Single-tone and Polyharmonic Eddy Current Metal Detection and Non-Destructive Testing Education Software

J Svatoš
Faculty of Electrical Engineering, Czech Technical University in Prague, Prague 6, Technicka 2, 166 27, Czech Republic

E-mail: svatoja1@fel.cvut.cz

Abstract. This paper describes the design of a measuring chain for polyharmonic metal detectors used for education in laboratory exercises at Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Measurement. The Measuring chain is composed of DDS signal generator, Digitiser and PC with software programmed in Labview. Eddy current principles or more specifically eddy current metal detectors are an important part of non-destructive testing, instrumentations and measurement. A short introduction to the background and principles of eddy current metal detectors are presented. Next part of the article deals with a brief description of the most common methods, as well as, non-traditional polyharmonic methods for eddy current metal detection. The following part contains an implementation of the proposed algorithms in LabVIEW graphical programming language. Finally, the created program for education of eddy current metal detectors and results obtained on the metal detector ATMID are discussed.

1. Introduction
Eddy current principles can be used in a wide range of applications. They can be used in non-destructive testing for crack detection, material thickness or to measure conductive material properties (conductivity or relative permeability). The limitation of this method is depth of penetration. Since the depth of penetration depends on frequency, frequency is important parameter to consider. They find also use as metal detectors in archeological and geological surveys, in security helps detect weapons (at airports and other public places) as well as in civil engineering to find steel bracing pipes in concrete walls, in agriculture to remove metal parts from cultivable areas, but are also used in pharmacy, food and chemical industries [1], [2] and [3]. There are many methods how to detect metal objects. Still, the most common detecting method is using eddy current principles. [4]
These currents arise thanks to varying primary magnetic fields transmitted as transmitting signal and create secondary magnetic fields. This secondary magnetic field is scanned as received signal and analyzed by the detector. There are two main groups of eddy current metal detector - Pulse Induction (PI) and Very Low Frequency (VLF) or continuous wave detectors. PI detectors evaluate signal in time domain, VLF detectors evaluate signal as a complex plane in frequency domain. Since VLF metal detectors are better in discrimination and recognition of metallic objects than PI detectors, the laboratory exercise is focused on these types of metal detectors. [5]
The information about metallic objects is mainly contained in the amplitude and the phase shift of the received signal [4]. It leads to limited discrimination ability due to the fact that some objects have a similar response. Possibility to excite the detector with different signals and with different frequencies...
[6] or [7] together with advanced signal processing of received signal can improve the discrimination ability of the detector.

2. Theoretical Background
Eddy current methods used in metal detection or non-destructive testing usually use probe that consists of transmitting and receiving coils. Time-varying electric current $I$ pass through transmitting coils and generates transmitting magnetic field. If the conductive object is presented, eddy currents generate at the surface of the object. This phenomenon is described by one of the Maxwell's equations - Ampere law (1).

$$\oint B_T \, dl = \mu_0 I$$

, where $\mu_0$ is permeability of the vacuum and $l$ is length of closed curve.
Eddy currents generate their own (opposite) magnetic field. The opposite magnetic field is detected usually by the receiver coil where is inducted voltage $U$ by the second Maxwell's equation - Faraday's law of induction (2).

$$\oint E \, dl = -\frac{d\Phi_B}{dt}$$

, where $E$ is electric field and $\Phi_B$ is magnetic flux.

![Eddy Currents](Figure 1)

The induced voltage in receiving coil is then processed. The amplitude and the phase of the received signal is evaluated. It is known that higher frequencies has better resolution but on the other hand lower frequencies has better penetration, skin effect is reduced and are less affected by the surroundings (e.g. when the object is buried in the ground).
Presented approach lies in the implementation of classical single-tone methods as well as an unconventional polyharmonic method like frequency sweep signal, step sweep sine or $\sin(x)/x$ signal [6], [8] and [9].
Polyharmonic approach in non-destructive testing brings opportunity to evaluate tested object with multiple frequencies at once, e.g. to locate cracks in different depth.
Eddy current Metal detectors excited by polyharmonic signals offers to measure Response function of the detected object, which improve the discrimination ability of the detector. [10] The measured data can be also evaluated in both the time and the frequency domains.
The laboratory exercises are focused on both methods of the excitation signal and both methods of signal processing. Thanks to a combination of all these methods better understanding of eddy current principles and determination of conductive objects are done.
3. Implementation
All stated methods are implemented to one workplace. Testing measuring chain is composed of DDS signal generator, which can generate all proposed signals, digitiser for analogue data conversion, PC with LabVIEW software and different probes for testing (differential, reflection, encircling or searching head of ATMID metal detector produced by Schiebel Company). [11] Block diagram of a working place with ATMID search head is shown in figure 2.

![Figure 2. Block diagram of testing workplace](image)

As a source of an excitation signal, function generator AFG 3102 with a resolution of 14 bits is used. For data digitizing a four channel oscilloscope TDS 3044B (resolution of 12 bits in hi-res mode) is used. Communication with instruments via GPIB uses VISA commands. For a program implementation a graphical programming platform LabVIEW is used. LabVIEW integrates graphical, text-based and other programming approaches within a single environment. It offers large integration with a great number of hardware devices and provides many built-in libraries for advanced analysis and data visualization. Thanks to that LabVIEW is suitable as an excellent education tool.

The claim is to minimize the user interaction with the instruments (function generator, oscilloscope). To ensure proper program execution Flat Sequence Structure is used. It consists of several frames, where parts of the program are stored. The main program is embedded in the main sequence structure, which consists of two frames. In the first frame, the initialization of all instruments is done. The second frame contains of the main loop of the program. The main loop consists of another sequence structure. This will ensure proper program flow.

When program starts, basic settings of instruments are executed automatically, additional settings can be controlled from the front panel. Front panel (figure 2) consists of three main parts. Part 1 (on the left side of the front panel) is for setting up the generator and oscilloscope. The program allows the user to change excitation signal of the generator from classical one-tone methods to non-traditional polyharmonic methods or \( \sin(x)/x \) signal as well as signal parameters like amplitude, phase and frequency for single tone and frequency span for polyharmonic methods. Time base scale (horizontal resolution) and vertical scale for individual channels, autoset and reset of the scope as well as switching between channels can be changed for the oscilloscope settings.

Part 2 shows the results of processed signal, measured by receiving coil, in complex (hodograph), time and frequency domain. This part consists of different tabs, where users can choose between all types of measurement and signal processing. Data visualization area changes with selected tab (figure 2 - in the middle of the front panel) i.e. selected excitation signal or data processing.

Time domain tab shows time waveform of both signals (transmitted and received). Frequency domain tab shows processed signal using Fast Fourier Transform algorithm (FFT) method [12]. This tab shows amplitude spectrum of the received signal, phase shift between transmitted and received signal and graph with amplitude difference of transmitted and received signal. Hodograph shows complex impedance plane for crack evaluation at individual frequencies.
As an excitation signal for Frequency domain tab, classical single tone method and non-traditional step sweep sine wave [9] or sin(x)/x signal [13] can be selected. Furthermore, user can find an exact value of magnitude and phase shift at the desired frequency (figure 4, left). There is also a file for selecting a window [12] which will be used in FFT.

Figure 3. Front panel of the program

Figure 4. Front panel of Frequency Domain (left) and Sweep (right) tabs
The tab Step sweep shows non-traditional step sweep sine signal. Step sweep sine signal increase uniformly sinusoidal frequency in every step. Thanks to this user obtain frequency response – Response function of the detected object over the wide frequency spectrum. Tab shows graphs with amplitude spectrum of the received step sweep sine signal, phase shift of each frequency and graph with amplitude differences between transmitted and received signal. User can set start and stop frequency, number of steps, amplitude and phase of the signal (figure 4, right).

Best Fit Sine tab uses standardized sine wave fit algorithm [14]. This method could bring the completely new approach to metal detection, but is still at the beginning of the research and is presented here only for compactness.

Hodograph tab shows complex impedance plane of the received signal for individual frequency. Thanks to various frequencies user can inspect different penetration depths, which means cracks in different depth.

All signals can be also saved. Measured data are send form the oscilloscope to the PC as a waveform. Data can be stored to .csv or .mat format for further advanced data processing.

Created programs and methods is designed for education needs of Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Measurement. Program will be introduced to subjects Analog Signal Processing and Digitalization (A3M38ZDS) and Diagnostics and Testing (A3M38DIT) of master degree program.

Crack measurements are made with various calibration standards with different cracks sizes and at various depth to show the dependency of the penetration depth on the frequency.

As a objects for metal detection experiments different size spheres from different ferromagnetic and non-ferromagnetic materials are used. Testing objects covers all sorts of electromagnetic properties (permeability and conductivity) and spheres sizes. Polyharmonic methods shows that induced voltage depends on electromagnetic properties, sizes but also on operating frequency. Low frequency magnetic fields, which penetrate deeper into the ground, are less affected by magnetic or mineralized soils and a skin effect is reduced. On the other hand high frequencies offer better resolution and sensitivity. [15]

Polyharmonic signal also offer possibility to measure the Response function of the detected object and thanks to that better characterise and determined detected material in terms of conductivity and permeability.

In Fig. 7 there is an example measurement using step sweep sine excitation signal without any object present (left) and with testing stainless steel sphere (right).

![Figure 5. Example of measurement without any object present (left) and with stainless steel sphere (right)](image-url)
4. Conclusion
A brief introduction to techniques for eddy current non-destructive testing and metal detection as well as designs of measuring chain for this type of eddy current principles has been described. Created program in graphical environment LabVIEW is designed for an education need of Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Measurement. During the implementation of algorithms emphasis on the clear arrangement of the methods, on transparency and readability of the block diagrams has been putted. The graphical user interface has been designed to give a comprehensive view of the program. A program has been created to meet all these criteria. The program is written to minimize the user interaction and allow exporting data for further advanced data processing. Possibility to excite the detector with different signals (single tone, step sweep, \(\sin(x)/x\)) and signal processing (FFT, best-fit sine method, hodograph) along with visualization, brings new opportunity to better understand the problem of eddy current techniques and principles. Proposed method of single-tone and polyharmonic metal object detection and inspection software in LabVIEW allow the education of the real eddy current principles behavior.

Acknowledgment
This research was supported by the grant SGS 10/207/OHK3/022/16 “Model-based testing methods for automotive electronics systems” by the Grant Agency of the Czech Technical University in Prague.

Reference
[1] Z. Bielecki, J. Janucki, A. Kawalec, J. Mikolajczyk, N. Palka, M. Pasternak, T. Pustelny, T. Stacewicz, and J. Wojtas, “Sensors and systems for the detection of explosive devices - An overview,” *Metrol. Meas. Syst.*, vol. 19, no. 1, pp. 3–28, 2012.
[2] J. García-Martín, J. Gómez-Gil, and E. Vázquez-Sánchez, “Non-destructive techniques based on eddy current testing,” *Sensors (Basel)*., vol. 11, no. 3, pp. 2525–65, Jan. 2011.
[3] L. F. Stine and D. L. Shumate, “Metal detecting: An effective tool for archaeological research and community engagement,” *North Am. Archaeol.*, vol. 36, no. 4, pp. 289–323, Jul. 2015.
[4] C. Bruschini, “A Multidisciplinary Analysis of Frequency Domain Metal Detectors for Humanitarian Demining,” Vrije Universiteit Brussel, 2002.
[5] B. Candy, “Metal Detector Basics And Theory,” Minleab, 2010. [Online]. Available: http://www.minelab.com/files/KBA_METAL_DETECTOR_BASICS_&_THEORY.pdf.
[6] J. Svatoš, P. Fexa, and J. Vedral, “Metal detector excited by polyharmonic signals,” in *2010 International Conference on Applied Electronics, AE 2010*, 2010, pp. 339–342.
[7] J. Svatoš, P. Nováček, and J. Vedral, “Summary of Non-traditional Methods for Metal Detection and Discrimination,” *Procedia Eng.*, vol. 47, pp. 298–301, 2012.
[8] J. Svatos and M. Linda, “Polyharmonic metal detector,” in *Engineering for Rural Development*, 2015, vol. 14, no. January, pp. 817–822.
[9] J. Svatos and J. Vedral, “The Usage of Frequency Swept Signals for Metal Detection,” *IEEE Trans. Magn.*, vol. 48, no. 4, pp. 1501–1504, Apr. 2012.
[10] J. Svatos, J. Vedral, and T. Pospisil, “Advanced Instrumentation for Polyharmonic Metal Detectors,” *IEEE Trans. Magn.*, vol. 52, no. 5, pp. 1–4, May 2016.
[11] A. Siegenfeld, “ATMID – Technologie und Schaltungsbeschreibung,” Schiebel, 2003.
[12] C. S. S. Burrus and T. W. Parks, *DFT/FFT and Convolution Algorithms: Theory and Implementation*, 1st ed. NY, 1991.
[13] J. Svatoš, P. Nováček, and J. Vedral, “\(\sin(x)/x\) signal utilization in metal detection and discrimination,” *J. Electr. Eng.*, vol. 63, no. 7 SUPPL, pp. 110–113, 2012.
[14] P. Händel, “Evaluation of a standardized sine wave fit algorithm,” in *Proceedings Nordic Signal Processing Symposium*, 2000, pp. 453–456.
[15] J. E. McFee, *Electromagnetic Remote Sensing, Low Frequency Electromagnetics*. Ralston: Suffield Special Publication, 1989.