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(54) Title: METHOD AND APPARATUS FOR DETERMINING CONDUCTIVITY BASED ON ELECTROMAGNETIC INDUCTANCE SPECTROSCOPY

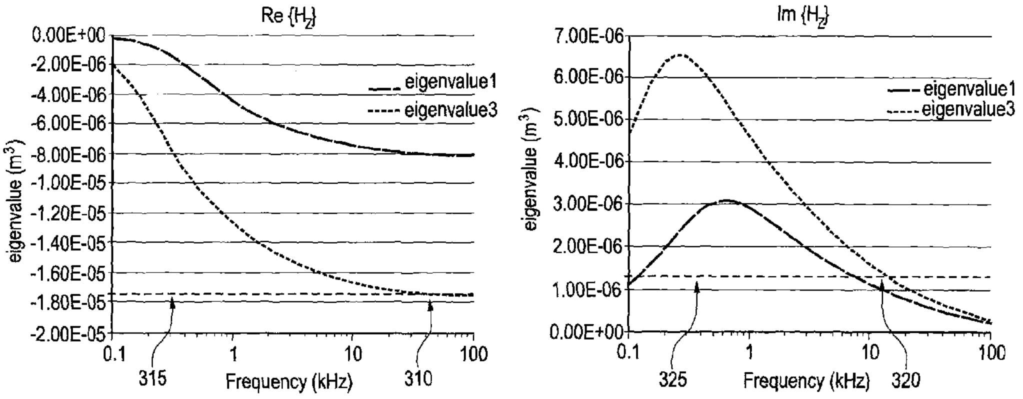

Figure 3

(57) **Abstract:** Embodiments of the present invention provide a method of and an apparatus for determining conductivity of a metal target. An interrogation magnetic field is provided and induces an electrical current in the metal target. A resultant magnetic field is generated by the electrical current. In-phase and out-of-phase components of the resultant magnetic field are determined for the target at a first frequency (conductivity limit due to skin depth) and a second frequency of the interrogation magnetic field respectively. The conductivity of the metal target is determined based on the in-phase and out-of-phase components at the first and second frequencies.

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METHOD AND APPARATUS FOR DETERMINING CONDUCTIVITY BASED ON ELECTROMAGNETIC INDUCTANCE SPECTROSCOPY

Background

Aspects of the invention relate to methods and apparatus for determining conductivity of non-magnetic metallic targets based on characteristics of their impedance spectra using non-contact electromagnetic sensors.

It is desired to quickly and efficiently inspect a target material for one or more properties. Accurate knowledge of these properties may allow the material of the target to be identified, such as to enable sorting of different materials. An example property of a metal target is a conductivity of the target.

Current systems for inspecting metals for their material properties involve hand sorting, magnetic separation for ferrous metals, eddy current separation for highly conductive non ferrous metals, heavy media separation such as sink or float separation, X-ray transmission or fluorescence, or Laser-Induced Breakdown Spectroscopy, LIBS. In LIBS for instance, the surface of the metal is targeted by a high power laser, and is partly vaporised to produce a plasma. A spectrum of the light emitted from the plasma is then detected by the LIBS system. The material properties are determined from the spectra of the emitted light.

It is an object of embodiments of the invention to at least mitigate one or more of the problems of the prior art.

Summary of the Invention

An aspect of the invention provides a method of determining conductivity of a metal target, comprising providing an interrogation magnetic field, receiving a resultant magnetic field from the metal target, wherein the resultant magnetic field is generated by an electrical current induced in the metal target by the interrogation magnetic field, determining an in-phase component of the resultant magnetic field for the metal target at a first frequency of the interrogation magnetic field, determining an out-of-phase component of the resultant magnetic field for the metal target at a second frequency of the interrogation magnetic field, and determining the conductivity of the metal target based on the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies. Advantageously, the conductivity of a metal target may be determined by providing an interrogating magnetic field and measuring a resultant magnetic field generated in the target by the interrogating magnetic field.

The method may comprise the conductivity of the metal target being determined based on the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies independent of a geometry of the metal target. Advantageously, the conductivity of the metal target may be determined based on the in-phase and out-of-phase components of the resultant magnetic field without prior knowledge of the geometry of the target.

The first frequency of the interrogation magnetic field may substantially correspond to an asymptote of a response curve of the in-phase component of the resultant magnetic field. Advantageously, the first frequency may be any frequency that substantially corresponds to an asymptote of a response curve of the in-phase component of the resultant magnetic field.

The first frequency of the interrogation magnetic field may be at least 10 kHz. The first frequency of the interrogation magnetic field may be at least 20 kHz. The first frequency of the interrogation magnetic field may be around 50-100 kHz. The first frequency of the interrogation magnetic field may be around 10-500 kHz.

The second frequency of the interrogation magnetic field may substantially correspond to a frequency at a substantially linear portion of a response curve of the out-of-phase component of the resultant magnetic field. Advantageously, the second frequency may be any frequency that corresponds to a frequency at a substantially linear portion of a response curve of the out-of-phase component of the resultant magnetic field. The response curve may be generally bell-shaped. The second frequency may be on a high-frequency side of the bell-shape. The second frequency may be at a higher-frequency than a peak of the response curve of the out-of-phase component. The second frequency may be lower than a frequency at which the response curve of the out-of-phase component has substantially tended to zero.

The second frequency of the interrogation magnetic field may be at least 10 kHz. The second frequency of the interrogation magnetic field may be around 10-50 kHz. The second frequency of the interrogation magnetic field may be around 10-500 kHz.

The method may comprise a value of the in-phase component of the resultant magnetic field at the first frequency being a function of geometry of the metal target. Advantageously, the value of the in-phase component of the resultant magnetic field is a function of only the geometry of the metal target.

The method may comprise a value of the out-of-phase component of the resultant magnetic field at the second frequency being a function of geometry and the conductivity of the metal target. Advantageously, the dependence on the geometry of the metal target may be removed by comparison to the in-phase component.

The conductivity of the metal target may be determined based on conductivity reference data. The determining of the conductivity may comprise assigning the metal target to a band of the conductivity reference data based on the determined values of the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies of the interrogation magnetic field and determining a conductivity of the band of the conductivity reference data based on a relationship between the data points in the band. Advantageously, the conductivity of the metal target may be determined with help from data from previous measurements of targets.

The method may comprise determining a type of metal of the metal target. The determining of the type of metal may comprise assigning the metal target to a band of conductivity reference data based on the determined in-phase and out-of-phase components of resultant magnetic field and assigning a type of metal to the band of the conductivity reference data. Advantageously, the type of metal of the metal target may be determined by providing an interrogating magnetic field and measuring a resultant magnetic field generated in the target by the interrogating magnetic field.

The method may comprise sorting the metal target based on the determined type of metal. Advantageously, targets determined to be made of different metals may be separated from each other.

A position of the metal target may be determined by the interrogation magnetic field based on a location of a source of the resultant magnetic field. Advantageously, targets may be located in order to be sorted.

One or more of a position of the metal target and a geometry of the metal target may be determined by a camera.

An aspect of the invention provides a method of classifying metallic targets based on characteristics of their impedance spectra using non-contact electromagnetic sensors, comprising providing an interrogation magnetic field, receiving a resultant magnetic field from the metal target, wherein the resultant magnetic field is generated by an electrical current induced in the metal target by the interrogation magnetic field, determining an in-phase component of the resultant magnetic field for the metal target at a first frequency of the interrogation magnetic field, determining an out-of-phase component of the resultant magnetic field for the metal target at a second frequency of the interrogation magnetic field, and classifying the metal target based on the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies. Advantageously, the metallic targets may be classified by providing an interrogating magnetic field and measuring a resultant magnetic field generated in the target by the interrogating magnetic field. Advantageously, the target may be classified without first explicitly calculating the conductivity.

The classification of the metal target may be determined based on the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies independent of a geometry of the metal target.

The first frequency of the interrogation magnetic field may substantially correspond to an asymptote of a response curve of the in-phase component of the resultant magnetic field.

The second frequency of the interrogation magnetic field may substantially correspond to a frequency at a substantially linear portion of a response curve of the out-of-phase component of the resultant magnetic field.

The classification of the metal target may comprise using a neural network.

The classification of the metal target may comprise using a nearest neighbour approach.

The neural network may use input samples of known classifications of metal targets to determine the classification of the metal targets.

According to another aspect of the invention, there is provided an apparatus for determining conductivity of a metal target, comprising an interrogation magnetic field generator for providing an interrogation magnetic field, controlled by a control unit, a magnetometer for receiving a resultant magnetic field from the metal target and outputting a signal indicative thereof, wherein the resultant magnetic field is generated by an electrical current induced in the metal target by the interrogation magnetic field, and the control unit, arranged to control the interrogation magnetic field generator to provide the interrogation magnetic field at a first frequency and a second frequency, receive the signal indicative of the resultant magnetic field, determine an in-phase and an out-of-phase component of the resultant magnetic field at the first and second frequencies of the interrogation magnetic field, and determine the conductivity of the metal target based on the in-phase and out-of-phase components of the resultant magnetic field.

The control unit may determine the conductivity of the metal target by assigning the metal target to a band of conductivity reference data based on the determined values of the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies of the interrogation magnetic field, and determining a conductivity of the band of the conductivity reference data based on a relationship between the data points in the band.

The control unit may be further arranged to assign the metal target to a band of conductivity reference data based on the determined in-phase and out-of-phase components of resultant magnetic field, assign a type of metal to the band of the conductivity reference data, and based on the assigned band of the metal target, determine a type of metal of the metal target.

The apparatus may further comprise a sorting device for sorting the metal target based on the determined type of metal, wherein the sorting device is controlled by the control unit.

The apparatus may further comprise a locating device for arranging the metal target proximal to the interrogation magnetic field generator and the magnetometer, wherein the locating device is controlled by the control unit.

One or more of the magnetometer or the interrogation magnetic field generator may comprise an array of inductor coils.

One or more of a number of the inductor coils in the array or a spacing between the inductor coils in the array may be adjustable.

The number of inductor coils in the array may be between 4 and 16. The number of inductor coils in the array may be between 4 and 64.

According to a further aspect of the invention, there is provided an apparatus for classifying non-magnetic metallic targets based on characteristics of their impedance spectra using non-contact electromagnetic sensors, comprising an interrogation magnetic field generator for providing an interrogation magnetic field, controlled by a control unit, a magnetometer for receiving a resultant magnetic field from the metal target and outputting a signal indicative thereof, wherein the resultant magnetic field is generated by an electrical current induced in the metal target by the interrogation magnetic field, and the control unit, arranged to control the interrogation magnetic field generator to provide the interrogation magnetic field at a first frequency and a second frequency, receive the signal indicative of the resultant magnetic field, determine an in-phase and an out-of-phase component of the resultant magnetic field at the first and second frequencies of the interrogation magnetic field, and classifying the metal target based on the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies.

The control unit may determine the classification of the metal target by assigning the metal target to a band of classification reference data based on the determined values of the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies of the interrogation magnetic field, and determining a classification of the band of the classification reference data based on a relationship between the data points in the band.

Brief Description of the Drawings

Embodiments of the invention will now be described by way of example only, with reference to the accompanying figures, in which:

Figure 1 is a block diagram of an apparatus according to an embodiment of the invention;

Figure 2 is a flow chart illustrating a method according to an embodiment of the invention;

Figures 3 (a) and (b) are graphs of frequency of an interrogation magnetic field against a value of an in-phase component of a resultant magnetic field and a value of an out-of-phase value of the resultant magnetic field respectively. Curves for two different shaped targets are plotted;

Figure 4 is a graph of values of the in-phase component against values of the out-of-phase component for a range of targets;

Figure 5 is an illustration of an arrangement of solenoids according to an embodiment of the invention;

Figure 6 is a block diagram of an apparatus according to a further embodiment of the invention where conductivity is used to determine metal type;

Figure 7 is a flow chart illustrating a method according to an embodiment of the invention;

Figure 8 is an illustration of an arrangement of solenoids and a conveyer belt according to an embodiment of the invention; and

Figure 9 is a graph of values of the in-phase component against values of the out-of-phase component for a range of targets.

Detailed Description of Embodiments of the Invention

Referring to Figure 1, there is shown a block diagram of an apparatus for determining conductivity of a metal target according to an embodiment of the invention, indicated generally by reference numeral 100. The apparatus 100 comprises a control unit 110, an interrogation magnetic field (IMF) generator 120 for providing an interrogation magnetic field and a magnetometer 130 for receiving a resultant magnetic field. The control unit 110 is arranged to provide an interrogation control signal 125 to the IMF generator 120 which is indicative of one or more properties of the interrogation magnetic field. The control unit 110 is arranged to receive a resultant signal 135 indicative of the resultant magnetic field received at the magnetometer 130. The apparatus 100 may be used to classify a non-magnetic metal target into one of a set of classes where each class is associated to a different conductivity or other material property.

The IMF generator 120 may comprise at least one interrogation coil 120 which is arranged to be energised by an interrogation voltage signal in dependence upon the interrogation control signal 125. In some embodiments, the control unit 110 provides the interrogation voltage signal 125 to the interrogation coil 120, which may be via an amplifier. The interrogation coil 120 is arranged to generate the interrogation magnetic field in dependence upon the interrogation voltage signal 125 i.e. at a frequency of the interrogation voltage signal 125. The interrogation coil 120 may be wound around a core, such as a ferrite core, to improve generation of the interrogation magnetic field as will be appreciated. In some embodiments, the IMF generator 120 comprises a plurality of coils.

In such embodiments, the plurality of coils may each be arranged to generate a respective portion of the interrogation magnetic field in response to the interrogation voltage signal 125 provided to each of the coils. The plurality of interrogation coils may be distributed across a sensitive region for which the apparatus 100 is arranged to determine the property of metal targets within. The sensitive region may be at least 400mm wide. The sensitive region may be up to 1m wide in some embodiments. In other embodiments the sensitive region is over 1m wide, such as 5m or more. The sensitive region may be arranged to encompass, in use, at least part of a path of the metal target. That is, the metal target may be caused to move through the sensitive region. The path may correspond to a portion of a conveyor which is arranged to, in use, convey the metal target through the sensitive region. In some embodiments, the path may correspond to a portion of a free fall system which is arranged to, in use, drop or slide the metal target through the sensitive region. The IMF generator 120 may comprise, in some embodiments, between 4 and 16 interrogation coils 120, although other numbers of coils may be envisaged. The interrogation coils may be spaced at periodic intervals, such as at least 50mm apart. The interrogation coils may be spaced, in one example embodiment, at 90mm intervals although it will be appreciated that other spacing distances may be used.

In addition, in some embodiments, each interrogation coil 120 may transmit the interrogation magnetic field at a different frequency to that of other coils, such as its neighbours. The frequency of interrogation magnetic field transmitted by each interrogation coil 120 may vary from that of its neighbours by a predetermined amount. The predetermined amount may be 5%, 10% or another suitable amount. The control means 110 may alter the interrogation control signal 125 in order to shift the frequencies of the interrogating magnetic field by the predetermined amount, thus creating a number of different multi-sine waveforms. In some embodiments, these waveforms are then each assigned to an interrogation coil 120 in such a way that no two adjacent interrogation coils 120 have the same waveform. This method reduces the possibility of cross-talk and ensures that the demodulated measured response from the metal target is due specifically to the excitation emitted by the correct interrogation coil 120.

The interrogation voltage signal 125 may be a time-varying voltage signal, such as a sinusoidal voltage signal, which is applied to the one or more interrogation coils 120 to generate the interrogation magnetic field. The interrogation voltage signal 125 has a frequency *f* which is controlled by the control unit 110. The control unit 110 may determine the frequency of the interrogation voltage signal 125 such that the interrogation magnetic field has a corresponding frequency. The control unit 110 may be arranged to cause the interrogation magnetic field to be generated at each of a plurality of frequencies. The plurality of frequencies may comprise at least a first frequency and a second frequency. In some embodiments, the first frequency may be at least 20 kHz, and may be between 50 kHz and 100 kHz, or other suitable frequencies. The second frequency may be at least 10 kHz and may be between 10 kHz and 50 kHz, or other suitable frequencies.

The magnetometer 130 may comprise at least one magnetometer coil 130. The magnetometer 130 is arranged to receive a resultant magnetic field generated by an electrical current induced in the metal target by the interrogation magnetic field. Thus the resultant magnetic field is generated in dependence of the interrogation magnetic field and is consequently time varying having the same frequency as the interrogation magnetic field. The magnetometer 130 is arranged to output the resultant signal 135 indicative of the resultant magnetic field to the control unit 110. The magnetometer 130 may comprise a plurality of magnetometer coils 130. In some embodiments a respective resultant signal is output corresponding to each magnetometer coil 130. In some embodiments, each magnetometer coil is associated with a respective interrogation coil. Thus there may be a plurality of interrogation-magnetometer coil-pairs in some embodiments. The plurality of magnetometer coils 130 may be distributed across the sensitive region. Each magnetometer coil 130 may be wound around a core, such as a ferrite core, to improve reception of the resultant magnetic field, as will be appreciated. An electrical output of each magnetometer coil 130 may be provided to an amplifier to amplify a voltage output by the respective magnetometer coil, where an output of the amplifier is provided to the control unit 110 as the resultant signal 135. In some embodiments, an interrogation coil 120 may be wound around the same core as a respective magnetometer coil 130.

The control unit 110 is arranged to determine a relationship between the, or each, resultant magnetic field and the interrogation magnetic field based on the interrogation signal 125 and the resultant signal 135. A component of the resultant magnetic field may be determined by the control unit 110 which is in-phase ("in-phase component") with the interrogation magnetic field and a component which is out-of-phase ("out-of-phase component") with the interrogation magnetic field. The out-of-phase component is 90° out-of-phase to the in-phase-component.

In some embodiments, the control unit 110 is arranged to cause the IMF generator 120 to generate the interrogation magnetic field at the first frequency and to determine an in-phase component of the resultant magnetic field at the first frequency, and to cause the IMF generator 120 to generate the interrogation magnetic field at the second frequency and to determine an out-of-phase component of the resultant magnetic field at the second frequency, as will be further explained below. Based on the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies, the conductivity of the metal target may be determined by the control unit 110.

Referring now to Figure 2, there is shown a flow chart illustrating a method of determining conductivity of a metal target according to an embodiment of the invention, indicated generally by reference numeral 200. The method 200 may be performed by the apparatus 100 illustrated in Figure 1.

In step 210, the interrogation magnetic field is provided. The interrogation magnetic field may be provided by the interrogation voltage signal 125 being provided to the one or more interrogation coils of the IMF generator 120. The interrogation magnetic field spreads outwards from its one or more sources, i.e. the one or more interrogation coils of the IMF generator 120. In some embodiments, the metal target is subjected to different field directions and magnitudes depending on its position relative to the one or more interrogation coils. Furthermore, in some embodiments, the metal target may be moved with respect to the one or more interrogation coils such as via the conveyor, or via the free fall system described above. The control unit 110 may provide the interrogation signal 125 to the IMF generator 120 in step 210 which is indicative of the interrogation field.

In step 220, the resultant magnetic field from the metal target is received. The resultant magnetic field is produced by an electrical current induced in the metal target by the interrogation magnetic field. The interrogation magnetic field spreading outwards causes electrical eddy-currents, dependent upon the target's material and geometrical characteristics, to be generated in the metal target about different axes. These eddy-currents induce the resultant magnetic field. The resultant magnetic field is dependent on a cross sectional area of the loop that the eddy-currents flow around inside the metal target. This loop must be inside the metal target and therefore the resultant magnetic field is dependent on the cross sectional area of the metal target. As will be appreciated, the depth that the eddy currents can flow within the metal target is dependent on a skin-depth of the eddy currents which is dependent on frequency of the interrogation magnetic field. The resultant signal 135 may be provided to the control unit 110 in step 220.

In some embodiments, step 210 may be performed at the first frequency f_1 of interrogation magnetic field and step 220 at the first frequency of the interrogation magnetic field; step 210 and 120 may then be repeated at the second frequency f_2 of the interrogation magnetic field. Steps 210 and 220 may be repeated for third and further frequencies in some embodiments.

In step 230, the in-phase component of the resultant magnetic field is determined. In step 240 the out-of-phase component of the resultant magnetic field is determined. In some embodiments, in step 230 the in-phase component of the resultant magnetic field is determined at the first frequency f_1 of interrogation magnetic field and in step 240 the out-of-phase component of the resultant magnetic field is determined at the second frequency f_2 of the interrogation magnetic field. Each of steps 230 and 240 may comprise the control unit 110 comparing the interrogation signal 125 and the resultant signal 135 at each frequency to determine the in-phase and out-of-phase components of the resultant signal 135.

In step 250 the conductivity of the target is determined. In step 250 the conductivity is determined based on the in-phase and out-of-phase components of the resultant magnetic field. In some embodiments, the conductivity is determined based on the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies, respectively, of the interrogation magnetic field.

The method 200 may include a step 260 in some embodiments. In step 260 the type of metal of the target is determined. Step 260 may be performed by the control unit 110. The type of metal of the metal target is determined by comparing the first and second frequency components of the metal target with the first and second frequency components of a training set or reference set of metal targets with known conductivity. A classifier or function may be used to assign each target to the class or metal type with the first and second frequency component as features or inputs to the classifier or function.

The first and second frequency components for the reference set may be determined by simulation of many objects with different geometries and conductivity or by measuring a set of known targets as is explained in more detail associated with the descriptions of Figures 7 and 8. The metal is assigned based on the known conductivity of the metal at room temperature. The known conductivities may have been determined by calibrating the system with a range of metal components of known conductivities. The determined type of metal may be one of aluminium, copper, brass or another suitable type of metal. Thus the type of metal of the metal target may be selected from one of a plurality of predetermined types of metal.

Referring to Figure 3(a), a graph of the value of the in-phase component (labelled as Re{H_z}) of the resultant magnetic field is shown for a range of frequencies of the interrogation magnetic field for two targets of different shape. Figure 3(b) shows a graph of the value of the out-of-phase component (labelled as Im{H_z}) of the resultant magnetic field for the range of frequencies for the same two differently shaped targets. The values for one of these targets – labelled as eigenvalue 3 in Figure 3 – is now discussed as an example.

At high frequencies a response curve of the in-phase component of the resultant magnetic field approaches an asymptote, as value of which is indicated in Figure 3(a) with a dashed line 315. At frequencies where the in-phase component approximates the asymptote 315, for example a frequency indicated with reference 310, the target acts as a perfect electrical conductor and therefore the value of the in-phase component of the magnetic field is independent of the material conductivity. The physical reason for this asymptote is that at high frequencies, a skin-depth of the circulating eddy-currents becomes very small and the currents no longer penetrate the target.

At frequencies where the in-phase component approximates the asymptote 315, the value of the in-phase component is only a function of the geometry (φ) i.e. as $f(\varphi)$ of the target. As proof of this, targets of the same shape have been shown to produce similar values of the in-phase component of the resultant magnetic field at the first frequency, thereby demonstrating that asymptotic value of the in-phase component of the resultant magnetic field is dependent on the geometry of the target alone. This has been shown in experiments using a prototype and a first interrogation magnetic field frequency of 64 kHz. In most cases, the first frequency having a value of 64 kHz is a sufficient approximation of the asymptote value. Other suitable frequencies may be used.

A response curve of the out-of-phase component, however, peaks at frequencies lower than at which the asymptotic values of the in-phase component is reached, and approaches zero at very high frequencies, as shown in Figure 3(b). At some frequencies, for example frequency 320, in between the peak and the substantially zero, the out-of-phase component of the resultant magnetic field has a substantially linear relationship with the logarithm of the frequency. The value of the out-of-phase component at which the relationship is substantially linear is shown in Figure 3(b) with a dashed line indicated as 325. At these frequencies a value of the out-of-phase component of the resultant magnetic field is taken as a function of the geometry and conductivity (σ) i.e. as $f(\varphi,\sigma)$ of the target metal. There are therefore two functions: one affected by conductivity and geometry of the metal target $f(\varphi,\sigma)$; the other only the geometry of the metal target $f(\varphi)$.

By taking the in-phase component at the first frequency – a high enough frequency that the value of the in-phase component is dependent only on the geometry of the target – and the out-of-phase component at the second frequency – where the value of the out-of-phase component is dependent on geometry and conductivity - the dependence of the conductivity on the geometry of the target can be reduced, and the conductivity of the target determined.

Referring to Figure 4, there is shown a graph of experimental data. The data comprises values of in-phase components at the first frequency and out-of-phase components at the second frequency for different targets. The targets are a range of different metals and a range of different shapes and sizes. The metal may be aluminium, copper, brass or another suitable type of metal. In Figure 4, the first frequency is 65354.6 Hz, and the second frequency is 17277.6 Hz. It will be appreciated that the first and second frequencies may be other suitable frequencies of the interrogation magnetic field.

When comparing the determined in-phase and out-of-phase components of the resultant magnetic field for a range of targets and at the first and second frequencies (referred to from now on as conductivity reference data), bands 410, 420, 430 emerge. The bands 410, 420, 430 are distinct at some frequencies of the interrogation magnetic field. For example, a second frequency of around 17 kHz may provide, in some situations, the best compromise between bands that are clearly defined at one end of the first frequency range but not at the other. This may indicate that different frequencies are suitable to be used for classifying depending on the range of the asymptote, and depending on the determined value of the in-phase component of the magnetic field.

The bands 410, 420, 430 correspond to different conductivities. The conductivity associated with each band 410, 420, 430 is calculated based on a relationship between the conductivity reference data collected for the range of targets in each of the bands 410, 420, 430. The conductivity reference data may be previously collected data, simulated data, or other suitable data. The conductivity reference data may be provided from a wide range of sizes, shapes and types of target. Thus the conductivity of the metal target is determined based on the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies independent of the geometry of the metal target.

Each band corresponds to a different conductivity, labelled in Figure 4 as high 440, medium 450 and low 460 conductivity. These conductivity bands correspond to brass in the low conductivity band, aluminium in the medium band and copper in the high conductivity band. The conductivity is determined by comparing the data points in the band and determining a relationship between them. In the case of Figure 4, the determined relationships are as follows:

i. High Conductivity 440:

   $C_H = 0.49*\ln(\mathrm{Re}\{H_z\})-\ln(\mathrm{Im}\{H_z\})-2.03$

ii. Medium Conductivity 450:

   $C_M = 0.49*\ln(\mathrm{Re}\{H_z\})-\ln(\mathrm{Im}(H_z))-1.8$

iii. Low Conductivity 460:

   $C_L = 0.49*\ln(\mathrm{Re}\{H_z\})-\ln(\mathrm{Im}\{H_z\})-1.5$

These relationships correspond to an intercept value of each dashed line 410, 420, 430 in Figure 4 – i.e. the gradient of each band. The in-phase at 65kHz component designated Re{Hz} in the above relation is the first frequency and the out-of-phase at 17kHz component designated Im{Hz} in the above relation is the second frequency. A metal object is classified by evaluating the two components according to each relation to obtain a value of C_H, C_M and C_L for each object. The object is then classified according to which value of C_H, C_M or C_L is smallest. For example, if the value C_H is smaller than C_M and smaller than C_L, the object is classified as high conductivity.

Other classification or machine learning methods may be used which classify using the in-phase and out-of-phase components as inputs or features. For example, in an embodiment the metal target is classified using a neural network. Reference data of samples of known classifications of metal targets is input into the neural network. The neural network is trained to use these known sample classifications to determine the classification of new targets. In this embodiment, the metal targets may be classified without necessarily explicitly calculating the conductivity of the metal target. In such embodiments where a machine learning method, such as a neural network, is used to classify the target, the method may not comprise an explicit step of determining the conductivity of the target i.e. step 250 may be absent. The machine learning may be applied directly to the in-phase and out-of-phase components determined in steps 230 and 240.

In other embodiments, the metal target is classified using a nearest neighbour approach. In this approach, first a test-piece is matched to targets in a training set with similar geometric features, producing a 'nearest-match' for each classification. Then, the classification of the test piece is compared to nearest-matching targets for each classification and assigned the class that matches spectra with the test piece.

Figure 5 shows an arrangement of a plurality of inductor coils 510 in an enclosure 520, according to an embodiment of the invention. The coils may be as previously discussed in the description of Figure 1. In some embodiments the IMF generator 120 may be an inductor coil. Similarly, the magnetometer 130 may be an inductor coil. The IMF generator 120 may be an array of inductor coils the magnetometer 130 may be an array of inductor coils. The IMF generator 120 and the magnetometer 130 may be a part of the same inductor coil or inductor coil array, or different inductor coils or inductor coil arrays. The inductor coil array may be a multi-frequency inductor coil array. The inductor coils may use a gradiometer design with ferrite cores to improve the inductor coil sensitivity, although other suitable designs may be used. The inductor coils may be solenoid coils or other suitable inductor coils. In the embodiment of Figure 5, 12 coils 510 are arranged spaced apart by approximately 90mm. Other suitable numbers and spacing of coils 510 may be used. The enclosure 520 is a box, which may have no top to the enclosure, or may have a non-metallic top, but other suitable enclosures may be used.

Referring now to Figure 6, there is shown a block diagram of an apparatus for sorting the metal target according to an embodiment of the invention, indicated generally by reference numeral 600. The apparatus 600 comprises the IMF generator 120, the magnetometer 130, the control unit 110, and a locating device 610 to arrange the metal target proximal to the IMF generator 120 and the magnetometer 130. The apparatus 600 further comprises a camera 630, a display means 640, and a sorting device 620. The metal target may be a plurality of metal targets. The metal target may be shredded metal pieces or other metal. The metal targets may be a range of shapes and sizes. The metal target may be an aluminium, copper or brass metal target. The metal target may be another suitable kind of metal target.

The control unit 110, the IMF generator 120 and the magnetometer 130 all behave as described in the description of Figures 1-6. The control unit 110 of the apparatus 600 is further arranged to determine the type of metal of the metal target (based on the conductivity of the target) and a position of the metal target, as will be described later. The position of the metal target may be determined relative to the IMF generator 120 and the magnetometer 130, in the sensitive region of the interrogation magnetic field.

In the embodiment shown in Figure 6, the locating device 610 comprises a conveyer belt 650, and a motor 660 that drives the conveyer belt 650. The metal target is arranged proximal to the IMF generator 120 and the magnetometer 130 by the locating device 610. The conveyer belt 650 is arranged over the IMF generator 120 and the magnetometer 130 so that when driven by the motor 660 a metal target on the conveyer belt 650 is passed through the sensitive region of the interrogation magnetic field, for which the apparatus 600 is arranged to determine the property of metal targets within. The sensitive region may advantageously be a similar width to or wider than the conveyer belt 650. The spacing of the IMF generator 120 and the magnetometer 130 allows any target arranged on the conveyer belt 650 to pass through the sensitive region of the interrogation magnetic field regardless of position on the conveyer belt 650.

Alternatively, the locating device 610 may comprise a free fall system wherein the metal target is dropped past the IMF generator 120 and the magnetometer 130, through the sensitive region. The free fall system may comprise a chute down which the metal target is dropped. The locating device 610 may comprise other suitable means for arranging the metal target proximal to the IMF generator 120 and the magnetometer 130.

The locating device 610 is controlled by the control unit 110. The motor 660 is arranged to be turned on or off dependent on a signal 615 received from the control unit 110. The control unit 110 may be arranged to turn on the motor 660 dependent on the position of the metal targets relative to the IMF generator 120 and the magnetometer 130 on the conveyer belt 650. For example, if there are no targets proximal to the IMF generator 120 and the magnetometer 130, the motor 660 may be instructed by the control unit 110 to drive the conveyer belt 650 so that targets are moved into the sensitive zone of the interrogation magnetic field.

The control unit 110 may be arranged to output a signal to the motor 660 dependent on which of the targets have had their conductivity determined. The control unit 110 may output a signal to cause the motor 660 to move the conveyer belt 650 forward or backward based on whether the targets need to pass through the sensitive region of the interrogation magnetic field in order for their conductivity and/or metal type to be determined.

To determine the type of metal of the metal target, the control unit 110 assigns a type of metal to each band 410, 420, 430 of conductivity reference data. The metal is assigned based on the known conductivity of the metal at room temperature. As noted above, the known conductivity may have been determined by calibrating the system with a range of metal components of known conductivities. The control unit 110 assigns the metal target to a band 410, 420, 430 of conductivity reference data based on the determined in-phase and out-of-phase components of the resultant magnetic field induced by eddy currents in the metal target. Thus the type of metal of the metal target is determined. The type of metal determined by the control unit may be aluminium, copper, brass or another suitable metal or type of metal. Advantageously, the method of determining the metal is very quick.

The position of the metal target may be determined by the control unit 110 based on a location of a source of the resultant magnetic field, or by the camera 630. The resultant magnetic field is induced in the target and thus the source of the resultant magnetic field is the target. Therefore, locating the source of the resultant magnetic field locates the position of the target. The control unit 110 may therefore determine the position of the target based on the received resultant signal 135 indicative of the resultant magnetic field.

The camera 630 may be arranged above the locating device 610 in order to have a clear view of all the metal targets. The camera is arranged to produce an image of the metal targets and output a signal indicative thereof 635 to the control unit 110. The control unit 110 may process the image of the metal targets in order to determine their position.

In an embodiment of the invention, the control unit 110 may also process the image captured by the camera 630 to determine the geometry of the metal targets. The geometry information may include for instance length of a longest side, length of a shortest side, area, minimum feret diameter, and maximum feret diameter of the target. Camera 630 may also be a 3D camera. 3D data is obtained by a simple structured lighting scheme with for instance a laser line generator, as is well-known to those conversant with the art. The 3D data may include for example highest point, mean height, maximum apparent volume, maximum apparent cross-sectional area on various sections. It will be appreciated that embodiments of the present invention could also exploit the camera information for determining more accurately the conductivity of the metallic target and for determining more accurately the type of metal of the metal target. For instance, the size information could be used to select one out of a range of algorithms, with each algorithm tailored to the best performance with the particular geometry of the target.

The sorting device 620, controlled by the control unit 110, sorts the metal target dependent on the type of metal of the target, the conductivity of the target, or other suitable information. The metal targets may be sorted into separate containers or onto a further locating device such as another conveyer belt. The metal targets may be sorted into other suitable objects. The sorting device 620 may be a series of air jets that fire pressurised air at the metal target in order to sort the metal target by the type of metal. The sorting device 620 may sort the metal target by other suitable means.

The control unit 110 is adapted to output a controlling signal 625 to the sorting device 620 dependent on the position of the target relative to the sorting device 620. When a target ready to be sorted is proximal to the sorting device 620, the control unit 110 is adapted to turn on the sorting device 620, and output a signal 625 indicative of how the target should be sorted, and what the target should be sorted into.

In the embodiment shown in Figure 6, the sorting device 620 is arranged at the end of the conveyer belt 650. In other embodiments of the invention, the sorting device 620 may be arranged adjacent to the IMF generator 120 and the magnetometer 130 as part of the free fall system, or in another position suitable for sorting the metal target after it has passed proximal to the IMF generator 120 and the magnetometer 130.

The control unit 110 may output a signal indicative of information about the metal target 645 to the display means 640. The information may be information about the position of the metal target, the determined metal type of the metal target, the determined conductivity of the metal target or other information about the metal target. The display means 640 may comprise a screen or other suitable device for displaying information. The display means 640 may display the determined conductivity or type of metal of each of the metal targets, or other suitable information.

Referring now to Figure 7, there is shown a flow chart illustrating a method of sorting metal, indicated generally by reference numeral 700. The method may be performed by the apparatus 600 illustrated in Figure 6.

In step 710, the target is arranged proximal to the sensitive region of the interrogation magnetic field, for which the apparatus 600 is arranged to determine the property of metal targets within. The target is arranged proximal to the sensitive region by the locating device 610, controlled by the control unit 110. The target is moved through the sensitive region for long enough to determine its conductivity, position and metal type.

Steps 210-250 are the same as described in the description of Figure 2.

In step 720, the type of metal of the metal target is determined. The type of metal of the metal target is determined based on the determined conductivity of the metal target, compared to the conductivity reference data. The metal target is assigned to a band 410, 420, 430 of the conductivity reference data based on the determined in-phase and out-of-phase components of resultant magnetic field, and a type of metal is assigned to each band of the conductivity reference data. The metal is assigned based on the known conductivity of the metal at room temperature. Thus the type of metal of the target is determined. The type of metal is determined by the control unit 110.

In step 730, the position of the metal target is determined. An image of the target is captured by the camera 630 and sent to the control unit 110, which determines the position of the metal target. Alternatively, the position is determined by locating the source of the resultant magnetic field. The resultant magnetic field is generated by electrical currents in the metal target, which are generated by the interrogation magnetic field. Therefore, the source of the resultant magnetic field is the target itself and by locating the source the target has also been located. The location of the source of the resultant magnetic field is determined by the control unit 110 based on the resultant signal 135 indicative of the resultant magnetic field.

In step 740 the metal target is sorted based on the determined type of metal of the metal target. The metal targets may be sorted into separate containers or onto a further locating device such as another conveyer belt. The metal targets may be sorted into other suitable objects. The target is sorted by the sorting device 620. After passing through the sensitive region the target is moved on towards the sorting device 620 by the locating device 610. The control unit 110 uses the determined position of the target to determine when to turn on the sorting device 620, and how to sort the target.

Figure 8 shows the arrangement of Figure 5 further comprising the conveyer belt 650, arranged to pass targets 810 proximal to the coils 510. The targets 810 are a range of shapes, sizes and types of metal. The conveyer belt 650 behaves as described in the description of Figure 6.

Referring to Figure 9, there is shown four graphs of experimental data. The data comprises values of in-phase components (Z’) at the first frequency and out-of-phase components (Z”) at the second frequency for different targets. The targets may be a range of different metals and a range of different shapes and sizes. The metal may be aluminium, copper, brass or another suitable type of metal, as shown in the key for each graph. Figure 9 shows graphs similar to that in Figure 4 with updated data for a range of second frequencies. Figure 9(a) has a second frequency of 2 kHz; Figure 9(b) has a second frequency of 4 kHz; Figure 9(c) has a second frequency of 8 kHz; Figure 9(d) has a second frequency of 16 kHz. The first frequency for each graph is 64kHz.

As with Figure 4, when comparing the determined in-phase and out-of-phase components of the resultant magnetic field for a range of targets and at the first and second frequencies, bands 910, 920, 930 emerge. Again, as in Figure 4, the bands 910, 920, 930 are distinct at some frequencies of the interrogation magnetic field and correspond to different conductivities.

The conductivity is determined by comparing the data points in the band and determining a relationship between them. In the case of Figure 9, the determined relationships are logistic-functions of the form

$$Z''_p = \frac{k_1}{1 + \exp\left(-k_2 Z'_{64kHz}\right)} + \frac{k_1}{2}$$

where p is the second frequency and depends on the figure, and k_1, k_2 are constants that define the shape of the curve.

It will be appreciated that embodiments of the present invention can be realised in the form of hardware, software or a combination of hardware and software. Any such software may be stored in the form of volatile or non-volatile storage such as, for example, a storage device like a ROM, whether erasable or rewritable or not, or in the form of memory such as, for example, RAM, memory chips, device or integrated circuits or on an optically or magnetically readable medium such as, for example, a CD, DVD, magnetic disk or magnetic tape. It will be appreciated that the storage devices and storage media are embodiments of machine-readable storage that are suitable for storing a program or programs that, when executed, implement embodiments of the present invention. Accordingly, embodiments provide a program comprising code for implementing a system or method as claimed in any preceding claim and a machine readable storage storing such a program. Still further, embodiments of the present invention may be conveyed electronically via any medium such as a communication signal carried over a wired or wireless connection and embodiments suitably encompass the same.

All of the features disclosed in this specification (including any accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive.

Each feature disclosed in this specification (including any accompanying claims, abstract and drawings), may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic series of equivalent or similar features.

The invention is not restricted to the details of any foregoing embodiments. The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims, abstract and drawings), or to any novel one, or any novel combination, of the steps of any method or process so disclosed. The claims should not be construed to cover merely the foregoing embodiments, but also any embodiments which fall within the scope of the claims.

CLAIMS

1. A method of determining conductivity of a metal target, comprising:

   providing an interrogation magnetic field;

   receiving a resultant magnetic field from the metal target, wherein the resultant magnetic field is generated by an electrical current induced in the metal target by the interrogation magnetic field;

   determining an in-phase component of the resultant magnetic field for the metal target at a first frequency of the interrogation magnetic field, wherein the first frequency of the interrogation magnetic field substantially corresponds to an asymptote of a response curve of the in-phase component of the resultant magnetic field;

   determining an out-of-phase component of the resultant magnetic field for the metal target at a second frequency of the interrogation magnetic field; and

   determining the conductivity of the metal target based on the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies.

2. The method of claim 1, wherein the conductivity of the metal target is determined based on the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies independent of a geometry of the metal target.

3. The method of claim 1 or 2, wherein the second frequency of the interrogation magnetic field substantially corresponds to a region of the response curve of the out-of-phase component responsive to conductivity.

4. The method of claim 1, 2 or 3, wherein the first frequency of the interrogation magnetic field is at least 20 kHz.

5. The method of claim 4, wherein the first frequency of the interrogation magnetic field is around 50-100 kHz

6. The method of any preceding claim, wherein the second frequency of the interrogation magnetic field substantially corresponds to a frequency at a substantially linear portion of a response curve of the out-of-phase component of the resultant magnetic field.

7. The method of any preceding claim, wherein the second frequency of the interrogation magnetic field is at least 10 kHz.

8. The method of claim 7, wherein the second frequency of the interrogation magnetic field is around 10-50 kHz.

9. The method of any preceding claim, wherein a value of the in-phase component of the resultant magnetic field at the first frequency is a function of geometry of the metal target.

10. The method of any preceding claim, wherein a value of the out-of-phase component of the resultant magnetic field at the second frequency is a function of geometry and the conductivity of the metal target.

11. The method of claim 10 wherein the conductivity of the metal target is determined based on conductivity reference data, wherein the determining the conductivity comprises:

assigning the metal target to a band of the conductivity reference data based on the determined values of the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies of the interrogation magnetic field; and

determining a conductivity of the band of the conductivity reference data based on a relationship between the data points in the band.

12. The method of any preceding claim further comprising determining a type of metal of the metal target, wherein the determining the type of metal comprises:

assigning the metal target to a band of conductivity reference data based on the determined in-phase and out-of-phase components of resultant magnetic field; and

assigning a type of metal to the band of the conductivity reference data.

13. The method of claim 12, comprising sorting the metal target based on the determined type of metal.

14. The method of any preceding claim wherein a position of the metal target is determined by the interrogation magnetic field based on a location of a source of the resultant magnetic field.

15. The method of any preceding claim wherein one or more of a position of the metal target and a geometry of the metal target are determined by a camera.

16. An apparatus for determining conductivity of a metal target, comprising:

an interrogation magnetic field generator for providing an interrogation magnetic field, controlled by a control unit;

a magnetometer for receiving a resultant magnetic field from the metal target and outputting a signal indicative thereof, wherein the resultant magnetic field is generated by an electrical current induced in the metal target by the interrogation magnetic field; and

the control unit, arranged to:

control the interrogation magnetic field generator to provide the interrogation magnetic field at a first frequency and a second frequency, wherein the first frequency of the interrogation magnetic field substantially corresponds to an asymptote of a response curve of the in-phase component of the resultant magnetic field;

receive the signal indicative of the resultant magnetic field; and

determine an in-phase and an out-of-phase component of the resultant magnetic field at the first and second frequencies of the interrogation magnetic field; and

determine the conductivity of the metal target based on the in-phase and out-of-phase components of the resultant magnetic field.

17. The apparatus of claim 16 wherein the control unit determining the conductivity of the metal target comprises:

assigning the metal target to a band of conductivity reference data based on the determined values of the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies of the interrogation magnetic field; and

determining a conductivity of the band of the conductivity reference data based on a relationship between the data points in the band.

18. The apparatus of claim 16 or 17 wherein the control unit is further arranged to:

assign the metal target to a band of conductivity reference data based on the determined in-phase and out-of-phase components of resultant magnetic field; and

assign a type of metal to the band of the conductivity reference data; and

based on the assigned band of the metal target, determine a type of metal of the metal target.

19. The apparatus of any of claims 16-18 further comprising a sorting device for sorting the metal target based on the determined type of metal, wherein the sorting device is controlled by the control unit.

20. The apparatus of any of claims 16-19 further comprising a locating device for arranging the metal target proximal to the interrogation magnetic field generator and the magnetometer, wherein the locating device is controlled by the control unit.

21. The apparatus of any of claims 16-20 wherein one or more of the magnetometer or the interrogation magnetic field generator comprises an array of inductor coils.

22. The apparatus of claim 21 wherein one or more of a number of the inductor coils in the array or a spacing between the inductor coils in the array is adjustable.

23. The apparatus of claim 22, wherein the number of inductor coils in the array is between 4 and 16.

24. A method of classifying metallic targets, comprising:

providing an interrogation magnetic field;

receiving a resultant magnetic field from the metal target, wherein the resultant magnetic field is generated by an electrical current induced in the metal target by the interrogation magnetic field;

determining an in-phase component of the resultant magnetic field for the metal target at a first frequency of the interrogation magnetic field, wherein the first frequency of the interrogation magnetic field substantially corresponds to an asymptote of a response curve of the in-phase component of the resultant magnetic field;

determining an out-of-phase component of the resultant magnetic field for the metal target at a second frequency of the interrogation magnetic field; and

classifying the metal target based on the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies.

25. The method of claim 24, wherein the classification of the metal target is determined based on the in-phase and out-of-phase components of the resultant magnetic field at the first and second frequencies independent of a geometry of the metal target.

26. The method of claim 24 or 25, wherein the second frequency of the interrogation magnetic field substantially corresponds to a region of the response curve of the out-of-phase component responsive to conductivity.

27. The method of any of claims 24-26, wherein the second frequency of the interrogation magnetic field substantially corresponds to a frequency at a substantially linear portion of a response curve of the out-of-phase component of the resultant magnetic field.

28. The method of any of claims 24-27, wherein the classification of the metal target is determined by a nearest neighbour approach.

29. The method of any of claims 24-27, wherein the classification of the metal target is determined by a neural network.

30. The method of claim 29 wherein the neural network uses input samples of known classifications of metal targets to determine the classification of the metal targets.

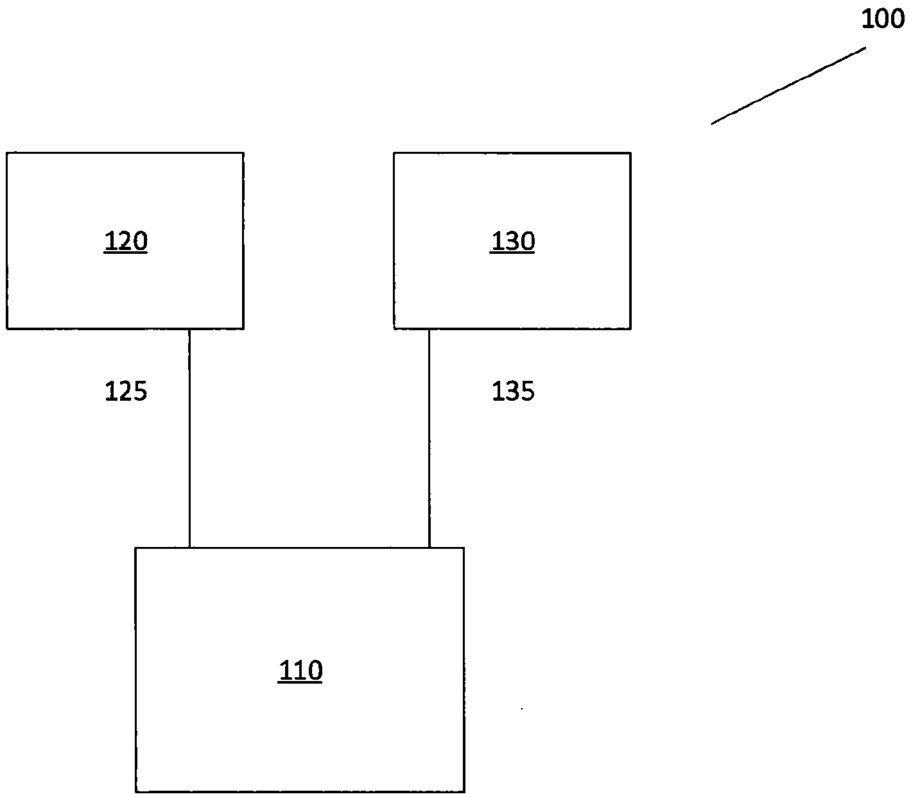


Figure 1

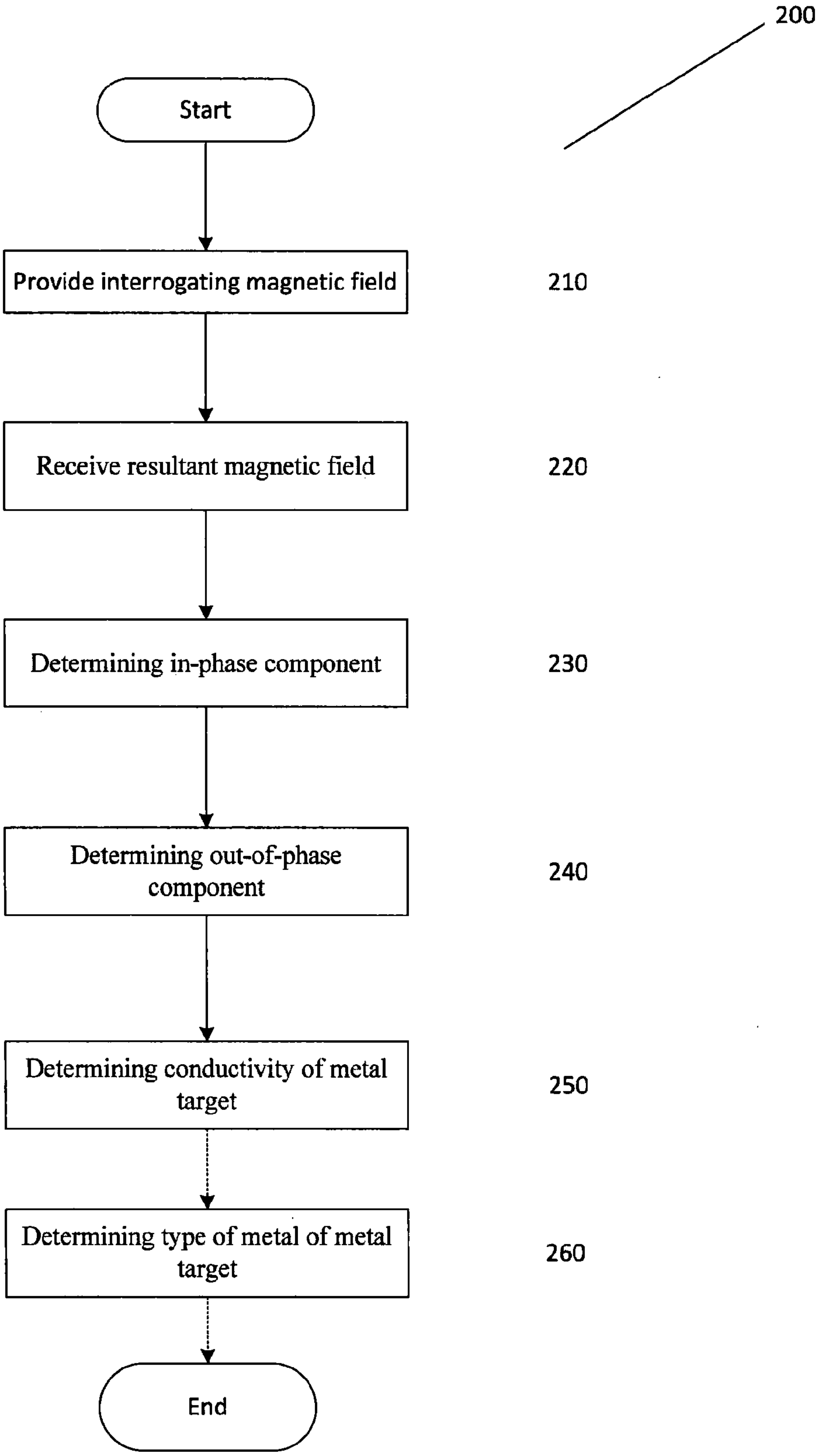
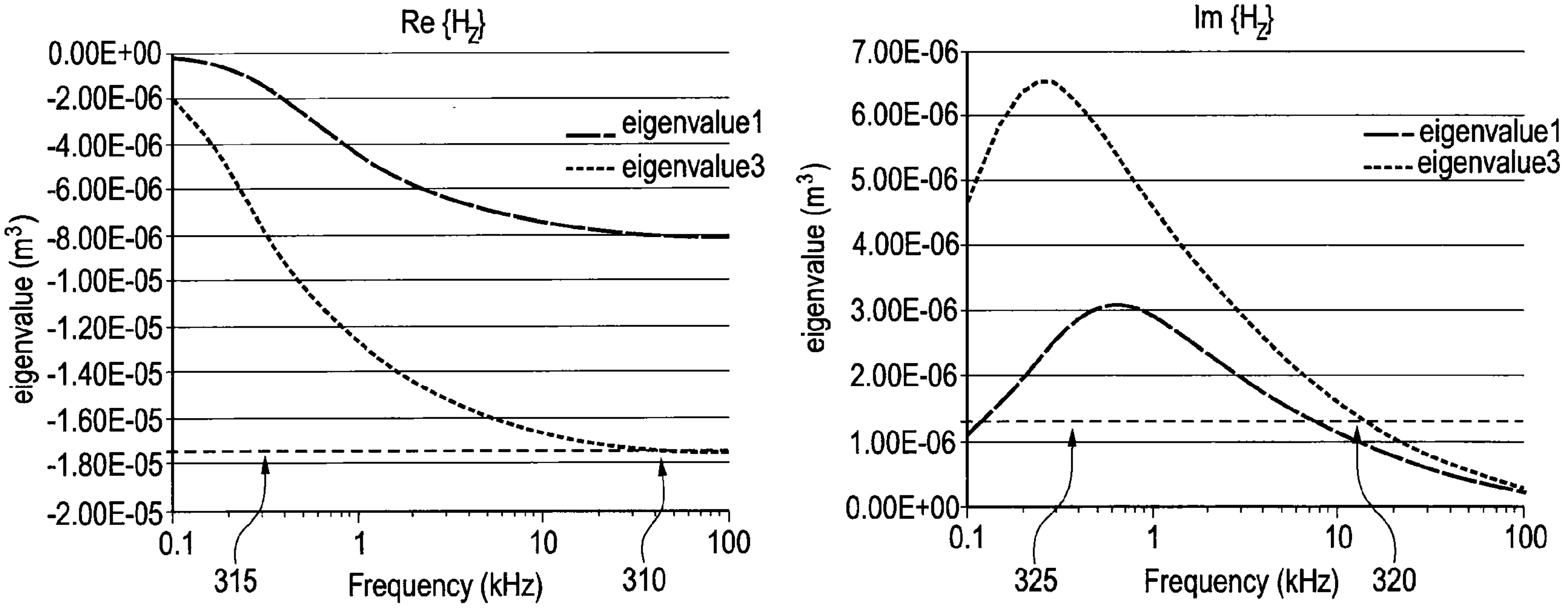

200
Start
Provide interrogating magnetic field
210
Receive resultant magnetic field
220
Determining in-phase component
230
Determining out-of-phase component
240
Determining conductivity of metal target
250
Determining type of metal of metal target
260
End

Figure 2


Re {H_Z}
0.00E+00
-2.00E-06
-4.00E-06
-6.00E-06
-8.00E-06
-1.00E-05
-1.20E-05
-1.40E-05
-1.60E-05
-1.80E-05
-2.00E-05
eigenvalue (m³)
eigenvalue1
eigenvalue3
0.1
1
10
100
Frequency (kHz)
315
310
Im {H_Z}
7.00E-06
6.00E-06
5.00E-06
4.00E-06
3.00E-06
2.00E-06
1.00E-06
0.00E+00
eigenvalue (m³)
eigenvalue1
eigenvalue3
0.1
1
10
100
Frequency (kHz)
325
320

a)

b)

Figure 3

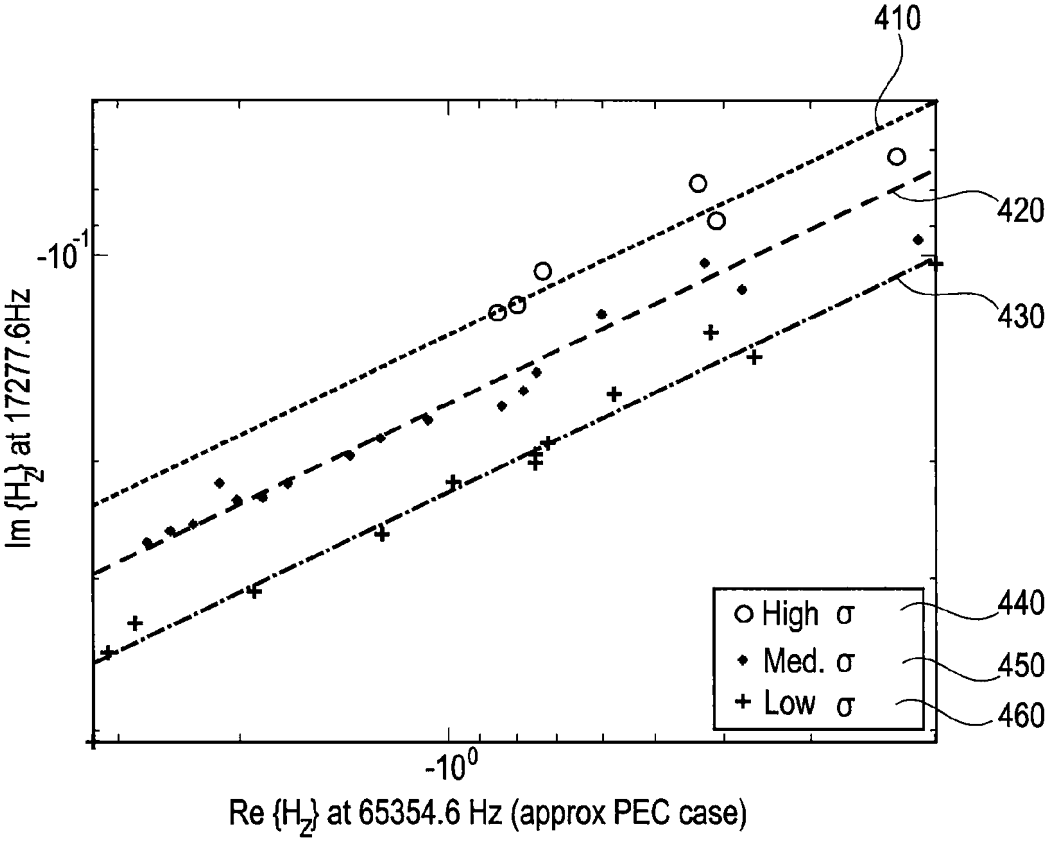


Figure 4

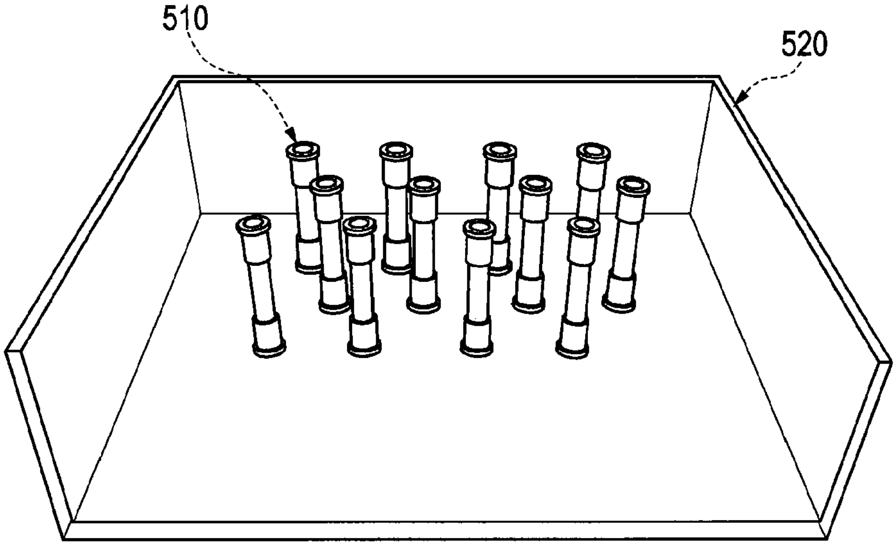


Figure 5

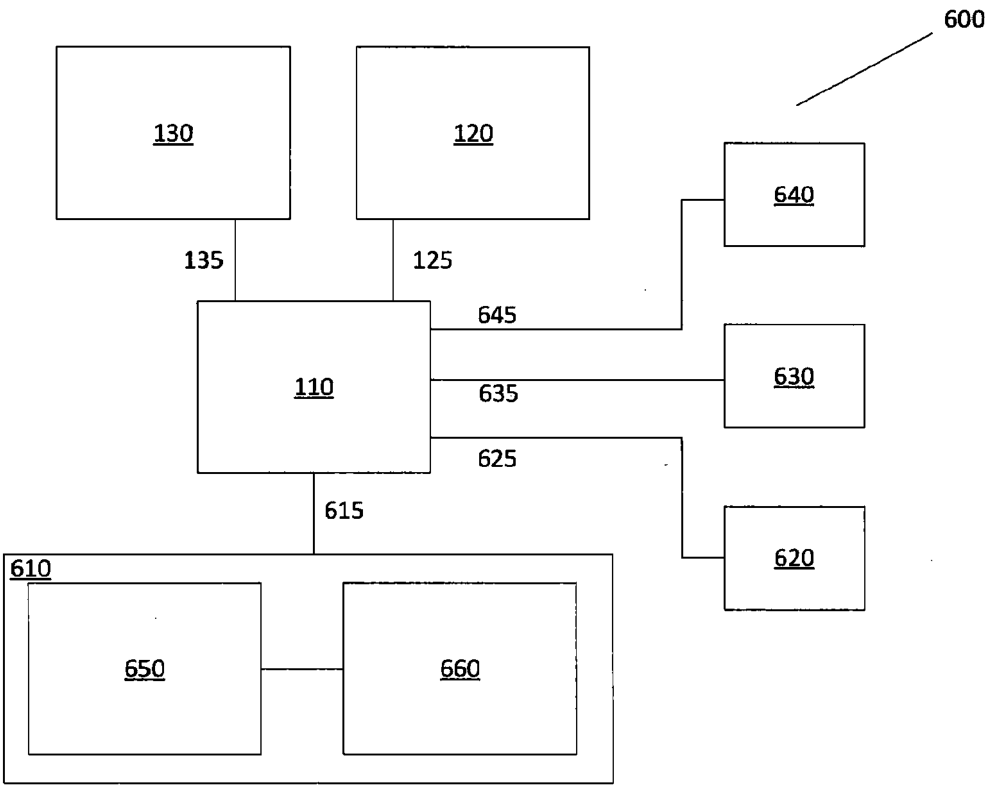


Figure 6

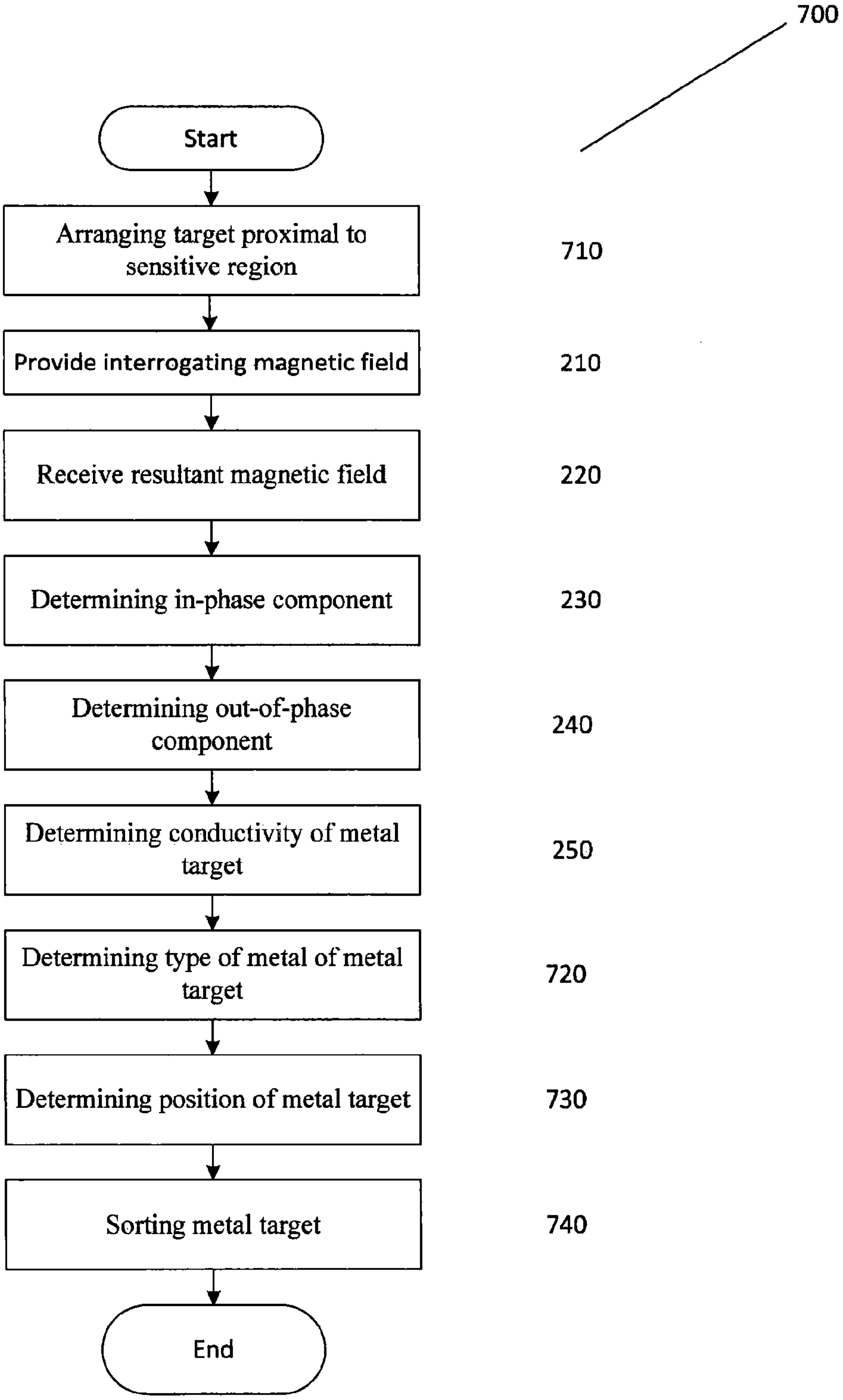

700
Start
Arranging target proximal to sensitive region
710
Provide interrogating magnetic field
210
Receive resultant magnetic field
220
Determining in-phase component
230
Determining out-of-phase component
240
Determining conductivity of metal target
250
Determining type of metal of metal target
720
Determining position of metal target
730
Sorting metal target
740
End

Figure 7

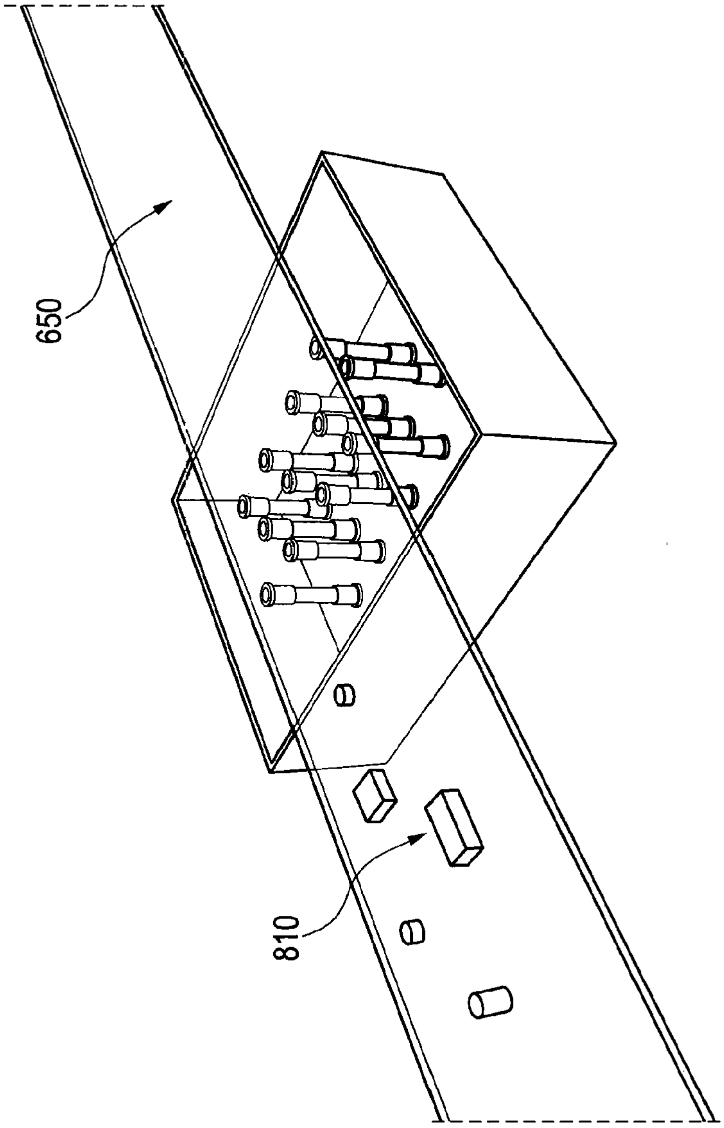


Figure 8

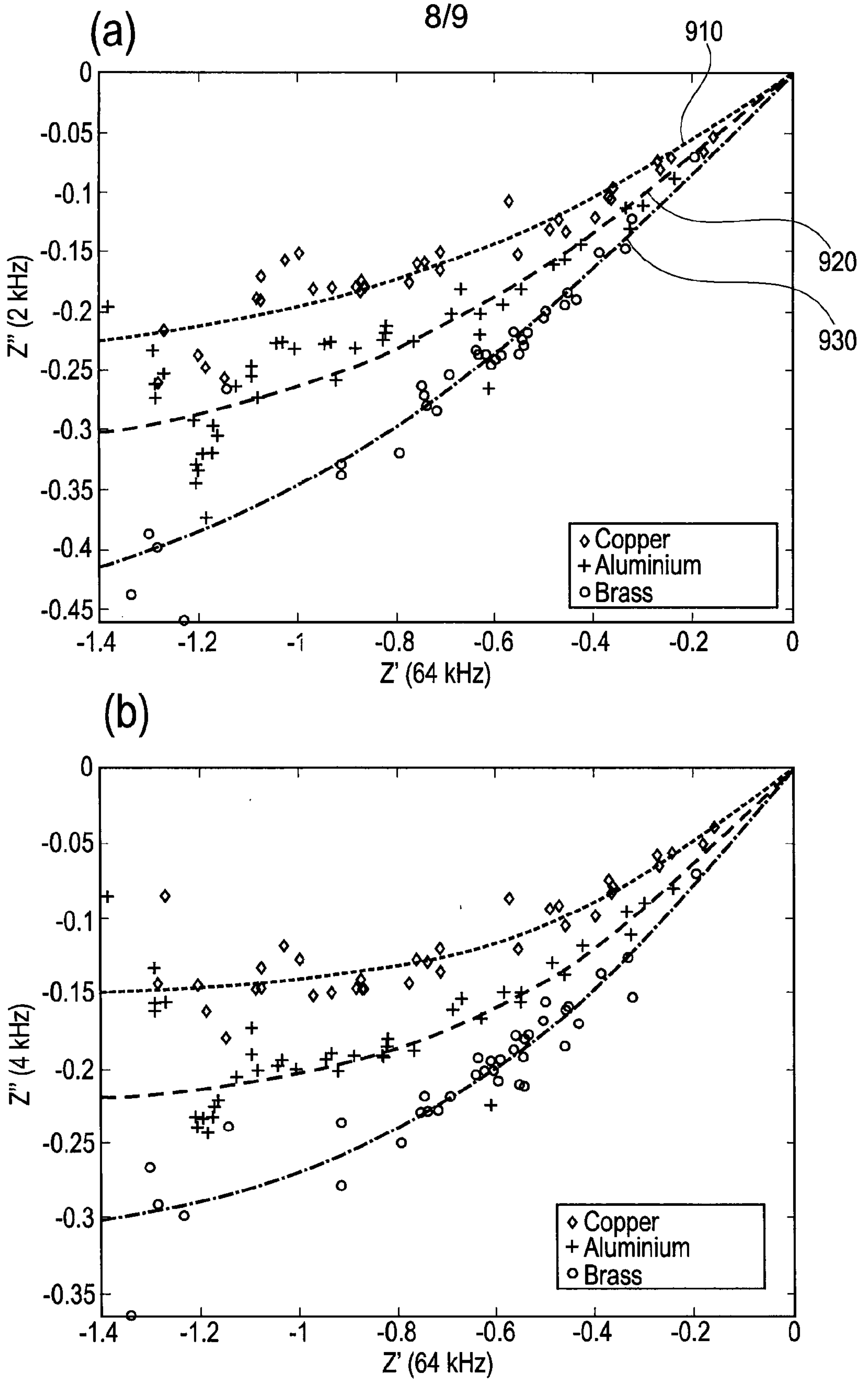

(a)
910
920
930
Z'' (2 kHz)
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
-0.45
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
Z' (64 kHz)
◇ Copper
+ Aluminium
○ Brass
(b)
Z'' (4 kHz)
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
Z' (64 kHz)
◇ Copper
+ Aluminium
○ Brass

Figure 9

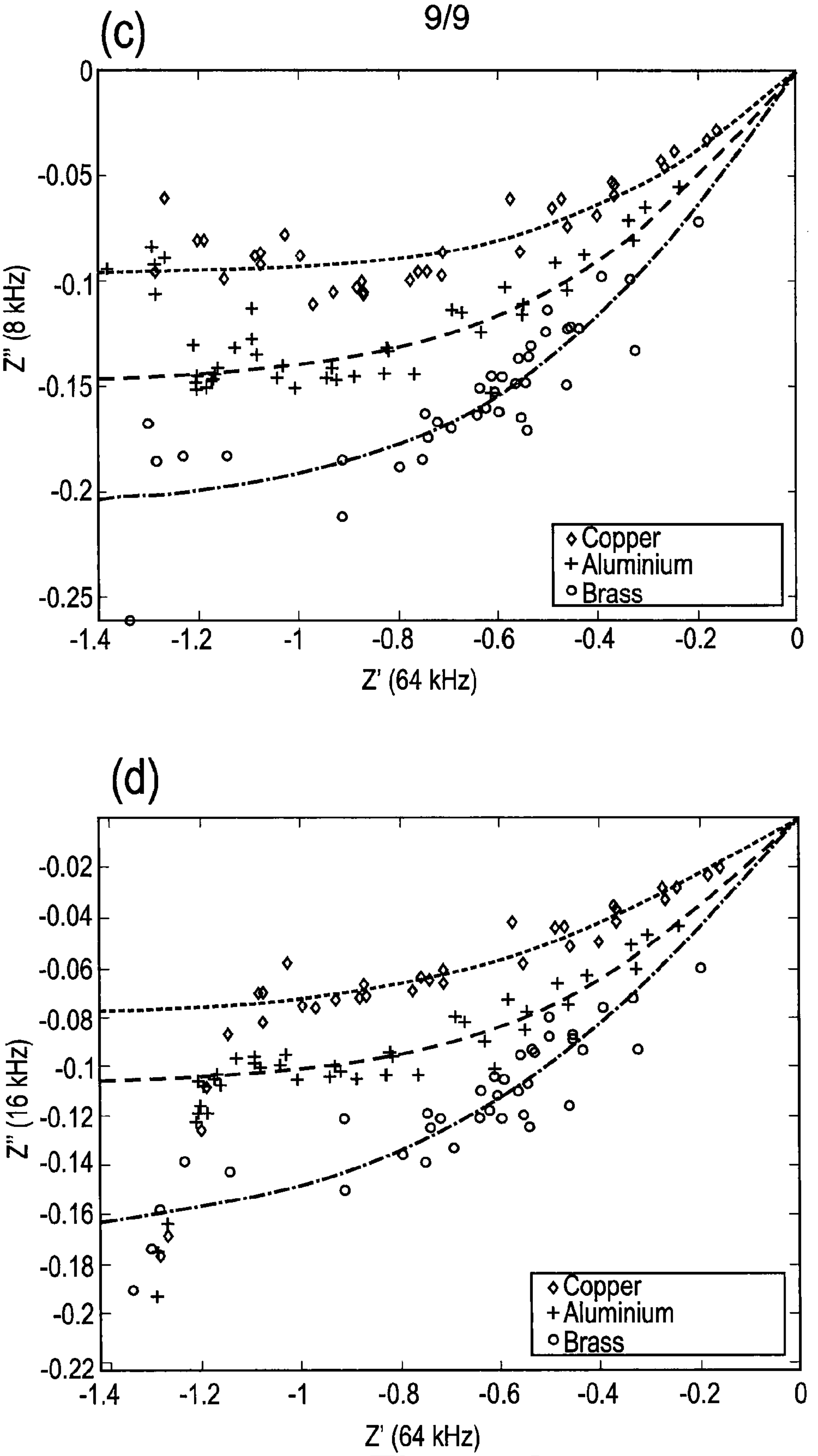

(c)
0
-0.05
-0.1
-0.15
-0.2
-0.25
Z'' (8 kHz)
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
Z' (64 kHz)
◇ Copper
+ Aluminium
○ Brass
(d)
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
-0.16
-0.18
-0.2
-0.22
Z'' (16 kHz)
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
Z' (64 kHz)
◇ Copper
+ Aluminium
○ Brass

Figure 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2018/051173

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N27/02 G01N27/04 G01N27/90 B07C5/344 G01V3/08
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01N B07C G01V G07D G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 5 213 190 A (FURNEAUX DAVID M [GB] ET AL) 25 May 1993 (1993-05-25) figures 1, 2 - 6, 8, 9, 10 column 5, line 3 - column 15, line 24 column 1, line 65 - column 4, line 30	1-21, 23-30 22
Y A	US 2003/038064 A1 (HARBECK HARTMUT [DE] ET AL) 27 February 2003 (2003-02-27) figures 1, 2 paragraph [0025] paragraph [0034] - paragraph [0046]	22 15,19,21
A	US 5 485 908 A (WANG CHUANMING [US] ET AL) 23 January 1996 (1996-01-23) figures 1-11 column 4, line 3 - column 9, line 36	29,30

-/--

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search
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INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2018/051173

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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T	MICHAEL OTOOLE ET AL: "Classification of Non-ferrous Metals using Magnetic Induction Spectroscopy", IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, vol. 1, 25 December 2017 (2017-12-25), pages 1-1, XP055487312, US ISSN: 1551-3203, DOI: 10.1109/TII.2017.2786778 the whole document -----	
A	HAOPING HUANG ET AL: "Characterization of UXO-like targets using broadband electromagnetic induction sensors", IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 41, no. 3, 13 March 2003 (2003-03-13), pages 652-663, XP011096308, ISSN: 0196-2892, DOI: 10.1109/TGRS.2003.809936 figure 3 Section: "III: THEORETICAL BACKGROUND"; page 652, column 2, paragraph 5 - page 657, column 1, paragraph 2 -----	1,6,16, 24,27
A	SHUBITIDZE F ET AL: "Investigation of broadband electromagnetic induction scattering by highly conductive, permeable, arbitrarily shaped 3-D objects", IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 42, no. 3, 15 March 2004 (2004-03-15), pages 540-556, XP011506976, ISSN: 0196-2892, DOI: 10.1109/TGRS.2003.821699 figures 4, 9 section: "II. FORMULATION"; page 542, column 1, paragraph 3 - page 544, column 2, paragraph 3 Section: "B. Effect of Sharp Edges and Points"; page 545, column 2, paragraph 2 - page 547, column 2, paragraph 2 -----	1,6,16, 24,27

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Information on patent family members

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