APPLICATION OF REAL TIME INVERSE EDDY CURRENT ANALYSIS

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INTRODUCTION

Rapid reduction of multifrequency eddy current data to direct material properties of conductivity and dimension has been a task for a number of years by Wallace et al. (1) and Seigfried (2,3). The direct solution of the electromagnetic boundary value problem and fitting data to experimental data can be accomplished but is slow and tedious(4,5,6). The direct solution approach has a slow cycle time and reduces both the spontaneous interaction of the operator to the test in progress and the resulting understanding of the process. The inverse approach of taking the raw eddy current data and producing physical data rapidly opens two possibilities for the measurement technique. In the area of process development and in difficult environments such as crystal growers, chemical reactors or heat treatment furnaces. It is possible to detect and stimulate transient events and isolate these reaction rapidly. Extending this application to automated operation one can use the resulting inverse data for control particularly in temperature measurement, where there is a conductivity dependence on temperature. For example in intrinsic semiconductors, copper and low carbon steels are currently important applications where traditional thermocouples or infrared gauging of temperature are not useful because of the difficult environments. For example where temperatures and thermal gradients are to be determined within a continuous product moving through a heat treatment furnace. More complex applications of inverse analysis is in determining reactions with bar surface due to diffusion and oxidation. Finally gauging for mean diameter and total volume of material is an area that is being explored with the next generation of experimental equipment that will have resolution of better

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TABLE I

Physical Requirements for Data Inversion

1) Minimum Three Frequencies or more if possible

2) Simultaneous Measurement

3) Absolute signal vector calibration

4) Noise threshold < .2%
   (transform stability requirement)

5) Frequency Selection spanning depths of interest

6) Characterized Standard

than 10 ppm. The key requirement for making measurements of conductivity and dimensioning are listed in Table I.

Data taking for inversion requires rather accurate data since the inverse transforms operates to generate a null results that is rather sensitive to proposed conductor structure. The multiple frequency inversion algorithm with good data will allow highly accurate determination of mean dimensions well beyond the accuracy of a single sample. This occurs because of the correlation of data within the inversion transform of the samples from the multiple frequencies.

The measurement system was designed around the operating requirement of the inversion transforms. This system is called the Datamac and it currently supports 4 simultaneous frequencies that typically operate from 10 Hz up to 5 Mhz. The calibration requirement were designed into the system so that standards which are not very close the unknown properties to be measured can be used. This is required because in semiconductors conductivities can easily vary over a range of an order of magnitude. In a simpler application of monitoring properties in the vicinity of the curie point in ferromagnetic material very large property changes can be detected.

General Discussion of the Inverse Transform

The inverse transform in cylindrical coordinates can be represented as a functional

T[data ; proposed structure].

Seigfried in his thesis gives the detailed an analytic representation as an integral transform(2) in cylindrical coordinates and Cartesian coordinates that could be characterized as:

$$T[f\{1\}, f\{2\}, \ldots f\{n\} ; r\{1\}, sigma\{1\}, r\{2\}, sigma\{2\} \ldots r\{m\}, sigma\{m\}]$$

```
2.3107E4
c
o
n
d
u
c
t
i
v
i
t
y
2.5675E3
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2.775E-2 { 1.092 inch}
r
a
d
i
u
s
1.850E-2 { 0.728 inch}
   0                    TIME (SECONDS)                    100
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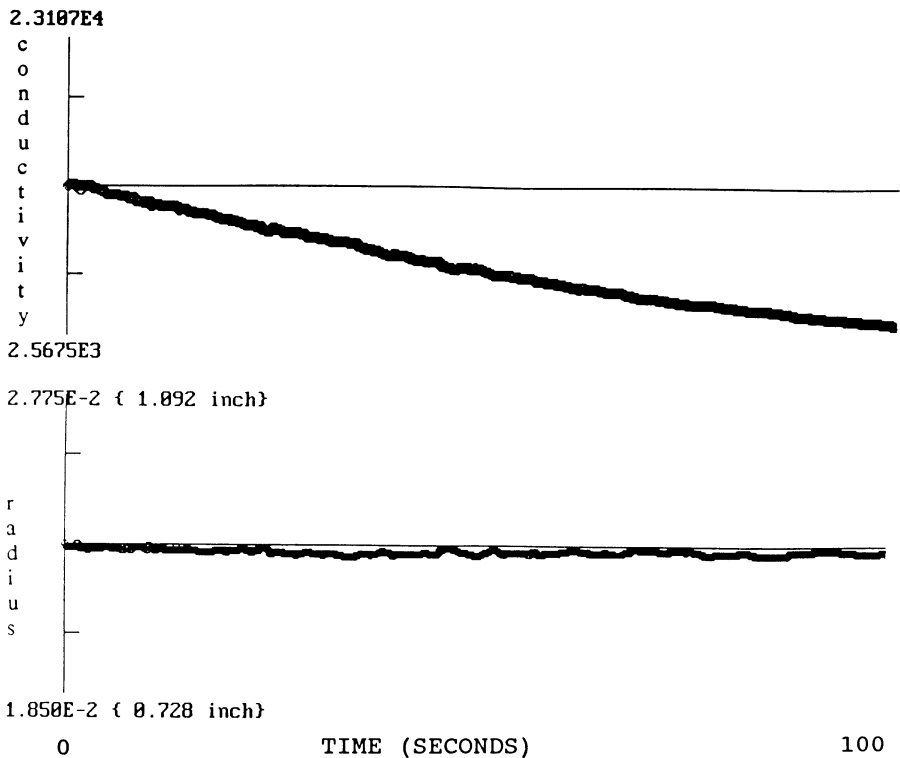
FIGURE   1   Exterior Inverse Analysis of a Cooling
                  50mm Dia. Silicon Crystal from 1100C
                  to 600C over 100 Seconds.   The Radial
                  Conductivity in Mhos/m are shown
                  Cooling. 19Khz, 43Khz, & 86Khz

Where f{i} represent frequencies, r{i} radial dimensions and
sigma{i} represent conductivities associated with a radial
location. These integral are quite complex and form the
core of a calculus of variation approach in using them as a
sensitive detector of property changes. This integral is
minimized by varying in the proposed structure in a self
consistent fashion. In the bulk industrial applications
requires speed and the most rapid calculation that can be
performed is to determine the mean radius r{1} and the mean
conductivity sigma{1} iteratively to :

 T[f{1}, f{2}, f{3}, ... f{n} ; r{1}, sigma{1}].

    In our nomenclature we call this the exterior inverse
analysis solution that produces the mean radius and
conductivity. The interior inverse analysis produces an
interior conductivity profile. An example of the exterior
inverse analysis is shown for cooling silicon ingot whose
temperature is being reduced from 1100C to 600C in Figure
1. Using three test frequencies on 16 Mhz 386/387 processor
it takes approximately .3 seconds to produce this simplest
of the inversions on a single sample for a cylindrical
sample. One can note that the radial data has a higher
degree of precision than the conductivity data. This
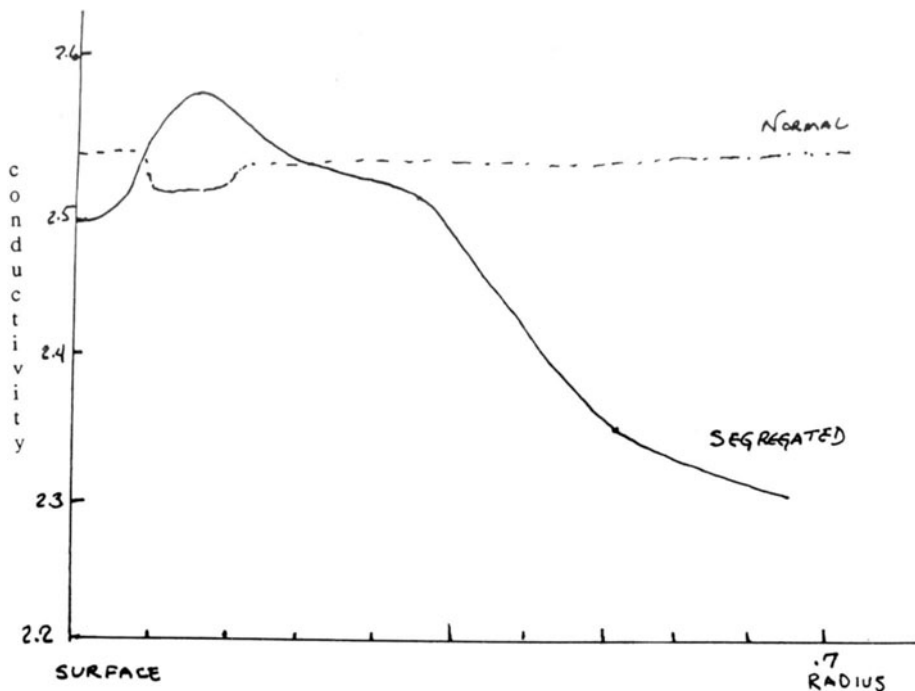difference in precision is due to the strong radial

FIGURE 2 Interior Inverse Profile of Several Al 7%Si
Ingots with One Ingot Showing Strong
Segregation Measured at 300 Hz, 740 Hz, &
1000 Hz

dependence in the boundary condition that couples the field
from the coil to the surface of the conductor. Currently
for in service high temperature measurements the limiting
accuracies are typically .1% for mean conductivity and .02%
on the mean radius. The variation in the materials
conductivity only appears within the propagation vector in
the material whereas the external radius appears in a ratio
multiplying the total response. This characteristic
requires that very accurate data for useful conductivity
data must be gathered. There is a limit to the number of
frequencies that can simultaneously be used since there is
a division of the total power by the number of frequencies
in use which will reduce the final signal to noise ratio at
each frequency. Frequency hopping rates are limited by the
detection output band width which would limit this type of
testing to static cases.   For example in CZ crystal growth
if melt studies are being performed interesting variations
within the system can be up to 30 Hertz and these rates
preclude the use of a frequency hopping systems.

     Extending the inverse procedure to produce internal
radial conductivity profiles can be performed as an
extension to the inverse procedure already described. The
values r{1} and sigma{1} can be set or determined by the
minimization procedure prior to determining internal
conductivity profiles. For the long cylindrical geometry,
we typically can select from the outer 20% to the outer 80%
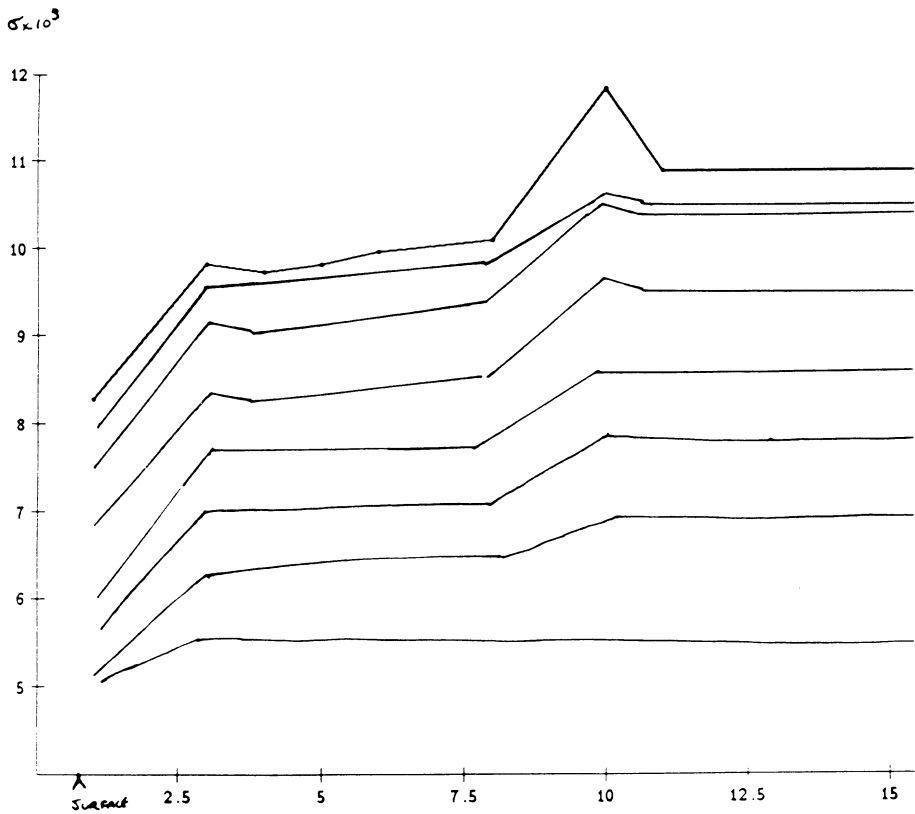of the radius of the cylinder divided into 10 segments to

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FIGURE 3   Sequence of Interior Inverse Analysis on the
Cooling Silicon Ingot of Figure 1.   This
Shows the Developement of the Thermal Gradient
Within the Crystal at Selected Samples Along
The Cooling Curve Over 100 Seconds.

determine the conductivity of each segment. The volume
selected depends on the frequency set selected and the
information desired.   The internal profile of conductivity
calculation if there is structure above a preset threshold
can take up 100 times longer than finding the mean
conductivity and radius by inversion. The exception to this
case is if the material has a constant conductivity over the
depth of interest and this is reported as rapidly as the
mean radius and conductivity determination.   Because of
the increase in time requirement on continuous product
multitasking processing for those sections showing changes
in either r(1) or sigma(1) are candidates for interior
conductivity profiling.   Typically this technique is used
to detect segregation, environmental interaction with the
surface, or cavities.   If homogeneous standards are
available then small conductivity variation as a function
of depth can be isolated.   In figure 2 is typical data on
the conductivity variation in Al 7%Si casting alloy which
is characteristic of dense and porous casting.   In figure
3 are direct inversion for interior temperatures profiles
from data that was produced on the same cooling silicon
cylinder that was used in figure 1.

Gauging the diameter of cylindrical objects can be
done quite accurately for the mean radius. However, only
on total volume measurements is this particularly useful or
in detecting surface reaction. The typical error can be
seen on a 1" diameter brass bar of .0005" with a minimum of
mechanical constraint in figure 4.

Figure 5 shows an exterior analysis on a step machined
copper bar to determine the radii. This measurement was
done at using three frequencies. A section was used as the
standard radius and it was found that there was minimal or
no variation between the measured and the determined value
by the exterior inverse program. The variation or error
increased or decreased significantly above or below the
standard. For this data, the error is about .02%. This
result indicates that this program can accurately be used to
gauge the mean radius of product with slightly varying
dimensions of material.

1.2042E-2 (0.5056 inch)   radius meters

├─ .5031"

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      · · · · · ·   ·   ·   · ·   ──
          ·   ↑
                                                   ±.0005"
├─ .4981"

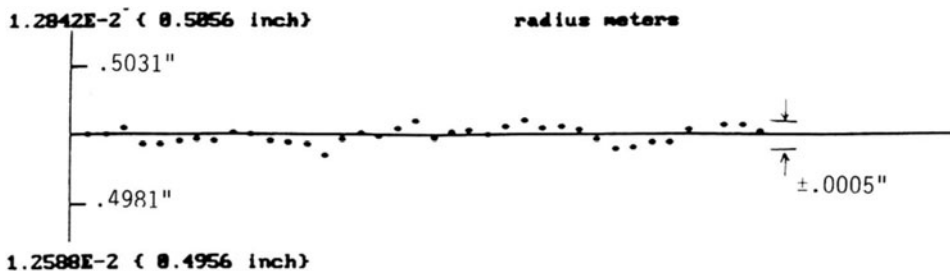1.2588E-2 (0.4956 inch)

FIGURE 4   The Variation in Radius of a 1" diameter.
            Brass Bar Tested at 100 Hz, 250 Hz and 410 Hz
            in the Exterior Inverse Mode.

The major application of these techniques are currently
in complex process development in difficult environments and
heat treatment. We are currently extending our
application programs to other test geometries and improving
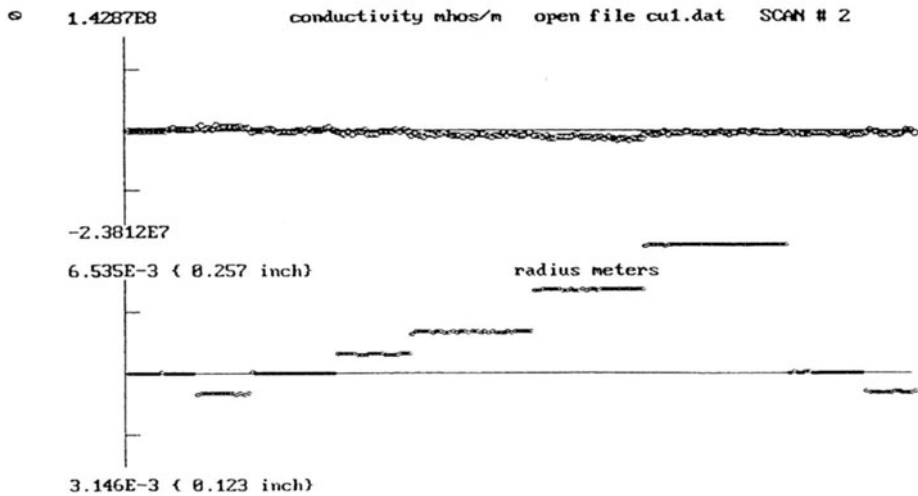the degree of accuracy of our physical measurements.
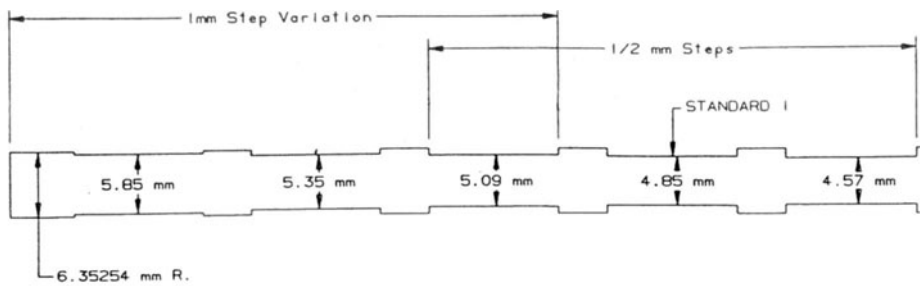
FIGURE 5   Copper Rod - Inverse Program.   1mm and 1/2 mm
            Step RAdius with 1 inch gap between steps.

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