THE SCIENCE BEHIND EDDY CURRENT AND REMOTE FIELD TESTING: FOR CONDENSER AND HEAT EXCHANGER TUBING

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ABSTRACT

With the increasing demand on the world's power grids, now more then ever it is important to keep power plant condensers, feedwater heaters and balance of plant heat exchangers running at peak efficiency. While it is well known that keeping these units clean is important for maximizing power output, so too is monitoring each unit's tube integrity and taking corrective action to prevent tube failure. The best way to monitor a unit's tube integrity, detect patterns of tube wear and damage, and determine the specific wear and damage to a particular tube is through Non-Destructive Testing. Depending on the tube material, the best Non-Destructive Testing method to employ would be either Eddy Current Testing, Remote Field Testing or other variations of these electromagnetic techniques.

This paper will discuss the science behind Eddy Current and Remote Field Testing, how they differ and which one to select depending on the situation. It will look at the construction of the probes and how they work. It will explain the difference between use of a single frequency or multiple frequencies and the advantages of multi-frequency testing. The paper will also identify the necessary procedure for a successful Non-Destructive Test, including the types of tubes that can be tested and tube preparation.

INTRODUCTION

The modern Eddy Current Testing industry owes its existence in a very real sense to Michael Faraday, (1791 to 1867). This brilliant scientist's discovery of and experiments into electromagnetic induction laid the foundation for the many Electromagnetic Testing techniques in use today. Though there has been much advancement in test instrument technology, computer software and test coil design, the basis of the electromagnetic techniques still rely heavily on the experiments performed by Faraday in the mid 1800's.

Both Eddy Current Testing (ECT) and Remote Field Testing (RFT), also known as Remote Field Eddy Current Testing, use the principles of electromagnetic induction to detect defects in condenser and heat exchanger tubes. In both ECT and RFT probes, an alternating current flows through a wire coil or coils, generating an alternating magnetic field around the probe. When the probe is inserted into a metal tube, a circular flow of electrons will begin to move through the metal, generating its own magnetic field. This circular flow of electrons is the eddy current. As the probe moves through the tube, the magnetic field generated by the eddy current will interact with the coil's magnetic field. Defects in the tube wall, such as pitting or cracking, and changes in wall thickness will interrupt or alter the amplitude and pattern of the eddy current, changing its magnetic field. This change in the magnetic field then affects the coil by varying its electrical impedance, which is monitored by the test instrument. By plotting the changes in the impedance amplitude and phase angle on a monitor, a trained operator can compare the pattern displayed on the monitor to patterns of known test samples to determine the condition of the tube being inspected.

PROBE CONSTRUCTION

All ECT and RFT Probes consist of a coil or coils wrapped around a structure to form the coil. It is the manner in which these elements are designed and their interaction with each other that will determine how the eddy currents are induced and how flaws are detected in the test material. Most coils are built on a non conductive body (air core) but many can be constructed using ferrite cores and conductive shielding to help shape the eddy current field for special applications.

THREE BASIC COIL TYPES

According to James Cox, author of "Nondestructive Testing, Eddy Current: Classroom Training Handbook", there are three basic coil types: [1]

1. Probe coil (Fig. 1) – Also referred to as a pancake coil, it is designed to test the surface of materials and can be applied to plates, welds or even tubing when fixed to a special device that spins the coil ("spinning probe

technique") inside a bolt hole or a tube. When a probe coil is fixed to this type of spinning device it is commonly referred to as a motorized rotating pancake coil (MRPC) (Fig. 2) in the heat exchanger industry. This probe type can provide some very detailed information but is time consuming and expensive to operate.

2. Bobbin Coil (Fig. 3 and Fig. 4) – This coil type allows for the inspection of installed heat exchanger tubing from the inside diameter (ID) surface. The bobbin coil interrogates the entire circumference of the tube as it is drawn through the tube. This type of coil is the most widely used and is considered the "workhorse" of the tube testing industry.

3. Encircling coil (Fig. 5) – Also known as Feedthrough Coils, this coil type allows the inspection of round objects such as tubes, wires and rods from the outside diameter (OD) surface. Much like the bobbin coil, the encircling coil also interrogates the entire circumference of the material as it is passed over the material or the material is fed through the coil. This type of coil is used mostly in production monitoring activities.

TEST COIL ARRANGEMENTS

How a coil is electrically configured to operate with the test instrument is an essential variable to optimal performance. The three basic coil arrangements are: [1]

1. Absolute (Fig. 1 and Fig. 2) – An arrangement where the coil works independently, making no reference to any other coil, and is affected by all changes in the material. This coil is usually limited to use by conductivity testers, coating thickness gauges and small surface riding pancake coils for surface scanning.

2. Differential – An arrangement where two or more coils are electrically connected in some fashion to oppose each other and look for an imbalance or "difference" between the coil impedance when a flaw is encountered. Differential coil arrangements are sub categorized into two types.

   a. Self Comparison (Fig. 3, Fig. 4 and Fig. 5) – In this differential arrangement, at least two coils are electrically connected, placed in close proximity to each other and wound in opposition. If both coils are affected by the same condition, the output or "difference" is zero. This arrangement is very sensitive to small volume flaws such as pits, cracks and any abrupt changes in wall thickness such as those caused by tube-to-baffle wear, while minimizing noise due to probe motion (wobble) as the probe traverses the tube, temperature variations and deposits in the tube. While effective in detecting abrupt changes in wall thickness, the self comparison differential cannot detect gradual wall loss associated with steam erosion or tube-to-tube wear.

   b. External Reference – In this differential arrangement, at least two coils are electrically connected to each other but not in close proximity. The coils are either separated on the same test part by a distance that does not allow any direct coupling between the two coils or one coil is on the test part while the other coil sits in a fixed location on a reference sample that represents nominal material conditions. This arrangement is sensitive to all measurable changes (much like an absolute coil but with better detection) including abrupt changes, gradual wall loss, temperature variations, probe wobble, and any other gradual condition that can produce noise. The data can be erratic and is typically reserved for defect confirmation against the self comparison differential channels and for detection of specific damage like erosion and tube-to-tube wear.

   To perform an adequate examination on any condenser or heat exchanger, it is imperative to utilize both modes of differential operation. The industry typically refers to the self comparison mode as differential and to the external reference mode as absolute because of the data display. Sensitivity to all measurable changes in the material under test is very similar to an absolute coil response.

3. Hybrid – Hybrid coils, also called driver pickup or reflection coils, have the widest range of configurations. The possibilities are as limited as the engineers' imagination. The basic configuration utilizes a separate excitation coil and an independent sensing (pick-up) coil or set of sensing coils. The excitation and sensing coils can be incorporated into each other or separated by certain distance. The coils can even be on opposite sides of thin foil or plate (through transmission) passing the eddy current field through the test part and measuring the change in field on the opposite side. Hybrid coils have endless configurations to meet special needs of the inspection industry, but are not necessarily the most affordable breeds.

ECT VS RFT PROBES

Eddy current probes used for inspection of heat exchangers in the majority are bobbin probes operating in the differential modes, self comparison and external reference. There are some minor variations in design such as a narrow groove bobbin which would have an enhanced sensitivity to small pits and cracks and magnetic bias probes to overcome slight permeability issues, but for the most part function the same way over a host of manufacturers. The biggest concern comes into the probe selection being compatible (impedance matching) with the test system being used.

A smaller grouping of eddy current probes falls into the hybrid category for specialized configurations. Some multi sensing element probes, such as array probes, operate in a driver pickup mode of operation. Care needs to be exercised in coil selection for hybrid designs; as sensitivity is gained for one specific damage mechanism, other mechanisms may be missed. Probe cost is also a consideration for hybrid probes as they can be very complex and very expensive. More advanced array probe (Fig. 6) designs incorporate a self comparison differential bobbin coil in the array probe to provide conventional eddy current data right along with the specific array data. Of course there is an added cost for complex design configurations, but overall, advanced array probe technology has reached a price level that is more affordable for the common condenser and heat exchanger inspection application.

Eddy Current Testing using absolute coils is not completely out of the question. Some MRPC probes and profilometry probes (8 x 1 pancake coil arrangement) use absolute, surface riding pancake coils to scan tubes from the inside and provide detailed defect information.

Other specialty eddy current tube probes include a myriad of magnetic bias probes which incorporate strong rare earth magnets to overcome mild permeability variations in certain metal alloys.

Remote field probes (Fig. 7) used for inspection of ferromagnetic tube materials all fall into the hybrid coil design. The basic function is the same for all, a large excitation coil generating the magnetic field to penetrate the tube wall and a pickup coil located two to three tube diameters from the exciter coil detecting the changes in field strength as the energy enters back into the tube wall. One can find RFT probes in many variations of exciter/pickup coil configurations, each having their own benefits for certain applications.

A variant to the RFT probe is a NFT probe. This probe is also a driver/pickup mode of operation but the sensing coil is placed in the near zone (close to the exciter) rather than using the far (remote) field energy for detection. This probe is helpful in applications where there is OD copper or aluminum fins on carbon steel tubes where RFT testing is ineffective.

FILL FACTOR

For all bobbin probe applications for tube testing, probe size is an essential variable. Ideally the probe would occupy as much of the diameter of the specimen to be tested as possible [2]. The probe size is a compromise between accessibility to the tube and the best possible energy intercepting the tube to provide for strong eddy currents. The stronger the eddy current field, the better the results. For most eddy current applications, 85% fill factor is a good target percentage. For Remote Field Testing, fill factor can be reduced to 70% and still produce viable results.

When calculating fill factor, the following the formula is important.

$$FF = d^2/D^2$$

In the above formula FF is the fill factor, d is the outside diameter of the coil and D is the inside diameter of the tube.

Many times the calculation is run without squaring the diameters resulting in over inflated fill factor percentage which provides for a poor eddy current energy. Poor fill factor can also result in increased baseline noise in the eddy current data.

When considering fill factor it is important to clean the tubes immediately prior to testing. This will eliminate blockages and allow for the use of maximum fill factor for best test results.

EDDY CURRENT VS REMOTE FIELD TESTING

Though both eddy current and remote field techniques rely on electromagnetic induction as a function of the inspection process, they are very different in operation and application.

Eddy Current Testing relies on direct coupling between the inspection coil and the test material and works very well for non-ferromagnetic materials. Materials which are magnetic have a major impact on the penetration of the eddy current field. Also, the permeability varies throughout the material and causes erratic signals and increased noise. ECT can be used on mildly permeable tubes by use of rare earth magnets (mag bias) placed near the inspection coil to “zero” out the permeability effects and let the eddy current alternating magnetic fields run free to do their job.

Remote Field Testing is designed to overcome the permeability effects in ferromagnetic tubing such as carbon steel and ferritic stainless steels. Before the development of RFT, test methods for inspecting carbon steel were very limited. As the name implies, remote field testing does not work in the direct coupled zone. The remote field zone is the region in which direct coupling between the exciter coil and the receiver coil(s) is negligible. Coupling takes place indirectly through the generation of eddy currents and their resulting magnetic field. The remote field zone starts to occur at approximately two tube diameters away from the exciter coil [3]. RFT does theoretically work on non permeable materials but it is not as accurate or effective as conventional ECT.

APPLICABILITY

Eddy Current Testing for tubing applications is limited to non permeable materials like copper, brass, copper-nickel, austenitic stainless steels and similar alloys. ECT can be used for mildly permeable tubes like Monel and ferritic stainless steels with the use of magnetic bias probes, provided they are strong enough to saturate the material. A limitation may be that with strong magnets traversing the probe can be difficult as the tube supports attract the probe as it passes intensifying the physical aspects of the inspection process.

For materials which are permeable and highly permeable like ferritic stainless steel, carbon steel and similar alloys, Remote Field Eddy Current Testing is a viable option. Going beyond the limits of eddy current testing using a magnetic bias probe, RFT can inspect the toughest carbon steel material with no restricted mobility. Since the energy used to penetrate the material is an alternating current field and is not a DC magnetic field, the probe is not attracted to the tube wall or tube supports as it passes through the tube. RFT is not as definitive as ECT, but for applications where tubes are not testable by ECT, RFT provides valuable data to provide for a reasonable condition assessment.

CALIBRATION

For all techniques of electromagnetic testing, it is crucial to perform a valid test system calibration to ensure functionality and sensitivity are adequate for the intended inspection. The ASME Boiler and Pressure Vessel Code, Section V identifies the basic requirements for nondestructive testing [4]. More specifically, article 8 and article 17 specify the requirements for Eddy Current Testing and Remote Field Testing, respectively. The articles define all essential elements of the inspection system including test probes, calibration standards, test system requirements, frequency selection, calibration settings and documentation.

ASME section V also defines certification requirements for inspection personnel. The inspection company is required to develop a written practice to define how they qualify and certify inspection personnel in accordance with recommended practices. From the applicable codes, inspection companies need to develop inspection procedures to provide instruction to the inspectors and maintain consistency and repeatability from one inspection to another and from one inspection performed over time on the same heat exchanger.

SINGLE FREQUENCY VS MULTI FREQUENCY TESTING

More is better, correct? Well, at least for Eddy Current Testing that is true. The ASME code only defines the prime frequency needed to obtain a desired response. It allows for the use of additional alternate frequencies, but does not require them. Subsequent frequencies each have their strengths for detection and allows for signal mixing to eliminate unwanted interference like tube support plate signals. The same holds true for the mode of operation where ASME defines differential and absolute modes but calls for either or both as an option. Running both is highly recommended. The variety of a number of eddy current channels and mode combinations allows an extensive analysis of defect (flaw) depth and characterization [5].

Unfortunately, Remote Field Testing does not easily lend itself to the variety of frequencies and signal mixing that ECT does. Due to the characteristic low frequency operation, one or two test frequencies are typical for a RFT inspection. Adding too many low frequencies has an impact on production by reducing the sample rate and in turn forces slower scanning speeds.

CONCLUSION

Electromagnetic testing techniques have been proven effective for many years and continue to provide viable inspection data for heat exchanger tubing condition assessment. Armed with the detailed information on a unit's tube integrity provided by Eddy Current Testing and Remote Field Testing, plant managers can take proactive steps to either repair, replace or plug damages tubes before they fail, preventing a forced outage

Understanding how each testing technique works and the capabilities and limits of each will provide the plant with the ability to choose which direction you should take, ECT with multiple frequencies for non-ferromagnetic tubes or RFT with one or two frequencies for ferromagnetic tubes. One size does not fit all, as each will provide information that is vital to your equipment assessment.

Don't go it alone. As discussed there are a wide range of variables to consider when selecting the best inspection technique for your specific application. Consulting with eddy current equipment manufacturers and service providers can help to navigate the many options available and select what will work the best for your circumstances.

With continued technological improvements, options for tubing applications are always expanding. However, we can revert back to the basics when selecting the appropriate technique for a specific application.

REFRENCES

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[5] Innospection (ND) "Multiple Frequency Eddy Current Technique," retrieved from http://www.innospection.com/pdfs/Multiple%20Frequency%20Eddy%20Current.pdf on 12-3-2015.

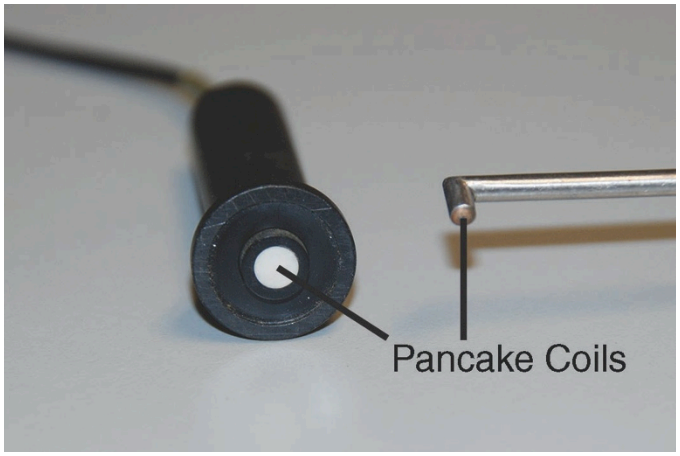

Figure 1.
Probe coils in an absolute arrangement used for surface scanning.
(Photo Courtesy of Conco Services Corp.)

Figure 2.
Probe coils mounted on a fixture to spin the coil inside of a tube to provide a focused surface scan.
(Photo Courtesy of Conco Services Corp.)

Figure 3.
Standard issue barnacle scraper style bobbin coil in a self comparison differential coil arrangement. This can be configured to run in the external reference mode simultaneously with the self comparison mode.
(Photo Courtesy of Conco Services Corp.)

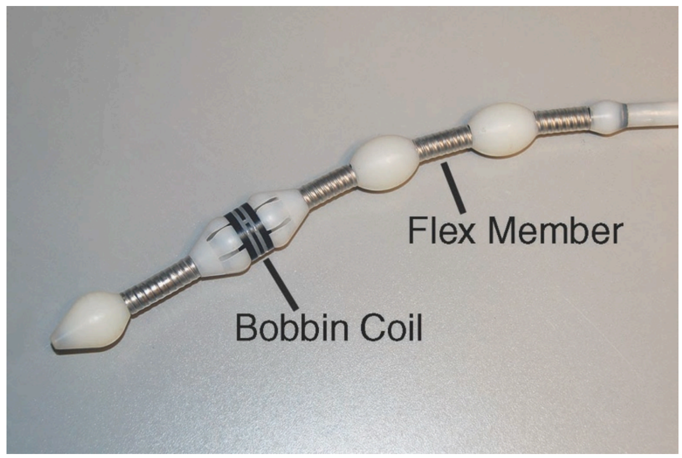

Figure 4.
Flexible bobbin coil design that can negotiate U-bend tubes.
(Photo Courtesy of Conco Services Corp.)

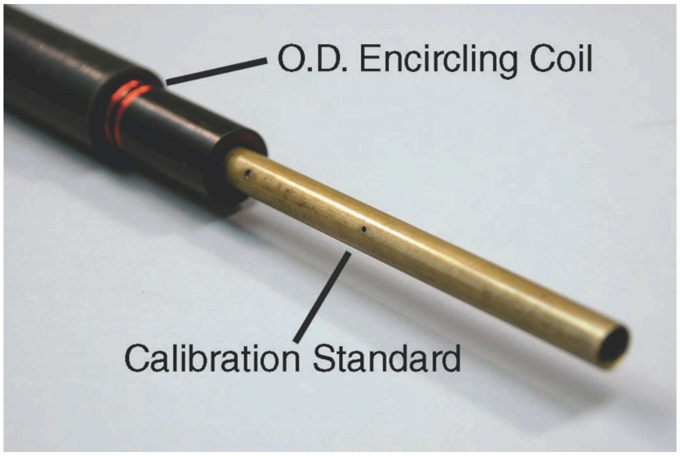

Figure 5.
Encircling probe (coil exposed) designed to test tubing from the OD. It is a similar configuration as the bobbin coil.
(Photo Courtesy of Conco Services Corp.)

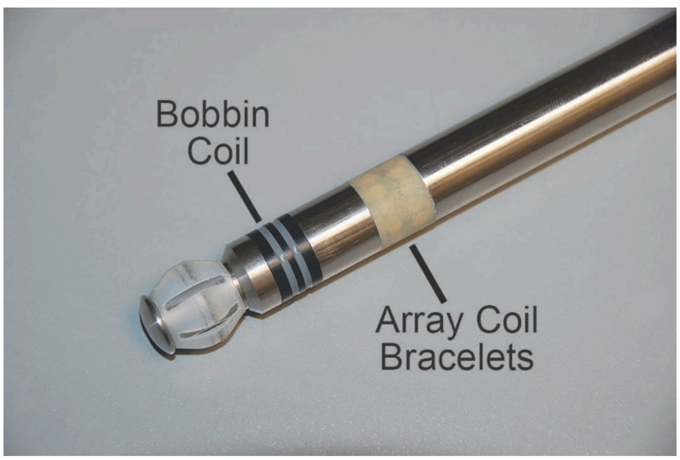

Figure 6.
Advanced array probe which includes a conventional bobbin coil.
(Photo Courtesy of Conco Services Corp.)

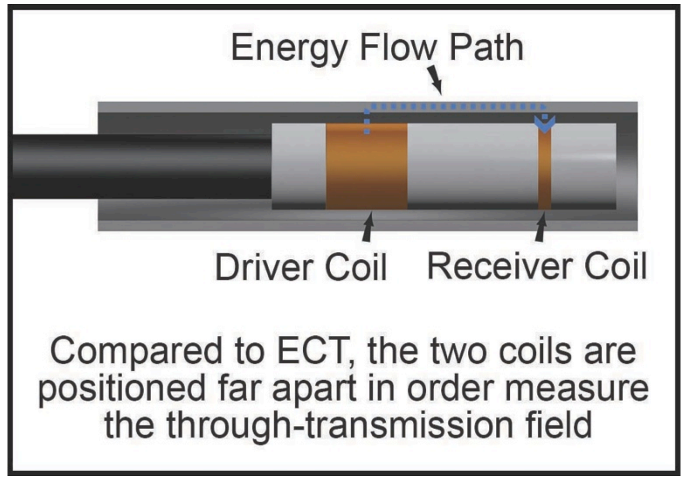

Figure 7.
RFT Probe – Basic operation is Driver/Pickup (receiver) and falls into the hybrid coil arrangement category.
(Photo Courtesy of http://www.et-ndt.org/wp-content/uploads/2015/07/RFT.png)