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Identification of the metal waste using an electromagnetic sensor

Ghlam Karima*, Ayad Abdelghani, Nafaa Dahman

Laboratoire de Recherche, Intelligent Control and Electrical Power Systems(ICEPS), 89, Rue Larbi Ben M'hidi, Université Djillali Liabès,Faculté de Génie Electrique, Sidi Bel Abbes 22000, Algerie

Corresponding Author Email: Karighlam16@yahoo.fr

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ABSTRACT

This article describes a new method for identification of non-ferrous scrap metals using an Electromagnetic Sensor (EMS) that is based on the Eddy Current (EC) principle. Electromagnetic sensor is a suitable tool for identifying recoverable waste products. The identification of particles is essential to facilitate their recovery. This study deals with the 3D modelling of electromagnetic sensor located above for a representative cylindrical form particle sample of the waste. Based on the EC, we are going to be estimating the electric conductivity of the metal waste by using least squares methods (LSM) and the inverse model. Results obtained by the finite element method (FEM) are compared with experimental tests**.** So, the results prove the applicability of presenting the approach for the identification of waste metal by the eddy currents.

1. INTRODUCTION

The Waste recycling from Electrical and Electronic Equipment (WEEE) is an important subject not only from the waste treatment viewpoint, but from the valuable materials recovery too [1]. WEEE typically includes a diverse range of materials potentially harmful to humans and the environment, but is also regarded as a resource of valuable metal [2]. Facing these facts, it is of paramount importance that research and development activities, focusing on the recycling of these metals are carried out.

Practically all electronic devices contain printed circuit boards (PCBs), which can be considered raw material for metal recovery [3]. The biggest problem associated with PCB recycling is related to its complex structure and material composition. It is extremely difficult to get detailed material composition information, as PCBs are by far the most complicated building blocks of the electrical products. PCBs differ widely in their composition and a comprehensive analysis is difficult to produce with any great degree of accuracy. The information about the PCB material composition can give a fair idea about the cost incurred and profit realized from the PCB recycling. From the research point of view, this information is useful in the development of new recycling methodology and improvement of current processes [4].

The metal content in an electronic scrap can be as high as 40% by weight. The first stage in the recycling of metal is its separation from other materials. The source of scrap metal is shredded to yield a ferrous and nonferrous metal fraction [5]. Non-ferrous metals recycling refers to the separation and identification of metal for materials recovery, which is critical to recapturing non-renewable resources [6-7]. It is of great importance to characterize consumer electronic equipment in order to develop a cost-effective and environmentally friendly recycling system [8]. The costs of sampling and analysis of base and precious metal scrap are quite high and they are often higher than the economics of processing. Furthermore, the quantity and composition of the scrap change continuously and therefore also the market value. Large metallurgical industries, e.g. copper or lead smelters, may be able to charge a high amount of WEEE but due to the decreasing quality and higher amount of plastic, it will be more difficult in the future [9].

This paper presents a new method for the characterization of non-ferrous scrap metals using electromagnetic sensor. Traditionally, the EMS is used for the detection of cracks in the metallurgy industry, transport and nuclear [10-11]. The EMS principle, as shown in Figure 1, Often, demonstrates that a coil is excited by an alternating electrical current when placed over a metal plate to be inspected. Initially, the Induced current in the test piece is generated due to the interaction of the coil field to the metal plate. Consequently, the reverse field created by the induced currents, with regard to Lenz's law, the coil impedance is modified [12-13]. The measurement of certain physical properties of materials can also be very informative, especially for identification. The conductivity can be a significant parameter about information on a material [14].

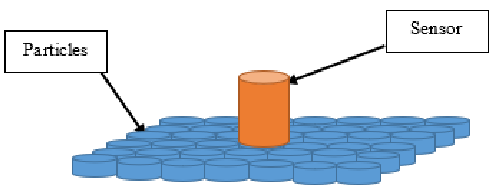


Figure 1. Schematic representation of the test problem

However, our goal is to design an "inverse model" for evaluating the electric conductivity of the metal waste from eddy current signals. The approach we adopted requires the preliminary knowledge of a "forward model" that estimates the eddy current signal knowing the conductivity of the test samples [15-16]. We proposed to build a general forward model that is appropriate to the inversion. Based on the least squares method [17], the model depends on the observations resulting from the finite element code. At the end of this work, the results obtained by simulation are compared with experimental tests where the inversion by the least squares method proves the efficiency of presenting an approach for the classification of waste material by the electromagnetic sensor.

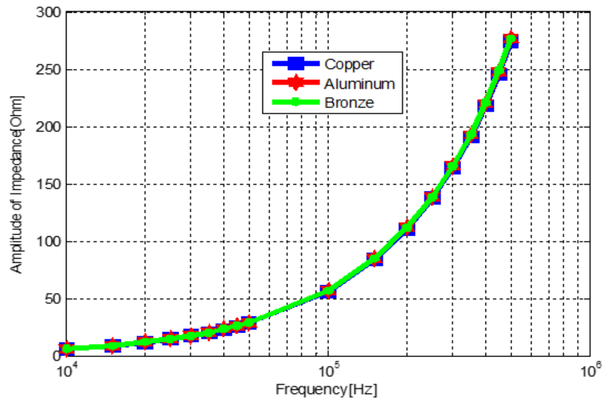
2. MATERIALS AND METHODS

Experiment device is mainly composed of the electromagnetic sensor; the last one is composed of 580 turns arranged in series, with a height of 13.5 mm and the inner and outer radius of 4.65mm and 5.6mm respectively. The coil is connected to an HP492A impedance analyzer, which provides it with a supply current and measures impedance (figure. 2). A crushing stage is necessary for an easier further management of the waste. We have chosen three waste sample: copper, aluminium, and bronze. The experiments were carried out using particles from an industrial shredder, which cuts the particles into irregular sizes ranging from 5 mm up to 10 mm.

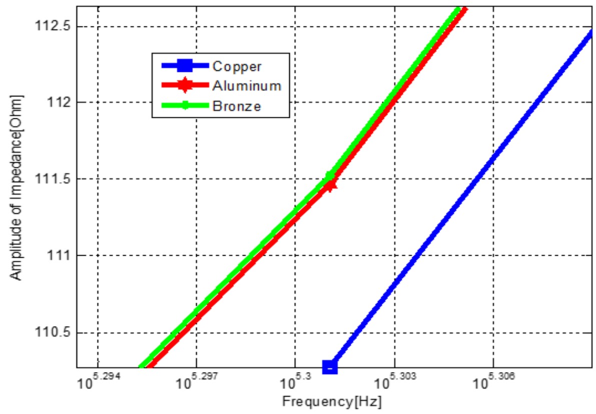
Figure 2. Experimental test by impedance analyzer

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

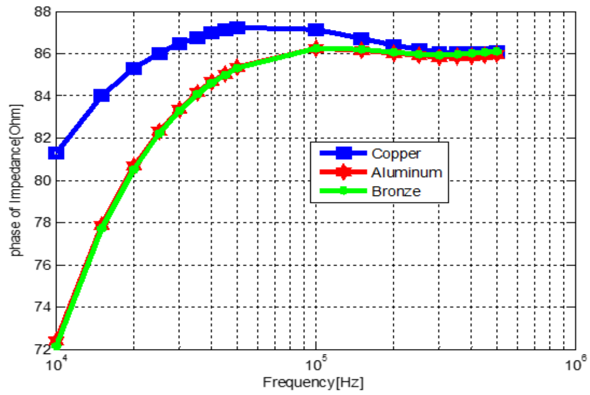
An EMS creates an alternating electromagnetic field that interacts with the metal particles placed close to the coil. This interaction is measured using the EMS, from which a signal is obtained. The method is first to detect the output response of eddy current sensor at a variable frequency between 10 KHz and 500 kHz. Then, the eddy current testing sensitivity is obtained under different excitation frequencies. The output response (impedance modulus) of the three specimen is shown in figure 3a and figure 3b under different excitation frequencies. There was a significant positive correlation between the excitation frequency and the impedance modulus. This means that the sensitivity will increase along with the increase of the excitation frequency. Therefore, the module of impedance increases with increasing frequency and is a function of electrical conductivity material. Copper can be more easily distinguished from other non-ferrous metals. Copper is highly conductive compared to aluminium and bronze. Because of higher conductivity, the experiments carried out with copper particles showed that impedance of copper was less affected in amplitude than that of aluminium and bronze. The output response (argument) of the three specimens is shown in figure.4c under different excitation frequencies. According to figure.3c, it can be concluded that the impedance argument almost do not change with the electric conductivity when the excitation frequency is higher than 200 KHz. The eddy current testing is not feasible at that frequency.



(a)



(b)

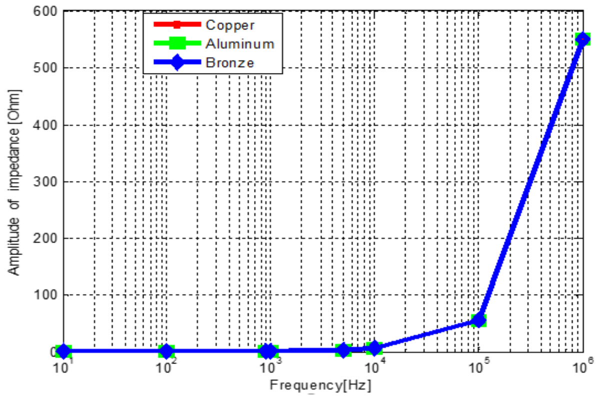


(c)

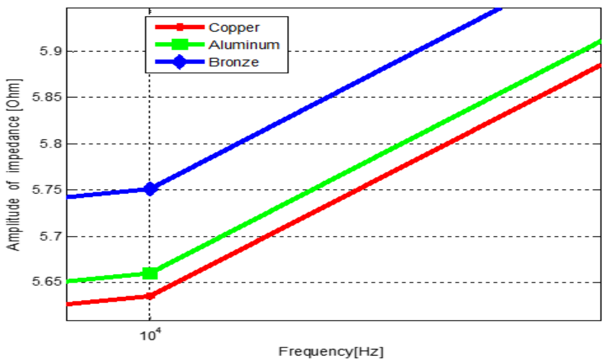
Figure 3. Measurement variation of impedance amplitude and phase according to the frequency (10 kHz-500 kHz) (a) Impedance amplitude (b) Zoom of the impedance amplitude (c) impedance phase

4. NUMERICAL SIMULATION AND DISCUSIONS

A 3D model was developed, using COMSOL Multiphysics Version 5.2a [18]. Specification of the simulation model is as follows: particles will have a smaller size ranging from 4 to 10 mm [19]. and induced Eddy current act on a particle during Eddy current test, as a result of the interaction with the magnetic field of the coil [20]. Based on the analysis of induced Eddy current in metal flake, according to current skin effect, the current forms yield to the shape of the maximal cross area of the particle [21]. The principal diameters D of the selected particles relating to the Eddy current process are established by determining the size of the largest circle (Eddy current). Therefore, the detailed shape of scrap particles is less important [22]. In this study, we use cylindrical shape of 3 mm radius and 2mm thickness. We have chosen three waste samples: copper, aluminum, and bronze. The method is to detect the output response of eddy current sensor at a variable frequency between 10 Hz and 1MHz.



(a)



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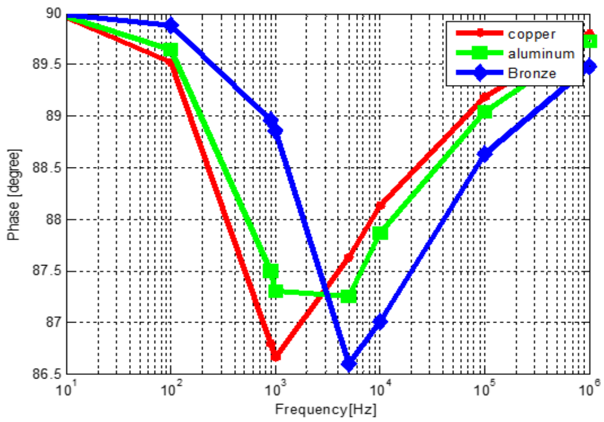

(c)

Figure 4. FEM variation of impedance amplitude and phase according to the frequency (10Hz-1MHz) (a) Impedance amplitude (b) Zoom of the impedance amplitude (c) impedance phase

The metal detectors are widely used in environmental system and materials industry. In this work, the electromagnetic sensors are used for characterization of the conductive metal. The output response of the EMS for different specimens of metals is shown in Figure.4 with different excitation frequencies. There was a significant positive correlation between the excitation frequency and the impedance modulus. This means that the sensitivity will increase along with the increase of the excitation frequency. According to Figure 4(c); of 10Hz – 100Hz, there is a small variation of the argument, and more than the frequencies are increased causing an increase of the impedance argument. The intersection points between the argument curves of different samples mean we are going to have the same impedance values for several different materials. Improvements in detection are possible by applying a multifrequency operation. The results of Figure.4 (b) show that the sensitivity of copper waste, aluminum, and bronze provide one to another curves shifting. According to Figure.4, it can be concluded that the response signal can be measured when the excitation frequency is higher. One control variable of the process was understudy: electric conductivity of the metal waste (Ms/m). The least square method was used to evaluate the effect of the electric conductivity.

4.1. Least squares for estimation

The method of least squares gives a way to find the best estimate, the aim is to minimize the error of predictions. Those errors (ε_i) are there for the vertical distances between the measuring points and the regression line. The calculation of this line takes into account the *n* measuring points of (X_i, Y_i) coordinates. The mean of the X, the variance of the X and the covariance of the (X, Y), respectively, are noted.

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{1}$$

$$V(X) = \frac{1}{n}\sum_{i=1}^{n} (X_i - \overline{X})^2 \tag{2}$$

$$\mathrm{cov}(X, Y) = \frac{1}{n}\sum_{i=1}^{n} (X_i - \overline{X})(Y_i - \overline{Y}) \tag{3}$$

In the most general case, a direct linear model can be expressed as follows:

$$\begin{cases} Y_i = aX_i + b + \varepsilon_i \\ \hat{Y}_i = aX_i + b \end{cases} \tag{4}$$

The coefficients *a* and *b* shall be determined by the least square regression that minimises the sum of the squared distances between each data point and the regression equation:

$$SCE = \sum_{i=1}^{n} (\varepsilon_i)^2 \tag{5}$$

Estimate *a* and *b* such as:

The SCE is minimized, where the slope *a* is given by the following formula:

$$a = \frac{\mathrm{cov}(X, Y)}{V(X)} \tag{6}$$

The regression line comes across two points m_y and m_x :
Or:

$$m_y = \overline{Y} = \frac{\sum Y_i}{n}$$

And

$$m_x = \overline{X} = \frac{\sum X_i}{n}$$

where:

$$b = m_y - \; am_x$$

The analysis of the FEM results was carried out using the MATLAB program, which calculates the coefficients *a* and *b* of the mathematical model, and identifies the best settings of the factors to optimize the process. The program evaluates statistical criteria: the ‘‘goodness of fit’’R^2. For a good model, the criteria R^2have numerical value close to unity.

4.2. Identification of material

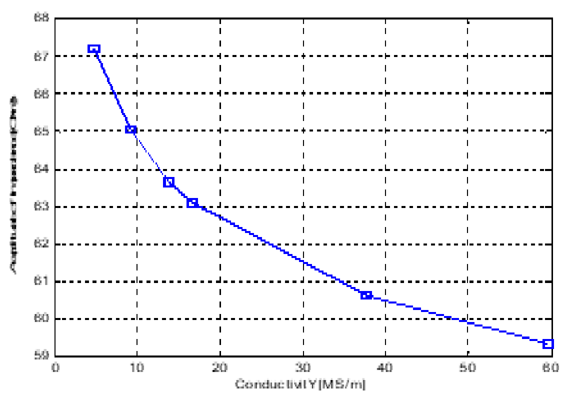

Figure 5. Amplitude of impedance according to the electrical conductivities for metal waste with 100 kHz of the excitation frequency

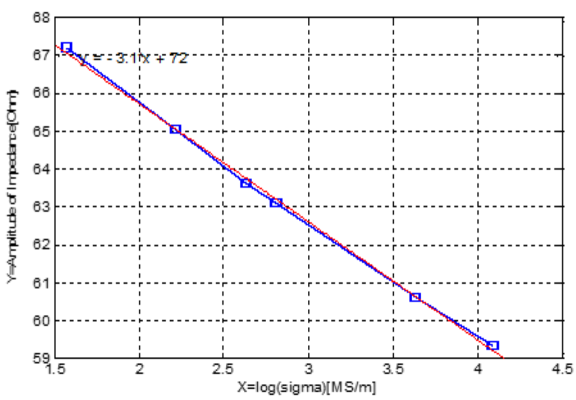

Figure 6. Nonlinear regression line of the impedance amplitude according to the electrical conductivities

Numerical simulation, that will help us to make different test configuration; flexibility, which do not offer the measures is always dependent on the equipment and the available samples.

One control variable of the process was understudy: electric conductivity of the metal waste σ (Ms/m). The least square method was used to evaluate the effect of the electric conductivity. Figure 5 presents the impedance module depending on electrical conductivities of the six metal samples with 100kHz of the excitation frequency.

(1) Concerning impedance module curve depending on electrical conductivities for each sampling of waste, there was an inverse correlation.

(2) According to figure 5, the relationship between the impedance module ($|Z|$) and electrical conductivities (σ) for samples is non-linear-type. Then, we are seeking to formalize the mean- relationship that unites $|Z|$ and σ using the nonlinear regression (The method of least squares) [23].

In this part, the method allows minimizing the sum of the squared distances between both the measured and estimated values. These are often Y measurements realized for an X measurement parameter:

(3) To have a linear relationship between $|Z|$ and σ (Figure 6), we have made a least square logarithmic fit. The data are fitted by posting:

$X_i = \mathbf{ln}(\sigma_i)$ and $Y_i = |Z_i|$, with i=1 to6.

This is; therefore, a prediction model. The objective is to predict error, the distance between the values $|Z|$calculated by the finite element code (Y_i) and estimated values by the linear regression line ($\hat{Y}_i$). The problem facing us is to determine the sample electric conductivity from the coil impedance measures for each waste metal (Copper, Aluminum, Zinc, Bronze, Lead, and Tin.) under 100 kHz of the excitation frequency. It is, therefore, assuming the availability of direct model, an inverse problem can be realized.

(1) According to the least-square method, the linear correlation coefficient between X_i and Y_i is:

R = cor (ln (σ), $|Z|$) = 0.999

According to the formulae (1), (2), (3), and (6), we find: a = -3.12 and b = 71.96

The linear regression by the least squares method is given by:

$$|Z|(\sigma) = -3.12 \ln\sigma + 71.96 \tag{7}$$

As the sum of squares of errors SCE = 0. 0585 is low and the coefficient = 0.9986 is close to one, we can, therefore, conclude that the adjustment is of good quality. In summary, we conclude that the evolution of the impedance absolute depends on electrical conductivities of the waste metal. Formally, this relationship can be expressed as follows by formula (7).

The estimate of a single material can be made from one relationship $|Z|(\sigma)$, previously characterized as a working frequency. A pre-characterization can be experimentally made on reference particle structures, or by computer simulation. The characteristic considered with a certain frequency *f* will be:

$$|Z|(f) = \alpha(f).\ln \quad \sigma + b \tag{8}$$

To estimatethe conductivity (σ) from the calculated impedance, it suffices to reverse the equation (8), we shall have the following formula:

$$\sigma = e^{(|z|(f) - b) * \alpha^{-1}(f))} \tag{9}$$

The formula (9) designates the values estimated by the nonlinear regression line. Then, we can deduce it from unknown sample impedance calculated (by simulation) and mean square errors (MSE) already calculated by LSM using the direct model (4). The found value is proposed as the input of the algorithm, which changes the estimation of sample electric conductivity. At each iteration, this change aims at identifying the sample used. Inversion is supposed to correct the gap and the process is stopped when the calculation by the formula (9) is equal to a set point value, for example, the aluminum electrical conductivity.

The main goal of the current study is to verify the efficiency of the inversion of the LSM for the conductivity calculations. The experimental results are presented in the following table:

Table 1. Calculation of the conductivity by the inversion LSM with the frequency equal to 100 kHz

Waste sample	**Copper**	**Aluminum**	**Zinc**	**Bronze**	**Lead**	**Tin**
FEM Impedance Module [Ohm]	59.3263	60.6228	63.0897	63.6300	65.0348	67.1966
Real Conductivity [MS/m]	59.6	37.7	16,7	13.9	9,17	4,81
Conductivity calculated by the LSM	59.6378	39.2544	17.7128	14.8797	9.4578	4.7090
Errors($\boldsymbol{\varepsilon}$)	-0.0378	-1.5544	-1.0128	-0.9797	-0.2878	0.101

The EC-NDT methods is a great way for identifying recoverable waste products. The characterization of a sample can be made from the relationship previously characterized with a working frequency.

5. VALIDATION MODEL

By using Finite Element Method (FEM) the simulation results obtained can be validated by experimental results and represented in tables 1, 2 and 3. In the experimental case of an inspection of a waste sample, we change the excitation current' s frequency of 10kHz – 50kHz and evaluate the impedance components (resistance, inductance, and module). The curves of the impedance components of copper, aluminium and bronze wastes were plotted and given in the Figure 7.

The above results show the good suitability between measurements and simulations, both in term phase variation regarding the magnitude of the impedance component. However, we also observe a slight difference between the numerical and experimental results. This difference is mainly due to the measurement parameters uncertainties, and their differential gap with those used in the simulation, for example the errors on geometric parameters and the lift-off distance sensors-inductors. For errors on the target properties and particle shape, they affect the phase and the amplitude of the signal.

Table 2. Comparison of impedance calculated by finite element method (FEM) and measurement for the copper waste sample

Frequency (kHz)	**10**	**25**	**50**
FEM (Copper):$\boldsymbol{Z_F}(\Omega)$	0.27+ j5.67	0.57+ j13.92	1.00+ j27.76
Measurement (Copper):$\boldsymbol{Z_M}(\Omega)$	0.86 +j5.65	0.98 +j14.12	1.37+ j28.18
Relative difference (Copper) $\boldsymbol{R_M}\%$	0.0079	0.0157	0.0156

Table 3. Comparison of impedance calculated by finite element method (FEM) and Measurement for the Aluminum waste sample

Frequency (kHz)	**10**	**25**	**50**
FEM (Aluminum) $\boldsymbol{Z_f}(\Omega)$	**0.27+ j5.74**	**0.62+ j14.05**	**1.1+ j27.79**
Measurement (Aluminum) $\boldsymbol{Z_M}(\Omega)$	**1.81+ j5.70**	**1.93+ j14.26**	**2.32+ j28.46**
Relative difference (Aluminum)$\boldsymbol{R_M}\%$	**0.0405**	**0.0229**	**0.0261**

Table 4. Comparison of impedance calculated by finite element method (FEM) and Measurement for the Bronze waste sample

Frequency (kHz)	**10**	**25**	**50**
FEM(Bronze)$\boldsymbol{Z_f}(\Omega)$	**0.18+ j5.83**	**1.61+ j14.23**	**2.33+ j28.21**
Measurement (Bronze)$\boldsymbol{Z_M}(\Omega)$	**1.84+ j5.71**	**1.95+ j14.26**	**2.33+ j28.46**
Relative difference (Bronze)$\boldsymbol{R_M}\%$	**0.0272**	**0.0103**	**0.0112**

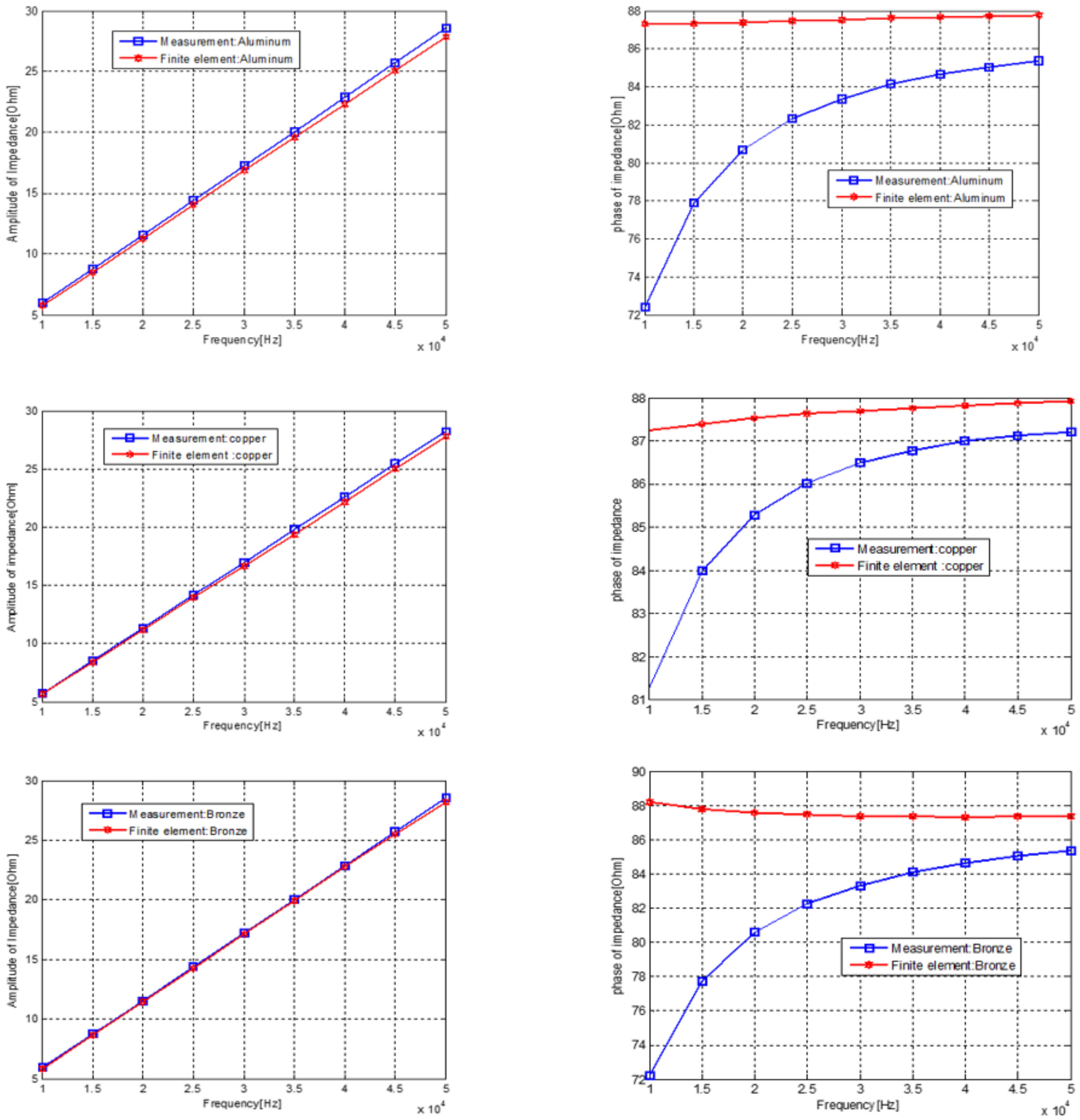

Figure 7. Measurement results and numerical calculations of impedance components for different excitation frequencies (10kHz-50kHz)

6. CONCLUSION

In this paper, we are proposing an identification of waste material by the eddy current, by calculating the impedance to identify the conductivity of sample waste.

By using the least squares method, the results show that there is a relationship between the impedance and electric conductivity. The results demonstrate that there are indications of the development of direct behavioral interactions between a sensor CF and a waste. The models could be used to develop a resolution of an inverse problem, which would identify the recoverable waste products by impedance measurements.

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