



(a) (b) (c) (d) (e) (f) (g) (h) (i)

Fig. 4. Empty cans to be identified; (a)- (d) are aluminum cans : (e) - (i) are steel cans. (a)- (i) are referred to as Nos. 1-9, respectively



(a) (b) (c) (d) (e) (f) (g) (h) (i)

Fig. 5. 3-D Lissajous diagrams of the cans in Fig. 4 (400Hz, 64×64 pixels) : (a)- (i) correspond to the diagrams when the cans shown in Figs. 4(a)-(i) are inserted into the sensor, respectively

measured signal precision, i.e. the maximum image resolution is the maximum resolution of the sensor signals, but reflects on the size of system matrix C in Eq. (1). Thereby, consideration of the AD converter resolution (11bit) of the used digital oscilloscope and computing time has lead to the 64×64 pixels resolution.

As shown in Fig.4,We prepared 4 aluminum cans and 5 steel cans with different shape for experiments. In cases of the steel cans, the diagrams shown in Figs. 5 (e)-(i) take the somewhat different in shape compared with that of aluminum cans shown in Figs. 5 (a)-(d) due to time domain phase difference caused by magnetization characteristics.

3.3 Cognition Let us identify the cans by means of the 3-D Lissajous diagrams shown in Fig. 5 and the image cognition methodology described in *Section 2-C*. We have 4 aluminum and 5 steel cans for constructing the database matrix C in Eq. (1). In this case, the dimension of matrix $m\times n$ becomes (64×64)×9. Therefore, we apply the least squares in (5) to solve (1) having the column-wise system matrix C. The 3-D Lissajous diagram data of Figs. 4 (a)-(i) corresponds to each of the database matrix C as its column vectors $\mathbf{C}_1$,-$\mathbf{C}_9$, respectively.

Figure 6 shows the solution vectors when each of the input vectors V in Eq. (1) is derived from the 3-D Lissajous diagrams independently measued to the column vectors $\mathbf{C}_1$,-$\mathbf{C}_9$ in system matrix C. As a result, this has lead that any of the solution vectors **U** are composed of the non-zero elements shown in Fig.6. Hence, it has been assumed that the elements taking the maximum value in the solution vectors reveals the cognized cans. Thus, we have succeeded in identifying the prepared 9 cans by our smart magnetic sensor system.

4. Conclusion

We have proposed one of the smart magnetic sensor systems, composed of the magnetic sensor, 3-D Lissajous diagram visualization, and image cognition engine. The 3-D Lissajous diagram converts from the sensor I/O signals to image data and implicitically contains the time information by histograms as the overlapped points on the conventional Lissajous diagram. This makes it possible to utilize image cognition to realize the smart function enabling us to cognize the distinct metallic materials. One of the practical applications for identifying metallic cans has successfully been accomplished by our smart magnetic sensor system. Many kinds of magnetic sensors, with magnetic materials, can be treated by our approach for variety of purposes.

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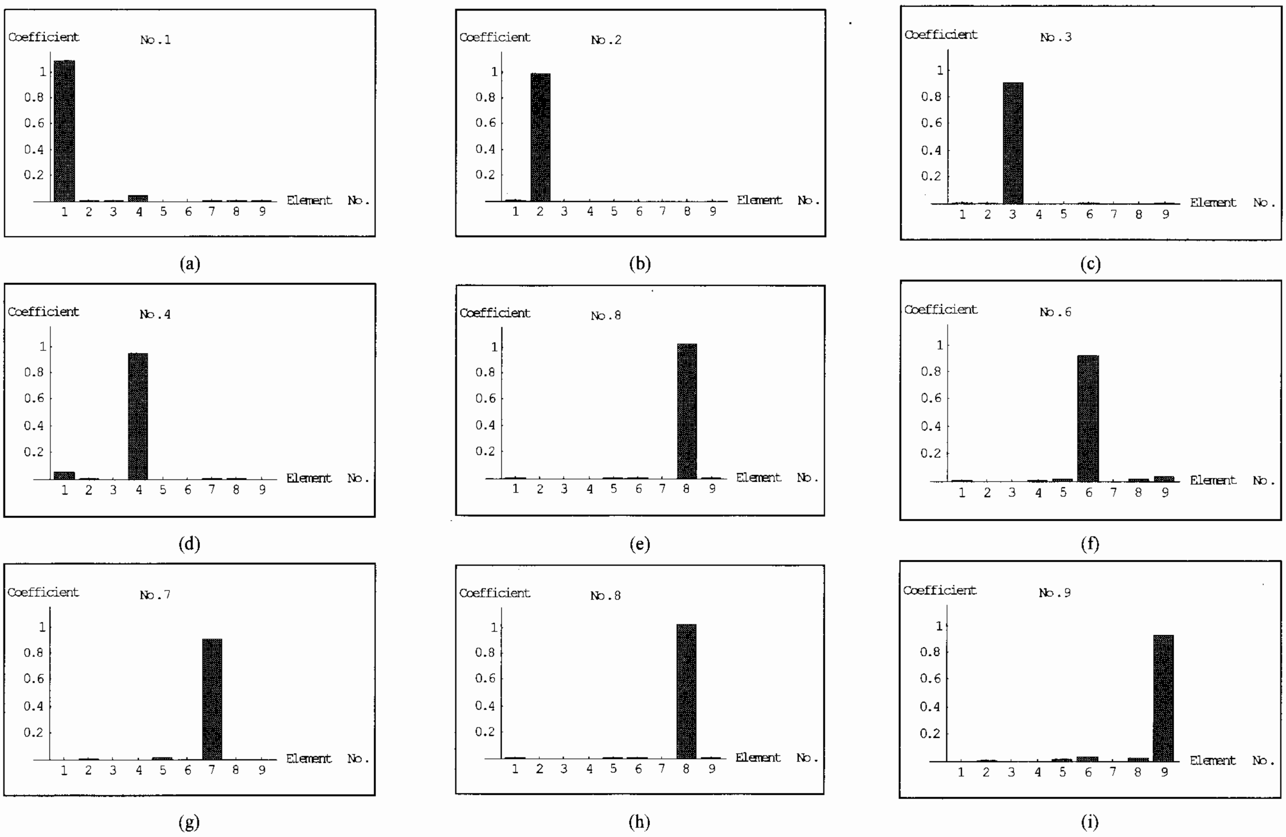

Fig. 6. Elements in solution vector U as the identified results : (a)- (i) correspond to the identification when the cans shown in Figs. 4(a)-(i) are inserted to the sensor, respectively. Vertical and horizontal axes are the magnitude and position number in the solution vector **U**, respectively

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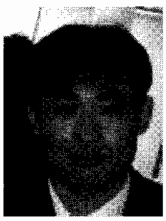

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