Applications of Electromagnetic Phenomena in Electrical and Mechanical Systems
S.Yamada, A.Nafalski and S.C. Mukhopadhyay (eds.)

# Smart lissajous method for metal cognition problem

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**ABSTRACT:** We are now exploiting a magnetic sensor, which makes it possible to detect metallic materials, embedded into the ground and concrete walls. In the present paper, we propose a method of analysis of the magnetic sensor signals. Based on the physical characteristic value, such as a time constant of the electric circuits, our methodology tries to work out an equivalent characteristic value (ECV) reflecting on the physical property of the targets.

As an initial experiment, we have carried out a classification whether the target metallic material is a steel or aluminum. As a result, we have succeeded in classifying the steel and aluminum. Thus, second stage of the developing of our smart magnetic sensor is to recognize each of the metallic materials by means of the ECV, least squares and eigen patterns.

## 1 INTRODUCTION

To prevent the accidents caused by the defects of metallic materials, non-destructive testing has an important role. For example, the defect inspection to the frame parts of airplanes, heat exchanger in the nuclear reactor should be carried out with the greatest care. To carry this in a most efficient manner, we are now developing a magnetic sensor to detect the metallic materials embedded into the ground and concrete walls.

The magnetic sensor classified into two major categories. The first is how to measure a direct current (DC) magnetic field indirectly. In many cases, a DC magnetic field is measured by using the semiconductor element exhibiting the high Hall effect, and the superconducting quantum effects. The other is the sensor which measures the alternative current (AC) magnetic field. The earth has magnetic field and also various magnetic materials are widely used for the car and train as the major structure materials, which include the magnetic devices such as the motor and transformer. Therefore, the output signal of any types magnetic sensors essentially contains circumference noise.

To overcome this difficulty, this paper proposes a method of the magnetic sensor signal analysis. Our method proposes how to extract the intrinsic physical characteristics included in the sensor output signals on the time domains. Since it is difficult to extract all of the physical characteristics from the magnetic sensor signal, we extract the single characteristic value representing an entire physical characteristic of the target from the magnetic sensor signal. This characteristic value is called the Equivalent Characteristic Value (ECV) as outlined by this paper to cope with it to the characteristic value of the initial value problem. [1-3].

To verify our methodology, we have worked out a prototype of magnetic sensor. Applying the ECV to this sensor output signals makes it possible to classify a target metallic material whether it is steel or aluminum. Furthermore, to recognize the distinct target from the sensor signals, we draw a three-dimensional complex locus comprising the real and imaginary parts of the ECV. As a result, it is revealed that each of the targets can be recognized by means of the three-dimensional complex locus, which is called eigen pattern, along with least squares.

## 2 MAGNETIC SENSOR SIGNAL ANALYSIS

### *2.1 Prototype of the magnetic sensor*

Principal purpose of our magnetic sensor is to distinguish some kinds of cans. Fig.1 shows a prototype of our magnetic sensor. Turning on ac current through an exciting coil in Fig. 1 yields AC magnetic field. The differential coil located inside the exciting coil gives an output signals as an induced voltage when inserting some kinds of cans into one side of differential coil. Fig. 2(a) and 2(b)-2(i) show respectively the input- and output-signals when inserting 8 kinds of cans into one side of differential coil. Figures 2(b)-2(e) are the output signals when inserting into 4 kinds of aluminum cans, and also Figs. 2(f)-(i) are the output signals when inserting into 4 kinds of steel cans.

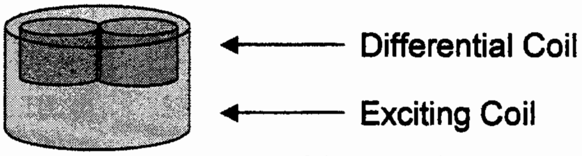
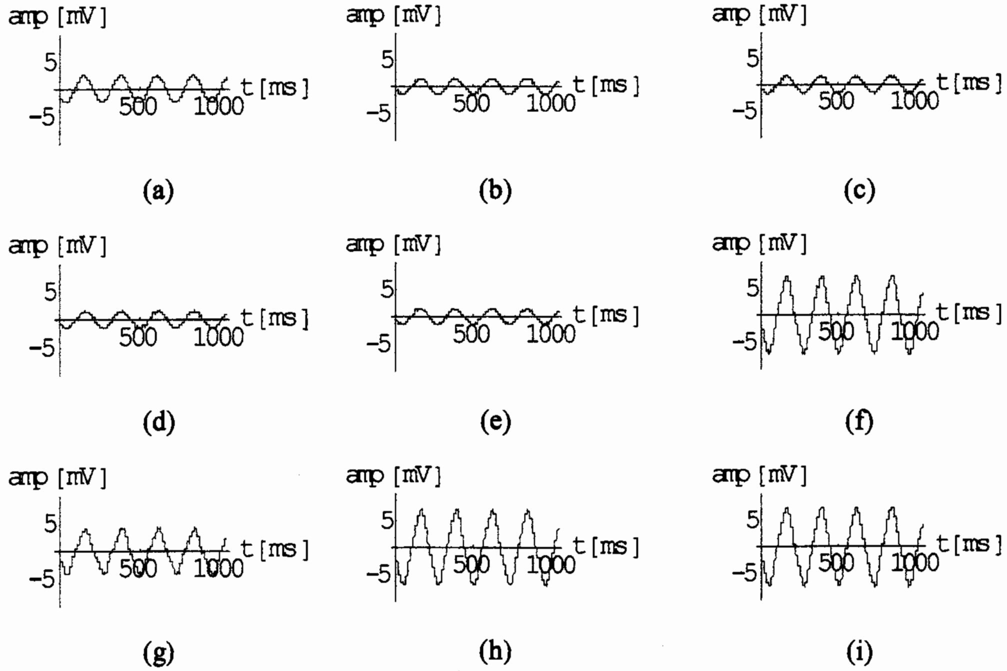


Fig.1 Prototype of the magnetic sensor



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig.2 Input and output signals of the magnetic sensor shown in Fig.1

### 2.2 ECV (Equivalent Characteristic Value)

#### 2.2.1 ECV of electric circuits

When DC voltage is impressed to a R-L series electric circuit with zero initial current, a response current becomes exponential curve as shown in Fig. 3.

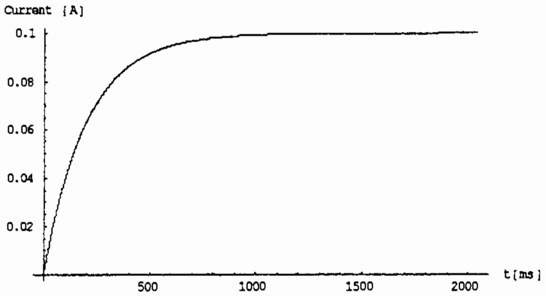


Fig.3 Transient current of a R-L series circuit when impressing DC input voltage

Let us sample the current in Fig. 3 with period $\Delta t$ , then current $i_{n\Delta t}$ in the time $n\Delta t$ can be approximately expressed by (1).

$$i_{n\Delta t} = i_{(n+1)\Delta t} + \left[i_{(n-1)\Delta t} - i_{(n+1)\Delta t}\right]\varepsilon^{-\lambda\Delta t}. \tag{1}$$

Thus, the ECV of this R-L series circuit is given by Eq. (2) [1-3].

$$\lambda = -\frac{1}{\Delta t}\ln\left[\frac{i_{n\Delta t} - i_{(n+1)\Delta t}}{i_{(n-1)\Delta t} - i_{(n+1)\Delta t}}\right]. \tag{2}$$

Appling (2) to the current in Fig. 3 gives the ECV as shown in Fig. 4. Obviously, the real part of ECV corresponds to the characteristic value of the R-L series electric circuit.

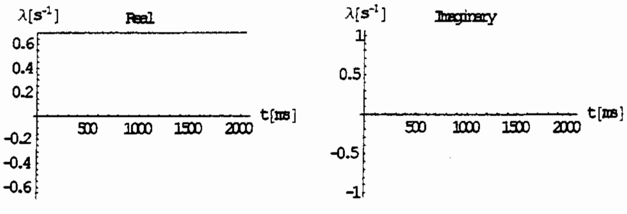


Fig.4 Equivalent characteristic values evaluated by applying
Eq. (2) to the current in Fig. 3

#### 2.2.2 Averaged sum of ECV

ECV is computed exactly from the response current to the DC voltage input. However, when the input voltage is a sinusoidal time varying voltage, the output of the magnetic sensor becomes a waveform as shown in Fig. 5. In this case, Fig. 6 shows the ECV containing spiky noise due to the singular points existence on the output waveform shown in Fig.5.

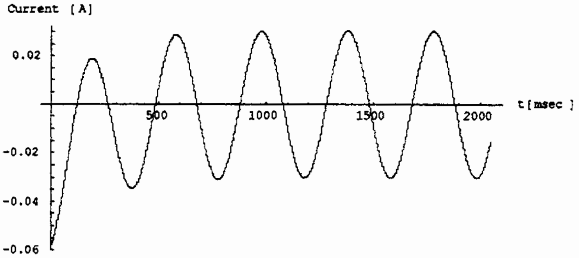


Fig.5 Transient current of a R-L series circuit when impressing a sinusoidal AC voltage

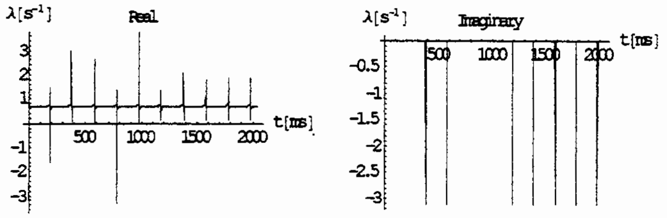


Fig.6 The ECV values evaluated from the current in Fig. 5
Left: real part, Right: imaginary part

To reduce the spiky noise in Fig.6, an additional averaged sum operation makes possible to reduce the ECV as shown in the Fig. 7. Comparison the real parts in Fig. 4 with those of Fig. 7 reveals that the ECV of the real part is settled to the same. On the other side, an imaginary part settles it in ECV, which copes with it to the angular frequency of input voltage.

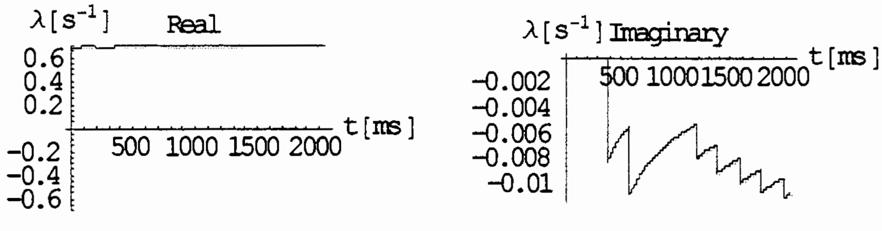
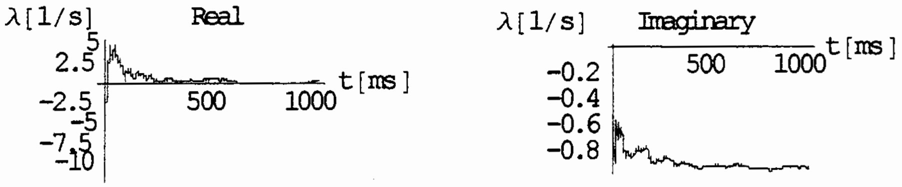


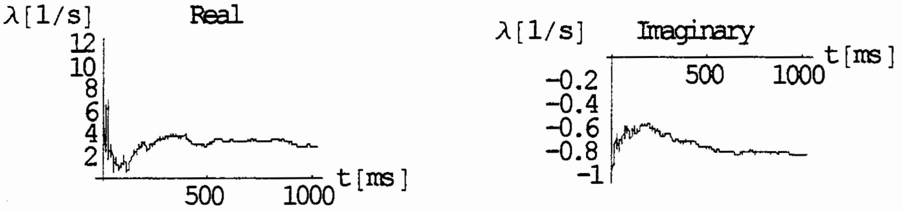
Fig.7 Averaged sum ECV evaluated from the AC response current in Fig. 5,
Left: real and Right: imaginary parts

Fig. 8 shows two of representative averaged sums ECV values of the magnetic sensor signals. In Fig.8, the real part of ECV to originate in steel reaches to a positive constant value. On the other hand, that of aluminum has the tendencies that it is finally settled in the zero. An imaginary part settles both ECV values in the constant value, which is in proportion to the input frequency.

In the other words, the real part of ECV reflects the magnetization of magnetic materials, and the imaginary part of the ECV reflects the exciting frequency. Thus, the target material is whether steel or aluminum is distinguished by notifying the real part of ECV to the sensor output signals.



(a) ECV of aluminum can



(b) ECV of steel can

Fig.8 Examples of the averaged sum ECV of the magnetic sensor signals

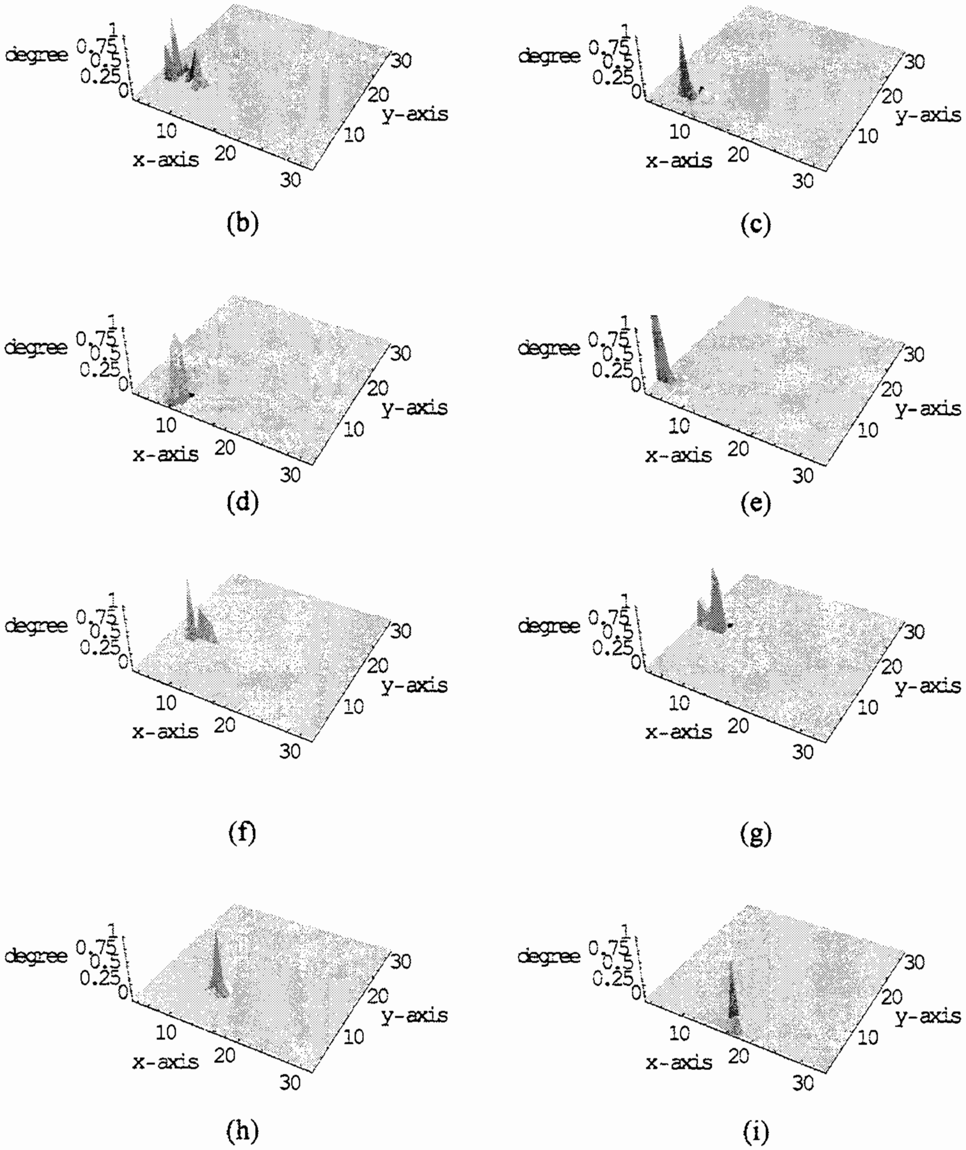
### *2.3 Cognition of the magnetic sensor signals*

The magnetic sensor signals take the distinct ECV values depending on the physical property as well as physical dimensions of the measuring targets. Final goal of our purpose is to distinguish every target by a sensor signal analysis. To achieve this, it is essential to build up a database methodology along with inverse approach. In the present paper, we try to recognize each of the cans from the entire signal database composed of the all target cans.

#### *2.3.1 Eigen Pattern*

Various kinds of information, e.g. the noise and kind of the metal and some physical dimensions, are included in the magnetic sensor signals. So, we propose the eigen pattern, which is a three-dimensional complex locus constructed by the real and imaginary parts of ECV, to represent the essential characteristics of the distinct target.

Eigen pattern makes an amendment Lissajous diagram in the real and imaginary parts of ECV. This amendment Lissajous diagram is different from conventional Lissajous diagram and does addition in the same position is taken in like a histogram. Therefore, it is called an eigen pattern. Fig.9 shows eigen patterns of the output magnetic signals when inserting 8 kinds of metallic cans.



(b) (c)

(d) (e)

(f) (g)

(h) (i)

Fig. 9 Eigen patterns

### *2.3.2 System of equations*

Each of the eigen patterns shown in Fig. 9 consists of the 32×32 elements. Those are rearranged into one-dimensional vectors form. By using number of $n^{\text{th}}$ eigen pattern vectors $\mathbf{c}_i$, $i=1,2,\ldots,n$, it is possible to obtain a system matrix $C$ with $n^{\text{th}}$ rows and 32×32 $^{\text{th}}$ columns as

$$C = [\mathbf{c}_1, \mathbf{c}_2, ., \mathbf{c}_n] \ . \tag{3}$$

Denoting an input vector **Y** obtained in a similar way to $\mathbf{c}_i$, $i=1,2,\dots,n,$, we have a linear system of equations:

$$\mathbf{Y} = C\mathbf{X} \tag{4}$$

where the biggest value in the elements of the solution vector **X** reveals a recognized signal.

*2.3.3 Least square solution*

If a number of the elements in vector **X** is smaller than those of equation, i.e., $n$<32×32, then a least squares solution, which minimizes a error norm

$$\varepsilon = \|\mathbf{Y} - C\mathbf{X}\| \ , \tag{5}$$

to Eq.(4) is formally given by

$$\mathbf{X} = \left(C^T C\right)^{-1} C^T \mathbf{Y} \, . \tag{6}$$

To build up the database, we have measured the 8 sensor signals having the different metallic materials and shapes, after that we have evaluated their eigen patterns. When we set the original signals as an input vectors, all of the signals have been completely recognized. Figure 10 shows the elements of each solution vector.

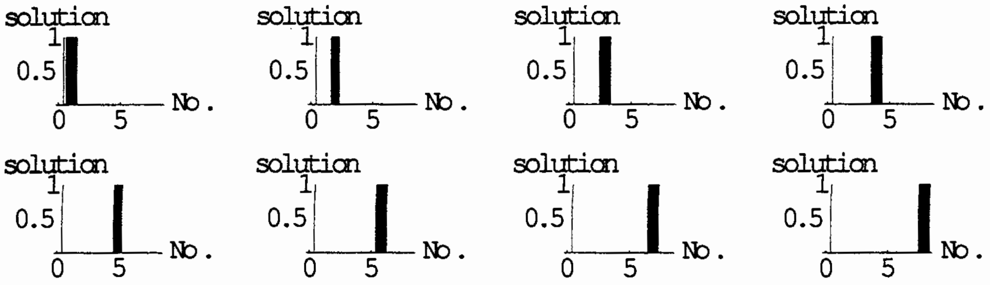


Fig.10 Elements of a solution vector

## 3 CONCLUSION

In this paper, we have proposed a simple magnetic sensor, which is capable of detecting the metallic materials embedded into the ground and concrete walls. To recognize the distinct target, the equivalent characteristic values as well as eigen pattern have been proposed. Least squares solution along with the eigen patterns has recognized any types of target from the magnetic sensor signals.

Thus, we have succeeded in establishing one of the deterministic methodologies for magnetic sensor signal analysis.

## 4 REFERENCES

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