LESSON
Target Properties in Frequency Domain. Transfer Impedance of Permeability and Conductivity

REFERENCES:

[1] Search in WEB for "Complex plane", "Impedance", "Bode plot" etc. For example
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[3] http://joe.buckley.net/papers/eddic.pdf - look at page 3
[4] Haslett et al. Patent US 3,159,784 - look at sheet 1, fig. 1
[5] Hentchel. Patent US 3,478,263 - look at page 2, fig. 3
[6] Mallick et al. Patent US 3,686,564 - look at sheet 3 figures 3 and 4.
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INTRODUCTION

Since metal detectors operate at low frequencies, only two properties - conductivity and ferromagnetism of targets and matrix can provoke signal in induction sensor. Matrix means environment of target - ground, masonry, salt water .

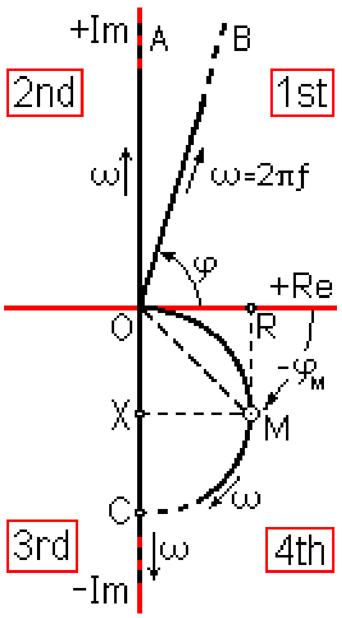

FIG 1. Transfer impedances of conductivity and permeability in complex plane

1) The straight line OA is impedanceform of lossless ferromagnetism (nonconductive ferrite core),
2) The straight line OB is impedanceform of lossy ferromagnetism (nonconductive "hot" rocks),
3) The straight line OC is impedanceform of super conductivity (non ferrous) and
4) The arched line OMC is impedanceform of a single eddy current loop (non ferrous, single timeconstant).
Each point on a line represents frequency and voltage.

FIG. 1 shows in complex plane frequency responses of 4 type targets having only ferromagnetism or only conductivity.

SENSING NETWORK

The system "Sensor & Object" of a metal detector can be represented by a two-port network shown as black box in FIG. 2. Inside the box are coils, target and environment. The leter T denotes gain (dependence of output quantity from input quantity).

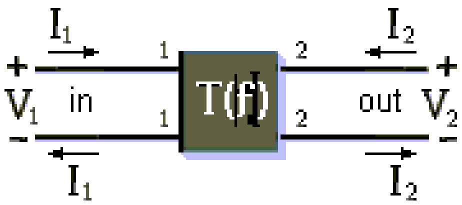

FIG. 2. Sensing network of a metal detector
Inside the black box are coils, target and environment. The leter T denotes gain. We should use letter Z instead T, because in input port 11 is TX current and in output port 22 is RX voltage

The gain in common case is a function of time (in the time domain) or of frequency (in periodic or frequency domain). Depending on dimensions of input's 11 and output's 22 quantities (current or voltage), instead letter T is used letter H, or Z, or Y, or G (for example letter H is used for nondimensional parameter **h21** (or parameter **hfe** for common emitter) of a bipolar transistor. Letter Y is used for dimensional parameter **y21** of field effect transistor).

The input quantity of our sensing network is TX coil current (dimension ampereturns); the output quantity is EMF induced in RX coil (dimension voltage). Therefore the gain is measured as impedance Z (ohm).

The main advantage of frequency domain is that gain calculates by simple math operation - division. In time domain should be used a comprehensive math operation - convolution [2]. The second advantage of frequency domain is visualization. It is far too dificult to display in time domain both properties permeability and conductivity.

In reality our sensing network has a fundamental drawback - tere is voltage in output port 22 even if there isn't target. That decreases modulation index of target signal, or shortly limits the depth. In the following explanation we assume that if no target, then no voltage in output port 22.

COMPLEX PLANE

Leading axis in complex plane is Re or real axis. It represents excitating quantity. Because of that, it is reference for measuring phase angle. For our sensing system, excitating qantity is magnetic field, therefore Re axis represents the phase angle zero of TX coil current. Each point on an impedance line represents TX frequency and RX voltage (EMF induced in RX coil at that freqency). The position of a point in complex plane is defined by two coordinates. They can be expressed in polar or in rectangular form.

For example, let point M is attributable to frequency 100Hz. The magnitude of RX voltage OM is 1V and angle (phase lag) is minus 45 deg. Magnitude (modulus) and phase angle (argument) are polar coordiates of point M.

Rectangular (Cartesian or Descarte) coordinates of point M are:
OR = 0.7V (real or Re coordinate, signal R) and
OX = -0.7V (imaginary or Im coordinate, signal X).

The real coordinate OR of point M represents exergy loss - dissipation of electrical energy (pure exergy) by heat in environment (anergy). The imaginary coordinate OX represents energy transformation without dissipation (one form of exergy transforms in other form of exergy). In this example, point M has negative Im coordinate OX, representing voltage induced in a negative transient inductance.

Both axes divide complex plane into 4 quadrants. First quadrant is the area between axes ***+Re*** and ***+Im***. Every point in this quadrant has positive ***Im*** coordinate, which is attributable to expressed ferromagnetic properties. Fourth quadrant is the area between axes ***+Re*** and ***-Im***. Every point in this quadrant has negative ***Im*** coordinate, which is attributable to expressed conductive properties.

Each point in second or third quadrant has negative ***Re*** coordinate, which is attributable to energy source. Since the target isn't energy source. its frequency response has points in 1st and 4th quadrants only.

ATTENTION: The names of quadrants and the positive phase angles of complex plane are arranged contra clockwise. That is irreal because all systems in real world are causal; the response can only delay from excitation in time domain since the system can't predict the future. In frequency domain, response should have allways negative angle or "phase lag", measured clockwise from Re axis. The term "positive phase angle" is misleading by transition from frequency domain in time domain.

TRANSFER IMPEDANCES OF FERROMAGNETISM AND CONDUCTIVITY

If we can compensate (balance) parasitic voltage in output port 22 of sensing system, we should mesure following impedanceforms of targets:

1. The straight line OA is impedanceform inherent to:

a) Lossless Ferromagnetism (HF ferrite core, dry mineralized soil, black sand, ceramic made of ferrous clay),

b) EMF (voltage) induced in RX coil by positive M (mutual inductance with TX coil).

c) EMF induced by selfinductance (sensor type "monocoil", "monoloop").

2. The straight line OB is impedanceform inherent to Lossy Ferrite (meteorites, "hot rocks"). This impedance line is shown with positive angle. The "phase lead" is misleading because shows that target response anticipates excitation. In time domain, the response can only delay because the system is causal.

As shown in [3], the phase angle of lossy ferrite is also independent from frequency. This is true only at low frequencies. The straight lines OA and OB are idealisation of ferromagnetism. In reality, the ferromagnetic properties are nonlinear.

3. The straight line OC is transfer impedanceform inherent to:

a) EMF induced in RX coil by negative mutual inductance with TX coil and

b) Nonferrous target having only superconductivity (no exergy loss).

In the both cases the phase lag is 90 deg (independent from frequency).

4. The arched line (halfcircumference) OMC represents special case of conductivity - target having a single eddy current (only one timeconstant). Such one object may be slender bracelet, or shorted turn of wire, or thin ring.

The common case of nonferrous conductivity is solid object without aperture. We may consider the solid object as build of many bracelets having different diameters and forming lesser timeconstants. That's why the impedance curves for nonferrous targets, published in [3 ~ 5], are different at high frequencies. The impedanceform of solid object or nonferrous ground seems like arc of circumference only for low frequencies. Above cutoff frequency (point M), curvature evident decreases.

Each impedance line represents frequency response function in impedance plane. The impedance function ***Z*(f)** has two components: even and odd. In rectangular coordinates the even function is **Re[*Z*(f)]**, attributable to exergy loss) and the odd function is **Im[*Z*(f)]**, atributable to lossless exergy transform. In polar coordinates the even function is amplitude (or magnitude) frequency response (AFR) and the odd function is angle (phase) frequency response (PFR).

The arrow shows direction in which a point moves, when the frequency increases. Note that at zero frequency, our sensing system can't generate signal. All impedance lines start from orirgin of coordinate system.

PERORATION

The lesson explains fundamental principles. They shed light on solving many design problems. We will discuss and solve problems in the exercises. The complex plane displays things in periodic (frequency) domain. This domain is more obvious than time domain, therefore it is very handy for analysis and calculation because convolution is substituted by division.

Sometimes frequency domain can be misleading because the time ***t*** is substituted by period ***T***. Remember how the wheels of a vehicle can rotate contrariwise in a video or movie because it is represented in periodic (frequency) domain. Similar problems arise and by DSP. However all is normal and without errors in the time domain and by CSP (continous signal processing or ASP - analog signal processing). Errors can be done at measurements and by transition from frequency in time domain. In exercises we will find and discuss errors in publications and designs.

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