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Metrology in Electromagnetic Nondestructive Testing: Correct Evaluation of Test Parameters

by V.V. Sukhorukov

Metrological assurance is an actual problem for nondestructive testing (NDT) applications, taking into consideration the proper choice of the relevant technology and instrument and the correct testing data interpretation. The problem becomes more significant in connection with the transition from detection of discontinuities to the measurement of their dimensions. This trend has been apparent over the last few decades. At the same time, metrology in NDT is rather specific because of a large number of factors influencing the test data, for instance, the discontinuity form and position, the object material characteristics, the instrument sensor location relative to the object, and many others.

There are various techniques used to define the instrument (or technology) metrological characteristics. Some of them are stated in standards and norms. Others are used by the NDT instrument manufacturers only. However, both of them are often not well known for the instrument users. Misunderstanding can arise in this case, which leads to unfounded demands for NDT instrument characteristics, for example, for accuracy, limit of sensitivity, and so on. The demands sometimes arise on the basis that the characteristics are usually specified by calibration procedure for definite testing conditions like the object material homogeneity, its surface state, and so on. But the real object under test conditions differs from that used by calibration or from that stated in the instrument specification. Different metrological parameters exist in reality: some are for instrument capability and others are for object inspections. The first ones stated (and certified) use reference standards and definite procedures, 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 for inspection. The difference between the parameters is shown as follows in respect to electromagnetic testing (ET). Real examples of the practice, mainly of steel wire rope inspection, are used for illustration.

Metrological Aspect of Discontinuity Detection

Almost every NDT technology and instrument belongs to indirect techniques and means of measurement, even such methods as magnetic particle testing (MT) or liquid penetrant testing (PT). However, the opinion exists that the instruments intended for discontinuity detection only are not the measuring tools and therefore do not need metrological assurance. But this approach is wrong because even set-on accuracy and stability of sensitivity limit (the detection threshold) must be defined quantitatively. Discontinuity detection reliability must also be evaluated 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, for example, without evaluation of discontinuity detection probability. The influence of the sensitivity limit instability on discontinuity detection probability is also not taken into account. All of this leads to errors by correct discontinuity detection and results in unfounded user complaints about the instruments.

The discontinuity detection limit of sensitivity is defined as the smallest discontinuity that can be detected by an instrument. So, the lower the limit the better the instrument's detectability. Note that the term "sensitivity" is often used instead of "limit of sensitivity" or "sensitivity limit." This is incorrect because the term "sensitivity" means a differential value that results as a relation of output difference to the measurable value difference.

At present, the decision about the presence or absence of a discontinuity is made most often subjectively by an operator. The operator decides on the basis of a visual image of the object under test (visual, X-ray, MT, and PT techniques) or on a virtual image (ultrasonic, electromagnetic, and eddy current techniques). In any case, the operator's decision depends on not only discontinuity characteristics but on noise character and also its level. The noise level and other characteristics (periodicity, spectrum) are a function of the object under test conditions such as the type and parameters of the instrument. The effect of environment can be the source of the noise too, for instance, picked up by industrial electromagnetic fields. However, their influence is mostly suppressed by standard techniques like shielding and filtering. One more source of noise is the noise of the instrument's own electronic circuits, sensors, and so on. But this is usually significantly less than the noise connected with the object.

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

Noise level evaluation may be done by different approaches: peak-to-peak value within definite scan interval; or noise power at the interval.

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

Standards, Imitators, and Reference Samples

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 its analog. Imitators, simulating the object under test, are also used, especially when the standard of the object part is not available or too complicated. A piece of steel rope with artificial discontinuities, which has been cut off from the rope under test, is an example of a reference sample. An imitation of the rope consisting of a bundle of steel rods is another example. Both are used for evaluation of metrological parameters of steel rope discontinuity detectors and for their calibration (ASTM, 2011).

A similar approach is used in ultrasonic testing and eddy current testing. A wire reference sample is used for the sensitivity limit evaluation 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 closely as possible. Evaluation of the instrument metrological parameters is the critical estimate in this case. Hence, if using the instrument for NDT of other objects with different features, one must pay attention to this. If not, the parameter evaluation can differ and testing results can be incorrect. For instance, the sensitivity limit of an ultrasonic discontinuity detector, evaluated by means of a smooth-faced ferrous steel reference sample, is significantly higher (that is, worse) when the detector is used for testing of a cast iron object with a rough surface. This is well known by NDT experts but often not for a wide circle of users.

There are situations when the difference in the features of an object under test and a reference sample are not so significant, but even this has an influence on testing data. Thus, even the slight difference between the chemical composition of ferrous steel objects and a reference sample can lead to errors by the electromagnetic sorting of the objects into groups with different thermal processing. This difference may be so slight that it meets requirements to a definite steel grade. To overcome this problem one must use the reference sample made from the same melt as the objects under test. A similar problem arises by the object grade steel sorting. To avoid possible errors one should take reference samples from definite grade steel objects with identical structures. The normalizing of all objects and reference samples is usually used for this.

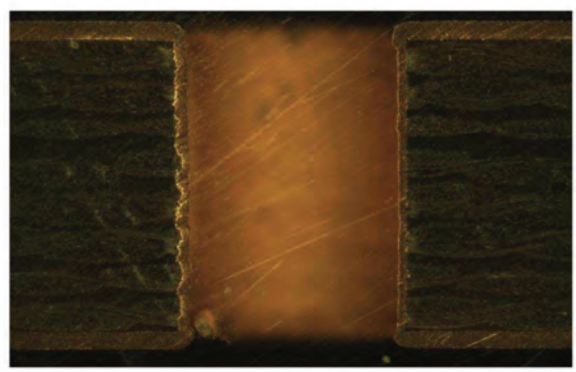
The cited examples illustrate a variety of reference samples and imitators used for instrument specification and calibration under different conditions. The most important metrological parameters are defined by the reference samples certified as the reference standards by the instrument producer or by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

Reference samples usually present the most typical test objects. They must be reproducible and certifiable. Requirements for them are contained in the various norms, manuals, and guidance. Usually, the reference samples (or standards) allow for checking only the main metrological parameters in the absence of disturbances. This should be taken into consideration in order to prevent dramatic error during instrument application. Evidently, the sensitivity limit as the most important parameter of a discontinuity detector will likely be evaluated incorrectly because of its dependence on noise level. It would be correct to say the sensitivity limit as the instrumental feature is specified with no regard to disturbance factor influence only, but not as the inspection (or testing) parameter. Accordingly, the metrological parameter evaluated with no disturbance factor influence should be chosen as the instrumental one and the parameter evaluated with the influence should be chosen as the inspection (or testing) one. Many different values for the inspection parameter can exist when an instrument with a definite instrumental parameter is used for different NDT objects (and/or at different testing conditions).

All of the aforementioned also relates to the imitation samples, and even more so, since they usually have simpler structure than the test objects, and some influencing factors of real test conditions can be missed.

Consider the metrological assurance of an eddy current thickness meter as an example. The gage was designed for measurement of copper coating thickness and its integrity inspection inside through-holes of printed circuit board (PCB). The hole diameter was 0.4 to 2.0 mm (0.02 to 0.08 in.), the coating layer thickness was approximately 25 µm (0.001 in), and the PCB thickness was 1 to 2.5 mm (0.04 to 0.1 in.). Figure 1 shows a micro-section of the hole along its axis.

Micro-section technology is neither simple nor cheap. Besides, it does not produce reproducible samples because it is a destructive technique. That is why it is used for instrument testing data verification only. Simpler and cheaper imitation samples are used to calibrate or check the working capacity of an instrument. Thus, a copper plate with a hole in it was used to check the working capacity. The hole diameter and


(a)

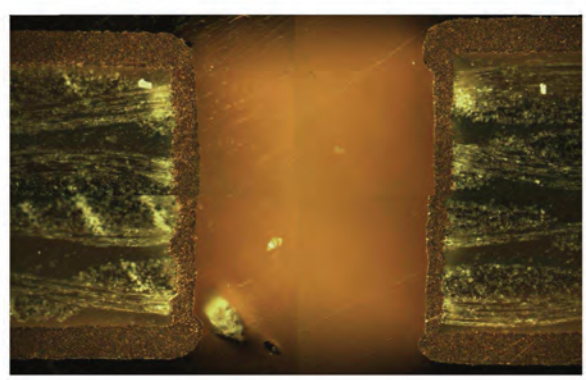

(b)

Figure 1. Micro-section of the printed circuit board's (PCB) 1.1 mm (0.4 in.) diameter through-hole with copper coating inside: (a) overview; and (b) four zones of the section adjacent to the PCB's surfaces composed in one picture and enlarged 2.5× to Figure 1a. The maximum and minimum values of coating thickness differ from each other by more than five times; standard deviation is 14%.

Metrology used in ET and magnetic flux leakage testing (MFL) technology has some specific features in addition to those relevant to most other NDT technologies.

plate thickness were the same as in the PCB under test. But other parameters of the imitator, including the specific conductivity, roughness of the wall surface in the hole, and so on, were different. So, the imitation sample allowed for checking the working capacity and only one point of the measurand.

Another example of the imitation sample was used to calibrate or check a magnetic flux leakage (MFL) steel rope discontinuity detector. It consisted of parallel steel wires assembled in a bundle. Of course the imitation did not reproduce the periodic structure of the strand rope; therefore, it did not produce the periodical noise typical for strand ropes.

A similar approach was used for checking MFL steel rope discontinuity detectors, when a piece of steel wire was added to a rope under test encircled by a magnetic head. One point of the measurand—loss of metallic area (LMA)—could be checked in this case (Golosinski et al., 1998). It was possible to roughly check the signal corresponding to one broken wire. However, this approach did not allow for estimating the main parameter of the instrument—the sensitivity limit—because the magnetic head did not move along a rope and noise connected to the rope structure and inhomogeneity was absent.

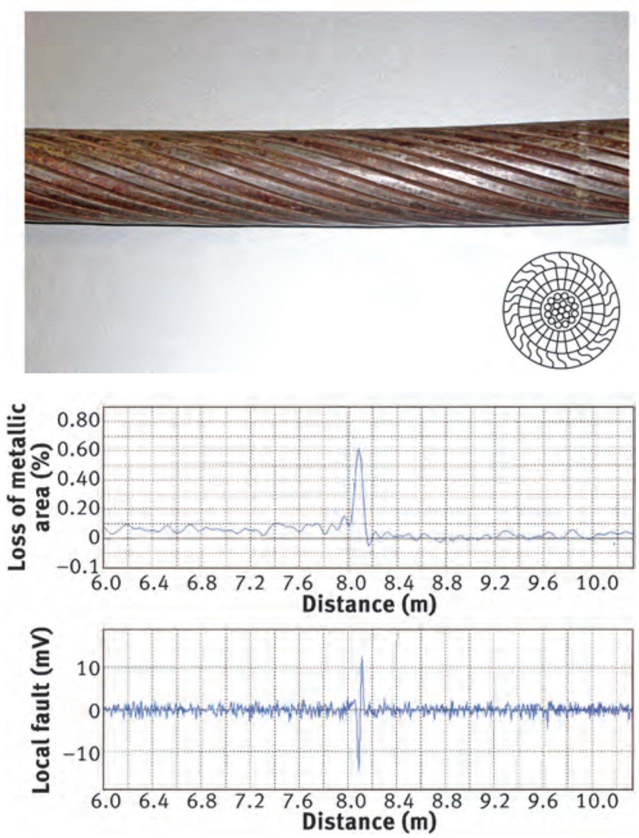


Figure 2. Locked rope: (a) view and cross-section; (b) loss of metallic area traces; and (c) local fault traces for rope part containing a broken wire (by the magnetic flux leakage inspection instrument).

Metrological Assurance by Magnetic Flux Leakage Technology of Steel Rope Nondestructive Testing

Metrology used in ET and MFL testing technology has some specific features in addition to those relevant to most other NDT technologies. Notice that ET is used for NDT of ferrous objects only, and consider some of the features.

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

Various techniques are used to minimize the influence of disturbing factors. Thus, magnetic saturation of a ferrous material is used to decrease the magnetic inhomogeneity by MFL technology. The magnetic saturation also allows for reduction of the measurement error generated by magnetic hysteresis, for example, by measurement of the object like a rope or tube cross-section area (Sukhorukov, 2013).

Some examples of the considered approaches to the metrological assurance of steel rope MFL technology are cited in the following.

The rope construction and cross-section area are very different. However, the instrument specifications are usually stated independently of this. For instance, the sensitivity limit for some MFL discontinuity detectors is expressed relative to one broken wire. One wire cross-section is to rope metal cross-section as 0.9 to 0.3% and less. Some manufacturers state the sensitivity limit as 0.1 to 0.05% to meet the one wire sensitivity limit requirement. Such values define the instrument parameters. In reality this is impossible because of the noise mentioned earlier. 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 the rope surface, but when it is inside the rope, especially at its axis, the signal decreases. That is why one should be careful when evaluating the real inspection sensitivity limit. The same also relates to LMA measurement accuracy. Statements of the outstanding instrument metrological parameters are most often an advertising matter only.

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

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

The highest (worst) sensitivity limit is by testing of strand rope (Figure 4). The periodic component of the noise is induced by the strand structure of the rope in this case. Figure 2b and Figure 4b trace comparison shows the best and worst values for the sensitivity limit. Note that they can differ from each other. Evidently, this should be taken into consideration during rope testing practice.

Strictly speaking, the signal detection of a fault can be fulfilled with some probability, as previously mentioned. Such an approach is conventionally done by "pigging"—the technology based on the pipeline inspection gage (PIG) application for pipeline testing. The sensitivity limit assigned as the artificial discontinuity of minimal sizes, which must be detected with a definite probability (usually 0.95), is the main metrological parameter of the PIG. Discontinuities 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

Figure 3. Spiral rope.

(a)

(b)

(c)

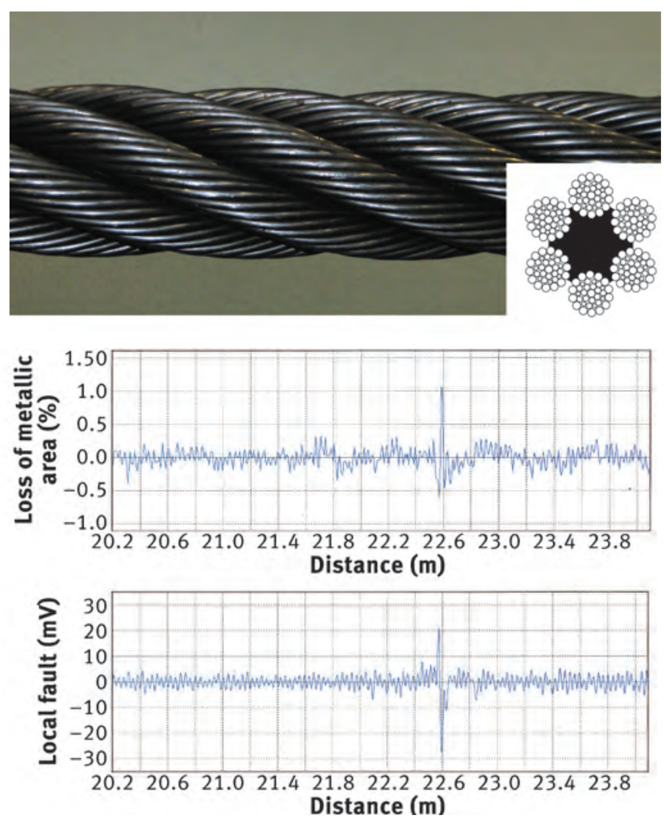


Figure 4. Strand rope: (a) view and cross-section; and (b) loss of metallic area traces; and (c) local fault traces for rope part containing a broken wire (by the magnetic flux leakage inspection instrument).

the hot-rolled pipe is significantly higher than for the welded pipe. A similar approach is used for metrological assurance of MFL and ET technology for steel tank floor inspection.

Unfortunately, only a few standards and norms on ET and MFL technologies for steel rope NDT contain metrological requirements. The three known documents regulating application of ET and MFL technologies that concern metrological aspects are reviewed briefly as follows.

The ASTM International standard practice includes sections on: reference standards, limitations of the practice to the object's examination, apparatuses (instruments) used, and examination procedure (ASTM, 2011). It should be noted that requirements of the practice for the wire rope reference standard enable the reproduction of real noise due to movement of the wire rope test loop through an instrument sensor head. It should also be noted that the wire rope reference standard practice requires that it reproduce real noise, such as that caused by movement 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 *EN 12927-8:2004* on safety of cableway installations (BSI, 2004). It also contains requirements for testing procedure and its verification including performance tests for the local fault and LMA channels.

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

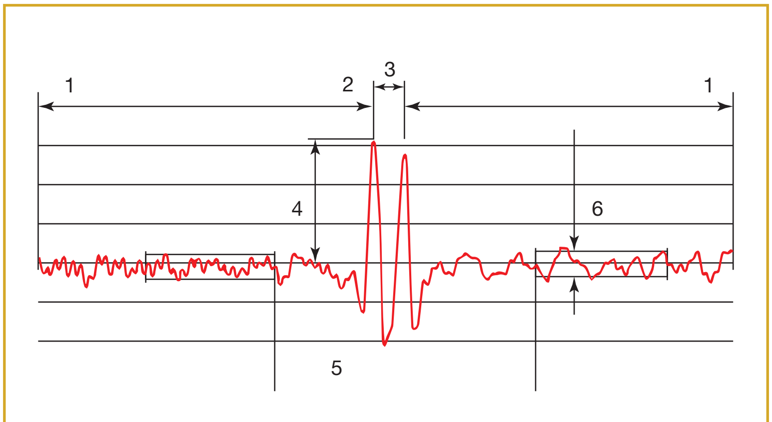


Figure 5. Trace of local fault performance test according to *EN 12927-8*. 1 = 2 m (6.56 ft) to rope end or 40 × *d*; 2 = two wire breakages; 3 = *s* (maximum 50 mm [1.97 in.]); 4 = signal height, amplitude at least 2× height of envelope; 5 = 200 mm (7.87 in.) not to be considered concerning envelope curve; and 6 = envelope.

The noise level is characterized as an 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" (BSI, 2004). 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 discontinuity detection of steel ropes is one more regulating document (Gosgortechnadzor, 2000). It contains detailed instructions on testing procedure, reference samples and imitators, and test data processing and interpreting. The norm is obligatory for all Russian owners of lifting constructions that use ferrous wire steel ropes, and for inspection companies examining constructions like mine hoists, elevators, cranes, cableways, and cable railroads.

All three of the aforementioned norms and standards include requirements for inspection personnel. Two levels of skill are usually determined. 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" (BSI, 2004). An individual of Level 2 "is entitled to perform and direct NDT according to established or recognized procedures" (BSI, 2004). Only a Level 2 is competent enough to interpret and evaluate results, "understand MRT standards and specifications and translate them into practical testing instructions adapted to actual working conditions," calibrate equipment, and so on (BSI, 2004). Therefore, it is assumed that the personnel engaged in MRT is skilled enough and understands the difference between the instrument and real inspection parameters depending on working conditions. Unfortunately this is not always the case. In particular, such an incorrect approach occurs fairly often if NDT technology is used by the personnel of companies for their own object inspections.

Training of personnel for MRT is provided by the manufacturers of the relevant instruments. Russian norms allow for performing MRT by personnel trained and assessed at organizations licensed by the State Safety Supervising Body (Gosgortechnadzor). Discontinuity detectors of steel wire ropes must be certified by the State Standardization Body (Gosstandart) as a measurement instrument and be included in the State Register of Measurement Instruments.

Conclusion

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

What follows are two main recommendations for the correct evaluation of the real inspection metrological parameters by a calibration procedure:

- Use sections of real objects under test (or close to one) as reference standards.
- Approximate the testing conditions as closely as possible to the real ones. Try to reproduce the influence of disturbing factors. Use a dynamic (not static) regime by the procedure if the real NDT must be dynamic (as with rope and tube NDT).

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

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

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