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Metrological Aspects of Electromagnetic NDT

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Metrology is very important for the correct and effective application of NDT. As it is well known, the accurate direct estimation of the metrological parameters of NDT devices (like accuracy, limit of sensitivity, etc.) and technologies is not so easy. Artificial standards, imitators and reference samples are used in many cases for this. Real testing conditions may differ significantly from that used by metrological calibration. To avoid a possible misunderstanding one should take into consideration this difference and check the parameters at the real conditions.
This concerns all of NDT devices and methods but especially of electromagnetic ones, when they are used for ferromagnetic objects.

Keywords: coating, corrosion, defects, electromagnetic, magnetic flux leakage, steel.

Introduction

Metrological assurance is actual problem for NDT applications, taking into consideration proper choice of the technology and instrument and the correct testing data interpretation. The problem becomes more significant in connection with transition from detection of defects to measurement of their dimensions. This trend is apparent for last decades. In the same time the metrology in NDT is rather specific because of large number of factors influencing the test data, for instance, the defect form and position, the object material characteristic, the instrument sensors location relative to the object and many others.

There are various methods to define the instrument (or technology) metrological characteristics. Some of them state in standards and norms. The others are used by the NDT instrument manufacturers only. But both of them are often not well known for the instrument users. The misunderstanding can arise in this case. This leads to the unfounded demands for the NDT instrument characteristics, e.g., for accuracy, limit of sensitivity, etc. The demands arise sometimes on the base of the characteristics usually are specified by calibration procedure for definite testing conditions like the object material homogeneity, its surface state, etc., but the real object under test condition differs from that one used by calibration or from that one stated in the instrument specification. The different metrological parameters exist in reality: ones are for instrument capability and others are for object inspections. The first ones stated (and certified) using definite methods and the others depend on testing conditions including object under test characteristics first of all. It can be said the first parameters are instrumental and the others are inspection ones. The difference between the parameters is shown below in respect to electromagnetic NDT. Real examples of the practice, mainly of steel wire rope inspection, are used for illustration.

Metrology in the NDT

Almost any NDT technology and instrument belongs to indirect methods and means of measurement. Even such methods as the magnetic particle or the liquid penetrants. However, the opinion exists that the instruments intended for flaw detection only are not the measuring tools and therefore don't need metrological assurance. But this approach is wrong because even set-on accuracy and stability of sensitivity limit (the detection threshold) must be defined. The flaw detection reliability must be evaluated also by the correct detection probability and the missing probability. Nevertheless, many NDT instrument users (and manufacturers) take into consideration only the sensitivity limit value without its stability evaluation as like as without evaluation of the flaw detection probability. The influence of the sensitivity limit instability on the flaw detection probability is not taken into account also. All of this leads to errors by the correct flaw detection and results in the unfounded user complaints to the instruments.

The limit of sensitivity of flaw detection is defined as the defect with minimal sizes which can be detected by an instrument. So, the less is the limit the better is the instrument's detectability. Note that term «sensitivity» is used often instead of «limit of sensitivity» or «sensitivity limit». This is incorrect because the term «sensitivity» means a differential value which results as relation of output difference to the measurable value difference.

Decision about presence or absence of a defect is made most often subjectively by an operator at present. He does it on the base of a visual image of the object under test (visual, X-ray, magnetic particle and penetration methods) or on a virtual image (ultrasonic, electromagnetic, eddy current methods). In any case the operator's decision depends on not only defect characteristics but on noise character and its level also. The noise level and its other characteristics (periodicity, spectrum) are a function of the object under test condition as like as of the type and parameters of the instrument. The effect of environment can be the source of the noise too. For instance, pickup by industrial electromagnetic fields, but mostly their influence is suppressed by standard methods like shielding and filtering. One more source of the noise is the own noise of the instrument electronic circuits, sensors, etc. But it is usually significantly less than the noise connected with the object.

The noise at NDT is various. Most often it is random but it can be regular or quasi regular also. The random noise connected with the object of NDT has one very important feature: its realization repeats at each object scan. That means the noise correlates with a signal. So it is not possible to use standard methods of signal detection under noisy conditions (like radar methods) if decorrelation is not used.

The noise level evaluation may be done by different approach:

- Peak-to-peak value within definite scan interval;
- Noise power at the interval.

Of course, an operator uses various criteria for defect detection, not only signal-to-noise ratio. But this criterion is the main usually. It is dramatically important for automatic detection (by special software), e.g. in the monitoring system of NDT.

The reference samples are usually used for the NDT instruments metrological parameters assessment and for their calibration. The reference samples are made from a part of the object under test or it's analog. Imitators, simulating the object under test, are used also, especially when the standard of the object part is not available or too complicate. In any case both types of the reference sample must be certified by means of metrological assurance approach. The piece of steel rope with artificial flaws, which is cut off from the rope under test, is an example of the reference sample. The imitator of the rope consisting of the steel rods bundle is another example. Both of them are used for evaluation of metrological parameters of steel rope flaw detectors and for their calibration [(1)].

Similar approach is used in ultrasonic and eddy current NDT. The wire reference sample is used for the sensitivity limit in X-ray technology. In this case the term «sensitivity» is used instead of «sensitivity limit».

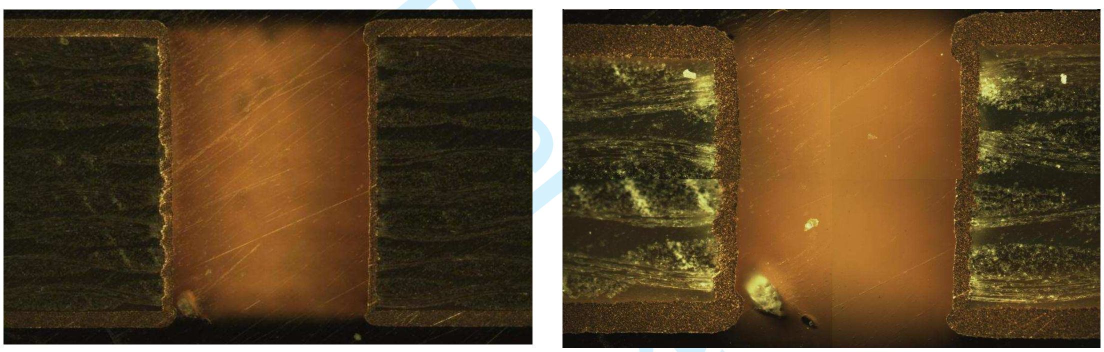
It is very important that all these reference samples and imitators meet definite requirements reproducing some object under test as close as possible. Evaluation of the instrument metrological parameters is the sharp estimate in this case. Hence if one uses the instrument for NDT of other objects with different features he must pay attention to this. If not, the parameters can differ and testing results can be incorrect. For instance, the sensitivity limit of an ultrasonic flaw detector, evaluated by means of ferrous steel smooth-faced reference sample, is significantly higher (that is worse) when the detector is used for testing of a cast iron object with rough surface. This is well known for the NDT experts but often not for wide circle of users. There are situations when the difference in features of an object under test and a calibration standard is not so significant but even this has influence on testing data. Thus, even the light difference in chemical composition of ferrous steel objects from the same of a calibration standard can leads to errors by the electromagnetic sorting of the object into groups with different thermal processing. This difference may be so light that it meets requirements to a definite steel grade. To overcome this problem one must use the calibration standard made from the same melt like the objects under test. Similar problem arises by the object grade steel sorting. To avoid possible errors one should take calibration standards from definite grade steel objects with identical structure. The normalizing of all objects and calibration standards is used for this usually.

The cited examples illustrate variety of reference samples and imitators used for instrument specification and calibration in different conditions. Most important metrological parameters are defined by the reference samples certified by the instrument producer or by the national metrology and standardization organization.

The reference samples present the most typical test objects usually. They must be reproducible and certifiable. Requirements for the reference samples are contained in the various norms, manuals, recommendations. Usually the reference samples (or standards) allow to check only main metrological parameters in absentia of disturbances. It should be taken into consideration in order to prevent the dramatic error while the instrument application. Evidently the sensitivity limit as the most important parameter of a flaw detector will be evaluated incorrectly because of its dependence on a noise level. It would be correct to say the sensitivity limit as the instrumental feature is specified with no regard to disturbance factors influence only, but not as the inspection (or testing) parameter.

The all above mentioned reasoning relates to the imitators too, to an even grater degree since the imitators have more simple structure then the test objects, and some influencing factors of real test condition can be missed.

Let us consider the metrological assurance of the eddy current thickness meter INTROMET as an example [(2)]. The gauge is designed for measurement of copper coating thickness and its integrity inspection inside through holes of printed circuit board (PCB). The hole diameter is (0,4-2,0)mm, the coating layer thickness is about 25 mcm, PCB thickness is (1-2,5) mm.(Figure1) shows the microsection of the hole along its axis.



a) b)

Figure 1. Microsection of the PCB's 1.1 mm diameter through hole with copper coating inside: a) overview; b) four zones of the section adjacent to PCB's surfaces composed in one picture and enlarged 2.5 times to picture (a). Maximal and minimal values of coating differ each other more than five times, standard deviation is 14%

The above mentioned technology is not simple and not cheap. That is why it is used for instrument certification. Nevertheless, real test object can differ from the imitator by the specific conductivity, by the form and size of contact pads.

Another example of the imitator is used to calibrate or to check the MFL steel rope flaw detector. It consists of a parallel steel wires assembled in a bundle. Of course the imitator doesn't reproduce the periodical structure of the strand rope; therefore it doesn't produce the periodical noise, typical for the strand ropes.

The more simple imitators are used to calibrate or check working capacity of an instrument. Thus, a copper plate with a hole in it is used to check the working capacity of the INTROMET. The hole diameter and the plate thickness are the same as in a PCB under test. But other parameters of the imitator, including the specific conductivity, roughness of the wall surface in the hole, etc. are different. So, the imitator allows to check the working capacity and only one point of the measurand.

The similar approach us used for checking of the MFL steel rope flaw detectors when one add a piece of steel wire to a rope under test encircled by a magnetic head. One point of measurand – loss of metallic area (LMA) can be checked in this case [(3)]. It is possible to check roughly the signal corresponding to one wire broken. But this approach doesn't allow to estimate the main parameter of the instrument – the sensitivity limit, because the magnetic head doesn't move along a rope and noise connected with rope structure and inhomogeneity is absent.

Metrological assurance in the electromagnetic (EM) and magnetic flux leakage (MFL) technology

Metrology in the EM and MFL technology has some specific features in addition to those ones relevant to the most of other NDT technologies. Take notice that the EM method is considered for NDT of ferrous objects only. Let us consider some of the features.

The most important feature of the EM and MFL technology of ferrous objects is the strong effect of the material magnetic characteristics on testing data. The output signal of sensor used in the EM and MFL instruments depends on the magnetic permeability μ strongly and the μ depends by-turn on the exciting magnetic field strength nonlinearly. Therefore the magnetizing condition effects on the sensor output data strongly. In addition it should be taken in consideration that the current magnetic condition depends on the magnetic prehistory of material because of magnetic hysteresis. As it is known, the magnetic condition is under influence of temperature, mechanical stress, chemical transformations, steel structure, time. Consequently, many disturbing factors appears while testing. For example, a local heating or bending of a steel rope produce the relevant μ change and causes a noise by the MFL testing. The same relates to EM testing of steel ropes or tubes.

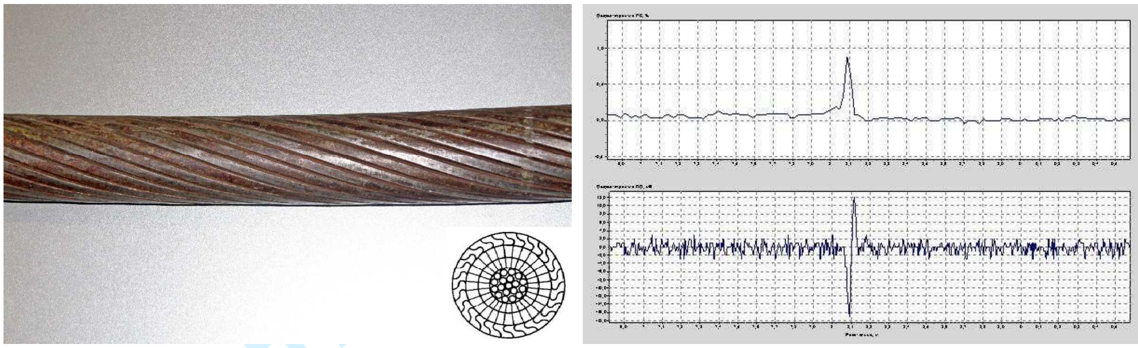
Various methods are used to minimize influence of the disturbing factors. Thus, magnetic saturation of a ferrous material is used to decrease magnetic inhomogeneity by MFL technology. The magnetic saturation allows also to reduce the measurement error generated by magnetic hysteresis. For example, by the measurement of the object like rope or tube cross section area [(4)].

By the EM testing the preliminary demagnetization is used as like as the steel structure normalization by thermal processing (if it is possible). Powerful magnetic systems with permanent magnets are used usually to provide magnetic saturation of a part of test object. But the weight and size of the magnetic system become rather large-scale when the area magnetized is large. For instance, the weight of the MFL testing head for steel rope (100-150) mm diameter testing is more 100 kg (more 200 kg with centering roller system) and size is about 1 m. And the MFL gauge for 508 mm diameter steel pipe testing (PIG – pipeline inspection gauge) weighs approximately 800 kg.

The large weight of PIG is not a problem by pipeline inspection, it is usual, but in case one has to test the 300 mm diameter suspended bridge rope this becomes a serious problem. One of the possible ways to overcome the difficulty is to use the EM technology. Then the large and heavy permanent magnets and magnetic core (often) are not required. The coil with alternating current encircles an object under test exciting the relatively weak alternating magnetic flux in the object. Of course, the noise because of the object magnetic inhomogeneities is more than by MFL technology with magnetic saturation, but its level can be acceptable sometimes. Besides, the disturbances because of «magnetic spots» (magnetized area) can be eliminated by the preliminary demagnetization as it mentioned above.

The approaches to metrological assurance of the MFL and EM flaw detectors are cited below. There are the groups of MFL (and EM) flaw detectors designed for the steel wire rope NDT. The rope construction and the cross section area are very different. But the instrument specifications state usually independently of this. For instance, the sensitivity limit for some MFL flaw detectors is declared like one broken wire. One wire cross section is to rope metal across section as (0.9 – 0.3) % and less. Some manufactures state the sensitivity limit like (0.1 – 0.05) % to meet the one wire sensitivity limit requirement. In reality this is impossible because of the noise mentioned above. This is possible if the parameter is defined by adding one wire to the rope fixed relative to the instrument magnetic head, that is without noise. Besides, the additional wire is located on a rope surface, but if it is inside the rope especially at its axis, the signal decreases. That is why one should be careful by evaluation of the real sensitivity limit. The same relates to the LMA measurement accuracy too. Statements of the outstanding instrument metrological parameters are most often an advertising matter.

The noise level depends on the type and the condition of the rope under test. The locked ropes produce the noise of the lowest (the best) level due to their smooth surface (Figure 2).



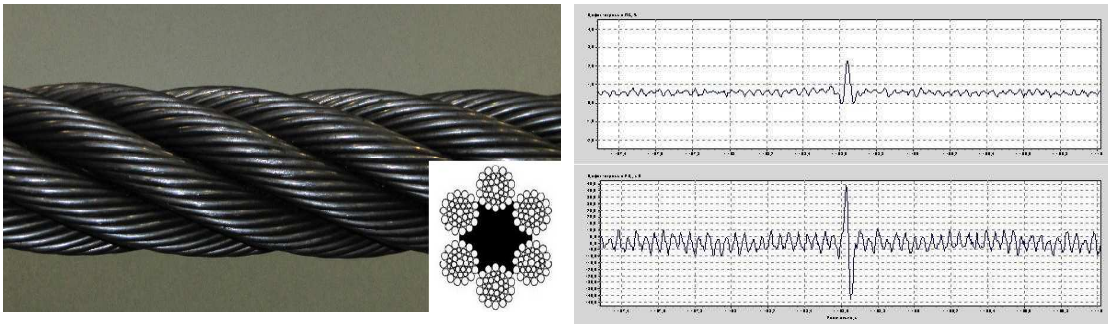
a) b)

Figure 2. (a) Locked rope and LMA and (b) LF traces for its part containing a broken wire

The wire of the locked rope have usually rather large relative cross section area. Therefore one broken wire can be detected certainly. Slightly higher (worse) is sensitivity limit by the spiral rope testing (Figure 3).

Figure 3. Spiral rope

And the highest (worst) sensitivity limit is by testing of the strand rope (Figure 4). Periodic component of the noise is induced by the strand structure of the rope in this case. The data comparison shows the best and the worst values of sensitivity limit which can differ each other several times. Evidently this should be taken into consideration by testing of a given rope.



a) b)

Figure 4. (a) Strand rope and (b) the traces for its part with a broken wire

Strictly speaking, the signal detection of a fault can be fulfilled with some probability as it is mentioned above. Such approach is conventional by «pigging» - the technology based on the PIG application for the pipeline testing. The sensitivity limit assigned as the artificial flaw of minimal sizes, which must be detected with a definite probability (0.95 usually) is the main metrological parameter of the PIG. The flaws of different shapes and sizes on the inside and outside pipe surface are certified by metrological service. However some ambiguity is possible even in this case because of the different pipe steel grades and the production technique. Particularly, the noise level of the hot-rolled pipe is significantly higher than for the welded pipe. Similar approach is used for metrological assurance of the MFL and EM technology of the steel tank floor inspection.

Unfortunately only a few standards and norms on EM and MFL technologies contain metrological requirements. There are three documents known regulating application of the EM and MFL technologies for steel rope NDT which concern metrological aspects reviewed shortly below. There exists the fourth document, the standard ISO 4309 on crane ropes [(5)]. But it doesn't contain not only metrological aspects but even considerable reference on NDT at all.

The ASTM Standard Practice [(1)] includes sections on reference standards; on limitations of the practice to the objects examination; on apparatus (instruments) used; on examination procedure. It should be noted that requirements of the practice for the wire rope reference standard enabled to reproduce real noise due to moving of the wire rope test-loop through an instrument sensor head. Of course, the noise corresponds to the current example of the rope and can differ from the noise of the rope under test.

Another document is the European Standard on safety of cableway installations [(6)]. It also contains requirements for testing procedure and its verification including performance tests for LD and LMA channels.

The tests are based on reference samples use also. Sample characteristics are described not so detail as in the ASTM practice, but there is procedure to check resolution capability (minimal distance between two successive wire brakes) of a flow detector. The procedure includes evaluation of the signal-to-noise ratio and method of the noise evaluation. Figure 5 illustrates this approach.

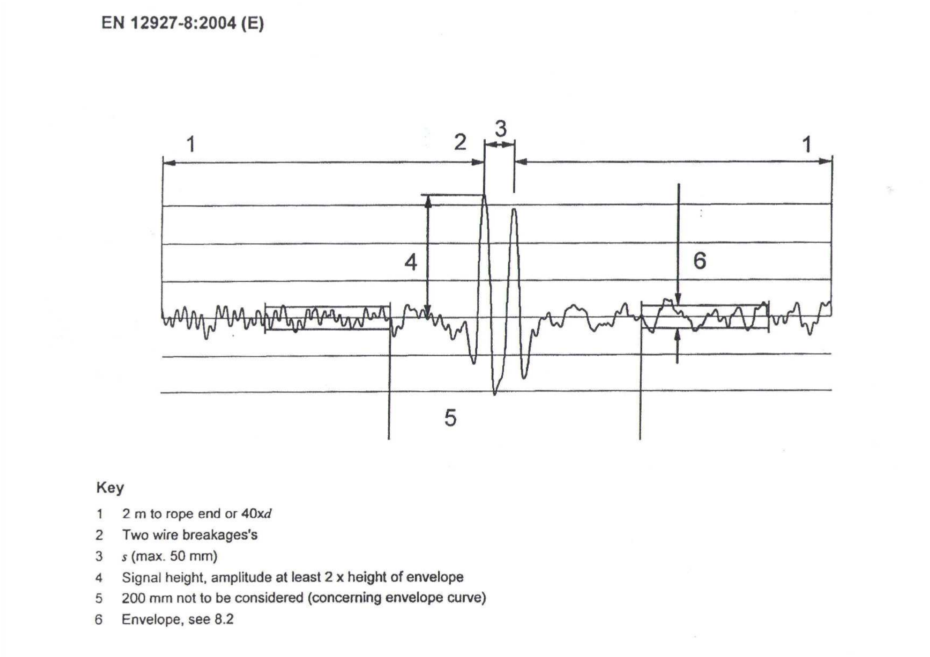


Figure 5. Trace of the LF performance test according to EN 12927 - 8

The noise level is characterized as envelope – "the distance of two parallel lines over the length of 25 times *d* on each side of the wire breaks, whereas in all no more than five peaks of signature cut the parallel lines". Here *d* is nominal rope diameter. Of course, the noise is inherent to given piece of rope and it can differ for a rope under test.

The Russian guideline on magnetic flaw detection of steel ropes is one more regulating document [(7)]. It contains detail instructions on testing procedure, reference samples and imitators, test data processing and interpreting. The norm is obligatory for all Russian owners of lifting constructions, which use ferrous wire steel ropes, and for inspection companies, examining the constructions like mine hoists, elevators, cranes, cableways, cable railroads.

The all three mentioned above norms and standards include requirements for inspection personnel. Two levels of skill are determined usually. The level 1 individual "is entitled to carry out MRT (magnetic rope testing) operations according to written instructions and under supervision of level 2 personnel" [5]. An individual of level 2 "is entitled to perform and direct NDT according to established or recognized procedures". Only he shall be competent to interpret and evaluate results, "understand MRT standards and specifications and translate them into practical testing instructions adopted to actual working conditions", calibrate equipment, etc. Thereby it is assumed the personnel engaged in MRT is skilled enough and understand difference between of the instrument used and real inspection parameters depending on working conditions. Unfortunately this is not always the fact. In particular such incorrect approach occurs fairly often if NDT technology used by personnel of companies for their own objects inspection.

Training of personnel for MRT is provided by manufacturers of relevant instruments. Russian norm [7] allows to perform MRT by personnel trained and assessed at organization licensed by The State Safety Supervising Body (GOSGORTECHNADZOR). The flaw detectors of steel wire ropes must be certified by The State Standardization Body (GOSSTANDART) as a measurement instrument and be included into The State Register of Measurement Instruments.

Russian company INTRON Plus, Ltd. trains and assessed the personnel for MRT according to the norms mentioned above for many years. The INTROS instrument designed and manufactured by the company is used to train personnel. Individual certified must be retrained and recertified each three years. He has to present materials conformed his practical experience within 3 years to be recertified. Due to this the company can control personnel skill and proper use of the instruments. During the retraining the personnel can get materials on MRT at various installations generalized company's experience. Company's personnel performs MRT too and its experts consult people on complicate cases of they practice.

Conclusion

Metrology in NDT is rather specific because measurements and evaluation of the object under test parameters are indirect and their results depend on the object's characteristics and condition. The instrument metrological parameters specified by manufacturers are valid for definite conditions only and cannot be transferred directly in the most cases of NDT practice. It is necessary to take in consideration effect of various disturbances because of influencing factors generating real noise. Metrological parameters of the real object's NDT are usually worse than instrument parameters. This is important especially by the magnetic and electromagnetic NDT of ferrous objects because of strong influence of test conditions, the object magnetic characteristics, and nonlinear dependence of magnetic permeability on exciting magnetic field.

Standards and norms regulating application of magnetic methods for steel wire ropes assist users in proper application of the technology. But further progress is needed in consideration of new achievements of the technology.

The proper personnel training makes it possible to provide the more correct evaluation of real metrological parameters by NDT technologies application.

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