A TRIO OF TECHNIQUES FOR EDDY CURRENT INSPECTION OF TUBES AND BARS

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Abstract

Encircling coil eddy current testing has been employed in tube mills since the middle of the last century. This was followed, several years later, by rotating probe eddy current inspection of bars for detection of longitudinal surface flaws. Availability of powerful computing platforms over the last decade has spurred development of a new technique for inspection of tubular products, employing eddy current probe arrays.

This paper outlines the dramatic evolution in test systems, and goes on to discuss the latest equipment exploiting each of the three techniques. It also offers an objective evaluation of strengths and weaknesses of each test method.

Origins

Eddy current non-destructive testing traces its roots to 1820 when Oersted demonstrated the link between electricity and magnetism in Copenhagen. Then Faraday demonstrated electromagnetic induction in 1831 and experimentally formulated the laws of induction. Contemporary luminaries like Ampere and Lenz furthered the knowledge of the electromagnetic phenomenon by scientific exploration and observation. In late 1840's, Neumann and Helmholtz were the first to tie these experiments together with mathematical treatment. This work was further refined by Maxwell in 1851 into the famous Maxwell's equations which remain the fundamental basis for all electromagnetic applications even today.

The first high-profile application of electromagnetism dates back to 1881, when Alexander Graham Bell tried to locate an assassin's bullet lodged in US President Garfield's body. First serious industrial applications of electromagnetic testing surfaced around 1930 as simple metal sorters. These were inadequate for defect detection, and work in that direction was proceeding on both sides of Atlantic. Eddy current NDE finally came of age after 1950 when Dr Friedrich Forster published his extensive research with detailed characterization of materials and the elegant concept of impedance plane diagrams.

Evolution

Non-destructive testing assumed critical importance with the advent of Nuclear power plants. Eddy current technique was especially valuable in inspection of the vast quantities of tubing used in these plants, both during the production of tubes and later during periodic maintenance shutdowns. Another motivating factor was the requirements of aero-space industry. Later, the automobile industry became equally demanding. These exacting requirements resulted in rapid advances in instrumentation, aided significantly by important breakthroughs in semi-conductor industry. Relatively recent spurts in computing power further enabled new algorithms, features and techniques, which were hard to imagine even twenty years back.

Eddy Current Encircling Coil Tests of Tubes and Bars

Metal tubes and bars find application in every engineering industry. Most modern applications require that these important inputs be "free of defects", apart from being of the specified material. Tubes used for heat exchangers and steam generators, as well as for petro-chemical and automotive applications are especially critical, and several national standards have evolved for eddy current inspection of tubes during production. Among the most used standards for these purposes are ASTM, BS, DIN, JIS and API specifications. These standards mostly specify that a hole of a certain diameter be drilled through the tube, and eddy current signal for such a hole be used as a threshold for acceptance. A few standards might also specify an inside-diameter or outside-diameter, transverse or longitudinal notch of certain dimensions. In case of bars, things are not as clear. Only a few definitive standards exist, and almost all of them specify a longitudinal notch of certain dimensions, depending on the condition of the bar (bright-finished, peeled, as-rolled etc), its diameter and end-use.

The earliest eddy current equipments for testing tubes were all encircling-coil type fixed frequency instruments, derived from the early metal sorters. The frequency would be pre-set for a given application, taking into account the depth of penetration of eddy currents in that material. The test coil used to form two arms of a bridge excited at test frequency. The bridge used to be balanced on a "good" portion of the tube under test. In this situation, similar eddy currents were induced in the tube under each arm of the bridge, and the small residual was balanced out. Any defective portions appearing under one arm of the bridge would obstruct the flow of eddy currents, thus changing the effective impedance of that arm. The resulting signal was then amplified and compared against a set threshold value. Any signals crossing this would mean that the tube portion passing through the test coil was unacceptable. While such basic instrumentation served the purpose in its day, there would be drift in the bridge, necessitating frequent balancing, and the signal-to-noise ratio was rather poor.

Later, systems with phase-sensitive detection improved the signal-to-noise ratio by being selective about the phase of the signal. Noise sources such as signals due to vibration could be greatly reduced. Better filtering further enhanced the signal-to-noise ratio and this resulted in a higher probability of detection. Instruments also started sporting variable frequency oscillators, and auto-balancing units that took care of initial adjustments. Further on, some systems developed effective non-balancing strategies, obviating the need for balancing altogether. The equipment was still basically all-analog save for the circuits after threshold comparison.

Somewhere along the line, segment coils came into existence for testing only a part of the tube surface, usually the weld line. Of course, magnetic saturation was used since the beginning for testing ferromagnetic tubes, so that the effect due to permeability variations was minimized. In many cases, demagnetization was then required further down the line so that the residual magnetism was reduced to acceptable levels. Encircling coils evolved from single impedance configurations to multiple send-receive configurations.

Multi-frequency eddy current tests started being used in Nuclear power plants by the end of seventies. But multi-frequency testing during production did not catch on till another decade or more. This was mainly driven by automotive applications that required not only through-wall conventional inspection, but also higher frequency tests for surface condition of tubes. Unlike the in-service application at power plants, frequency mixes have rarely been used in production testing.

Early eighties saw the meteoritic rise of the microprocessor. Mixed signal designs enabled "fully digital" systems by the end of that decade. Of course, they still had sinusoidal waveforms exciting the test coil and the signals stayed in analog domain till they were finally digitized for display and control. The dials and switches of old panels gave way to keyboards, and the oscilloscope-type CRT displays were replaced by LCD screens and monitors. Less than ten years later, this "advanced digital" technology was almost obsolete. Embedded Pentium processors added some serious horsepower under the hood. This enabled implementation of several new features and advanced digital signal processing techniques.

Fig 1: Advanced Multi-frequency Encircling Coil System: Technofour Flawmark-EX

Throughout this dizzying journey of technological advances, the basics of encircling coil eddy current tests have remained constant over all these years. Most, if not all, coil configurations are differential, and therefore best suited for detection of short or transverse defects. While this is generally acceptable in case of welded tubes, there are cases like drawn bars, or seamless tubes where longitudinal defects occur predominantly due to the process involved. In such cases, other techniques like rotating probes have to be resorted to.

Rotating Probe Eddy Current Test Systems

By the late sixties, encircling coil inspection was firmly entrenched in most modern tube mills. However, due to the aforesaid need for detection of longitudinal defects, a new paradigm had to be evolved. This spurred the development of a device where two eddy current probe coils were mounted on a disc that rotated around a bar or a tube that passed through it. Thus, the probe coils described a helical path on the surface of the bar. Each coil was so adjusted as to be just clear of the bar, close enough to be able to induce eddy currents in the bar. The excitation current and the signals were exchanged with the stationary world through a set of slip-rings. It was possible to adjust the axial feed of the bar such that the probes could interrogate the entire surface of the bar. Each time the probe crossed a longitudinal defect, it would see a change in impedance because of the deflections of eddy currents, thus detecting the defect.

Initial rotating probe devices were slow and prone to wear and tear of slip rings. Eventually, vendors developed electromagnetic coupling between the stator and rotor parts, thereby avoiding the slip rings and their associated problems. Now the probes could be rotated faster, improving test throughput. One disadvantage of using probes was that they were much more sensitive to lift-off variations. Thus it was necessary to maintain a constant distance between the probe and the bar surface, by guiding the test bar concentrically through the rotating head. In practice, this still left some eccentricity uncorrected, resulting in rather poor repeatability. This led to the development of automatic gap compensation technique. An additional probe measured the gap between the test probe and the metal surface, and this information was used to modulate the signal gain suitably, so that relatively constant signal amplitude was obtained despite small variations in the gap.

Probes had considerably smaller electromagnetic footprint than an encircling coil, thereby making them much more sensitive. However, the technique inherently favored longitudinal defects, while detection of transverse flaws suffered in comparison. For more complete testing, it was often necessary to combine both encircling coils and the rotating probes in the same test line.

Eddy Current Probe Array

The advent of Probe Arrays in electromagnetic tests is a recent phenomenon, made possible because of huge advances in micro-electronics. Arrays found their first application in steam generator inspection in Nuclear power plants. It has the potential of detecting both transverse and longitudinal flaws at one go. Small stationary probes are arranged around the tube or bar to be tested. One probe element is excited at a time, and resulting eddy current signals stored in a computer. A few microseconds later, the next element is excited, and so on till it is the turn of the first element all over again. There are no moving parts, and this "electronic rotation" can be faster than a mechanical device easily by an order of magnitude.

Individual probe elements are typically arranged in two or more rings, so that defects that do not quite pass under an element in the first ring can be spotted by an element in the next ring, which is arranged at an angular offset. It is also possible to determine the orientation of a defect, and present the information in an easy-to-interpret 3-D image.

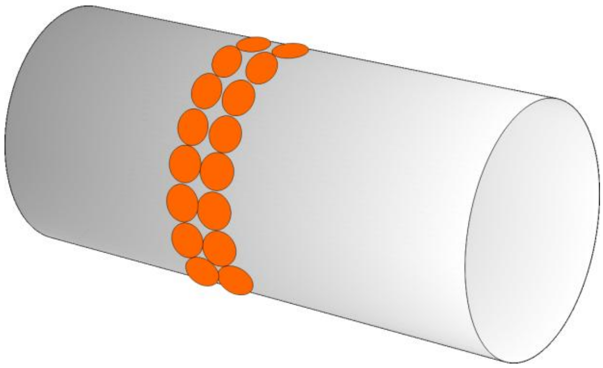

Fig 2 A typical eddy current probe array around a tube.

Modern Eddy Current Systems

Some advanced systems combine the techniques, often adding encircling test channels to a rotating probe system. One such system, the Rotoprobe-EX, is offered by Technofour. Anchored by multiple embedded processors, the system presents the familiar Windows-XP user interface. Rotoprobe-EX can test tubes and bars with high-speed rotating heads excited by variable frequency, and sports automatic setup and automatic gap compensation by real-time digital signal processing. Throughput can exceed 100 meters/min for smaller diameters. The system has TCP/IP servers that enable remote monitoring of the system and diagnostics over the Internet. The system can e-mail test reports, logs and statistics at scheduled intervals. An additional encircling channel takes care of short and transverse defects. Yet another channel can be added for material sorting, all in the same test line.

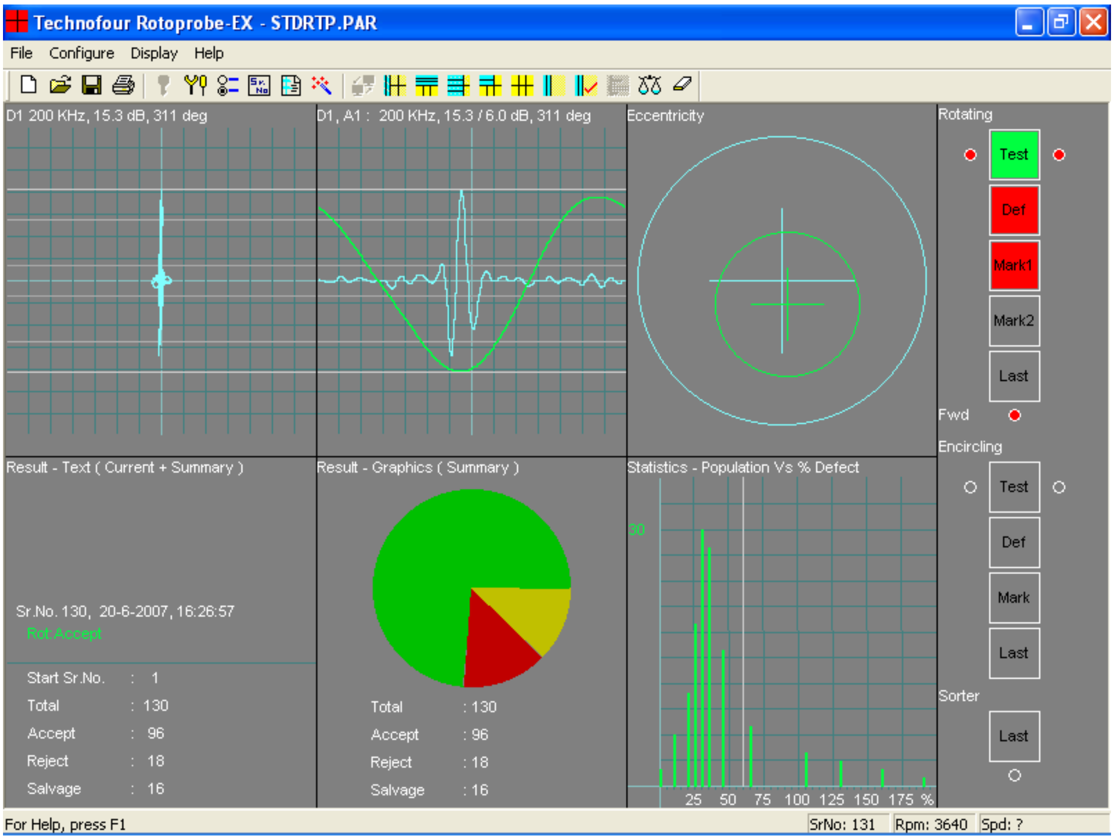

Figure 3: One of dozens of possible displays from Technofour Rotoprobe-EX.

Technofour also offer an advanced probe array system PARAS-EX with up to 256 probe elements and 512 test channels at single or multiple frequencies. Capable of very high multiplexing rates, it can virtually rotate at well over 100000 rpm. This translates to impressive throughputs that can be 10 to 20 times those can be achieved by physically rotating probes, especially for higher diameters. The system can differentiate between transverse and longitudinal flaws and can present 3-D exploded views of a tube or a bar. It shares connectivity and automation features with other members of Technofour EX series.

How Do The Three Techniques Stack Up?

Encircling coil technique essentially compares two sections of a tube in two coils. Thus, it is sensitive for detecting short or transverse defects. It can also theoretically detect the start and end of longitudinal defects. In practice, however, longitudinal defects are more likely to be boat-shaped, i.e., shallow at beginning and end, tapering relatively gradually to full depth. Thus, differential coils do not see much of a change. The other main drawback of encircling coils is the relatively large electromagnetic footprint. A small defect is apparent only to a small extent of the coils, and the resultant sensitivity is somewhat low. Other than these two drawbacks, there is nothing really negative about encircling coils, except that several test coils may be required depending on the diameter range produced at a location. The technique is the lowest cost of the three. It is also the fastest. It is the least sensitive to changes in lift-offs. Typically, defect sensitivity changes at the rate of 3 to 4 dB per mm of radial gap change. Thus, one test coil can take care of a range of tube sizes. Test coils are relatively inexpensive, and can last long with due care. The technique has been applied for several decades now, and most eddy current technicians are familiar with it. A variation of encircling coils is the segment coil, which is useful for testing just the weld line of a tube, especially high diameter pipe, before it is cut by a flying saw. Together, the encircling and segment coils cover the largest range of diameters such as 1mm wire to 500mm diameter pipe. Suitable coils can also be designed for other regular shapes like rectangles, squares, hexagons, ovals etc, although guiding the tubes through the coils can become rather tricky.

Rotating probes offer significantly higher defect resolution because of the small size of the probes. This technique reliably detects the longitudinal defects in real life. Test frequencies used are typically in the 100KHz to 500KHz range, and often good signal-to-noise ratios can be obtained without magnetizing bars. This also means that the rather difficult process of demagnetization can be avoided. One rotating test head covers a range of diameters, such as 12mm to 90mm, and the same probes can be used to cover the entire range. However, as it relies on physical rotation, the technique is the slowest of the three. It also implies increased wear and tear, as well as maintenance. Multiple probes have to be used for reasonable throughput and the test equipment becomes considerably more expensive than encircling coil systems. Rotating probes offer poor sensitivity to transverse defects, especially those along the helical path the probes describe on the bar surface. Variation in lift-off is significantly poorer, with typical values on steel bars at 10 to 12 dB per mm. This limitation, however, can be corrected by using systems with automatic gap compensation, although this can push the cost a little bit higher. By its very nature, the technique is suitable only for round tubes and bars. It is impractical to build rotating heads for diameters bigger than 220mm. On the lower side, one cannot go much below 3mm because of the physical size of the probe.

Eddy current probe arrays are capable of detecting both transverse and longitudinal defects at one go. Testing speeds are an order of magnitude higher than rotating probes, although not quite as fast as encircling coils. Defect resolution is as good as the rotating probes, and much better than encircling coils. Since there are no mechanical moving parts, it does not need much of maintenance. Probe arrays can be shaped to match any inspection need, including flats, rails, curved surfaces etc. However, several probe elements are required to cover the circumference of the tube or bar. The number can exceed a hundred for larger sizes. Accordingly, it needs complex electronics and software to operate. This makes probe arrays the most expensive of the trio. Each array can only cover a small range of sizes. Thus many sets are required to cover a given range. Each set is considerably more expensive compared to encircling coil or rotating probes. Thus, replacement costs are quite high. Used in bridge-mode, lift-off performance is as poor as rotating probes. Lift-off effects do improve marginally with transmit-receive configurations. Most configurations of probe array systems do not have any facility to correct for variation in lift-offs, other than mechanically keeping the gap constant by means of a centering mechanism. Although probe elements are placed in multiple rings to cover gaps left by the previous ring, the circular variations for the same defect are poorer in probe arrays. An often-overlooked fact is the variation in sensitivity for different orientation of defects. Combined with the lack of lift-off compensation, this technique fares the worst in repeatability tests. It is difficult to construct an array for diameters lower than 6mm. For high diameters, it can get impractical due to the number of elements required to cover the circumference.

Conclusion

Encircling coil technique scores in speed, ease-of-use, procurement and running costs, diameter range, lift-off performance and detection of short defects. Rotating probes shine in detection of longitudinal defects. Combined encircling coil and rotating probe systems can provide a cost-effective solution for detecting transverse as well as longitudinal defects, although the throughput will be limited by rotating probes. While technologically elegant, Eddy current probe arrays cannot be considered an automatic choice unless a higher throughput is required than possible with a combined conventional system, or for cross sections other than circular.