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Non-Destructive Testing of Structures Using Optical and Other Methods: A Review

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Abstract: Non-destructive testing (NDT) of structures is one of the most important tasks of the proper maintenance and diagnosis of machines and constructions structural condition. NDT methods contribute to the damage tolerance philosophy used in the aircraft design methodology as well as many other operation and maintenance programs of machinery and constructions. The following study is focusing on overviewing an important group of NDT methods: the optical and other ones, which found broad applicability in scientific and industrial studies nowadays. The paper discusses the selected most widely applicable methods, namely, visual testing, ultrasonic testing, radiographic testing, infrared thermography as well as electronic speckle pattern interferometry and shearographic testing. Besides the basic principles of testing using these methods, their potential applications in various industrial and technological branches are broadly discussed. The analysis as categorization of the NDT methods provided in this paper may help in selection of such methods in diagnosis of various types of structures and defects and damage occurring in these structures.

Keywords: Non-destructive testing, optical NDT methods, testing of structures, damage identification.

1 Introduction

Non-destructive testing (NDT) of structures is related to the examination of materials, components or systems for characterization or finding defects and flaws in contrary to standards without harming of the object being tested or altering the original attributes. These methods contribute to the damage tolerance philosophy in the aircraft design methodology, which states that defects should sustain until repair or replacement of the component can be affected [Vogelesang and Vlot (2000)]. This viewpoint is used in the other fields of industries, e.g. wind power, civil, automotive, and relates to condition-based maintenance (CBM). The purpose of CBM is to monitor the actual condition of the asset to decide, what maintenance should be performed. Moreover, the task of this philosophy is a reduction of maintenance costs, operational safety improvement as well as reduction of quantity and severity of in-service system failures. For now, it is the most widely used strategy in wind power industry, where turbine blades are achieved by scheduled preservation in order to detect incipient faults early, and afterwards determine

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appropriate maintenance task, which is repair or replacement of a damaged part [Besnard (2010); Márquez, Tobias and Pérez (2012)].

The following study is focusing on overviewing an important group of NDT methods: the optical and non-optical ones, which found broad applicability in scientific and industrial studies of structures nowadays. The paper discusses the selected most widely applicable methods, namely, visual testing, ultrasonic testing, radiographic testing, infrared thermography as well as electronic speckle pattern interferometry and shearographic testing. Besides the basic principles, advantages and limitations of testing using these methods, their potential applications in various industrial and technological branches are broadly discussed. Then, the described and presented NDT methods are compared with each other and relevant conclusions are depicted. The analysis as categorization of the NDT methods provided in this paper may help in selection of such methods in diagnosis of various types of structures and defects and damage occurring in these structures.

2 Visual testing

Visual testing (VT) is the most widely used NDT method performed with unaided eye or using simple low-cost devices, which allow to detect surface defects as well as access difficulty accessible surfaces of a structure. Due to its simplicity, it is robust and the cheapest NDT method. A quick process of VT is the biggest advantage in contrary to other NDT methods [Gholizadeh (2016)]. In almost all industries it is used as an initial testing approach [Mix (2005)]. During the ground service in aircraft industry, where timing is crucial factor, visual inspection is used in 80% cases [Katunin (2015); Bossi and Giurgiutiu (2015] of all non-destructive tests. Moreover, in several applications it can be automated by using cameras, which scans a structure autonomously.

Inspection carried out by VT must take place in a clean and comfortable environment with adequate lighting, which is a crucial factor [International Atomic Energy Agency (1999)]. Natural daylight is the best type, but in many cases inspection can be handled by using artificial lighting. Tested component should be clean, free of dirt, protective coatings, because it can lead to oversights of discontinuities. Then, experience of the operator has great importance as much as the good eyesight [British Institute of Non-Destructive Testing (2016)]. VT can be divided for several viewing techniques. The first one is direct viewing, where operator has direct access and immediate presence of inspected component. The second one is called remote viewing, carried out by using special equipment, i.e. hand-held lenses, measuring magnifiers, microscopes, rigid borescopes, endoscopes or miniature video cameras [Katunin (2015)].

Exemplary application of VT is an inspection of coatings [Bortak (2002)] and seals by video borescope to localize corrosion, pitting or weld roots. Masonry arch railway bridges are inspected by borescope as well. Rotary drill makes boreholes perpendicular to the arch surface and moves into borescopes [Orbán and Gutermann (2009)]. Moreover, hardly accessible areas of the fuselage in aerospace industry, where corrosion or fatigue crack can occur, are obtained by VT [Piascik and Willard (1997)]. The chemical industry uses this technique to test combustion, chambers, pressure vessels or furnaces [Inspection for Industry (2018)]. Nonetheless, VT is limited to detection of surface flaws e.g. porosity, corrosion, slag defects, ruptures, cracks and under-surface damage if the structure is transparent or semi-transparent [Katunin (2015)]. Moreover, VT does not provide precise outcomes which can be obtained by other methods, i.e. shearography, infrared thermography, ultrasonic, radiographic, magnetic testing.

3 Ultrasonic testing

Ultrasonic testing (UT) is NDT method based on beams of high frequency sound waves (typically in the range between 0.5 and 15 MHz) in order to detect and localize external and internal flaws. Commonly, it is also known as a pulse-echo and through transmission method, where the first one is more useful because of the one-sided access. UT is one of certified methods in inspection of aerospace composites structures [Garnier, Pastor and Eyma (2011)]. Moreover, this method is widely used for characterization of metal and alloys [Nesvijski (2000)]. Most of the equipment consists of receiver, which produces high voltage electrical pulses and transducer, which creates high frequency ultrasonic energy and display device, on which results are shown. Sound waves with some attenuation of energy, infiltrate tested material to detect flaws on its surface and sub-surface by reflecting them at interfaces. Subsequently, the beam is detected and after on analyzed to define location of flaws. If the wave locates the discontinuity in its path, it reflects from the flaw surface and then is turned into electric signal and is displayed on the screen. However, if it does not encounter a defect, it goes through the structure without obstacles [International Atomic Energy Agency (1999)]. The most available UT devices are based on liquid coupling [Katunin (2015)]. Nevertheless, plenty of specialized devices uses air coupling instead of liquid [Hillger (1994)].

Generally, in UT most common coupling mediums are mineral oil, gel or water, to enhance the transfer of sound energy to tested specimen. Moreover, depending on configuration of the transducers, couple of measurement techniques can be mentioned. The A-scan (Amplitude scan) is the method, where an echo magnitude is plotted with a transit time on a simple grid, where a vertical axis represents the amplitude and horizontal axis represents time. It allows for detection of an external and internal damage on a single line. Next is the B-scan, more advanced in contrary to the A-scan, commonly used with conventional flaw detectors and corrosion thickness gages, to plot the depth of reflectors with respect to their linear position. The A-scan is a projection of the B-scan with a reference to the vertical axis. Another presentation option is the C-scan. It is performed by moving a probe in planar coordinates. A two-dimensional presentation of data is performed as a top of planar view of a test piece, related to its graphic perspective to an X-ray image, where colors represent the gated signal amplitude or depth to each point in the test piece mapped in its position [Langenberg, Marklein and Mayer (2012)]. Modification of the C-scan provides the D-scan, which shows a cross-section of the test object perpendicular to the image obtained by the C-scan and perpendicular to the projection of the beam axis on the scanning surface in a form of a defect depth map. Afterwards is the S-scan, which refers to the sector scan. The collected data is displayed as the B-scan image, where an angular segment covered by the beam is presented [British Institute of Non-Destructive Testing (2016)] due to its high accuracy and instantaneous result.

UT is used in all major industries, e.g. in automotive industry to inspect adhesive bonds between thin metal sheets [Goglio and Rossetto (1999)] or welded joints [Athi, Wylie and Cullen (2009)]. Aerospace industry uses it to inspect condition of CFRP structures [Stone and Clarke (1975); Meola, Boccardi, Carlomagno et al. (2015)], for example aircraft antenna radomes [Shin, Park, Hong et al. (2017)], and others. UT effectively evaluates defects in high-speed railway wheels made of different types of steel [Salzburger, Schuppmann and Li (2009)]. Maritime industry uses UT for quality control after manual welding in order to find voids, inclusions, defects [Ditchburn, Burke and Scala (1996); Sifa and Endramanaw (2017)]. Moreover, by using Lamb waves, it is possible to monitor entire tested structures [Cawley and Alleyene (1996); Katunin (2015)].

As every NDT method, UT also has limitations. First, rough, curved and irregular in shape materials are difficult to inspect. Subsequently, linear defects which are parallel to sound beam, cannot be identified by sound wave. Additionally, coarse grained materials and cast iron due to low sound transmission and signal noise, are difficult to inspect using UT. Moreover, UT must be combined with the surface by a coupling medium to stimulate the transfer of waves to tested material.

4 Radiographic testing

Radiographic testing (RT) together with UT belongs to the group of volumetric NDT methods. It is based on the short wavelength electromagnetic radiation in order to penetrate a structure of the material. A tested part is placed between the radiation source and the radiation sensitive film. Typically for the radiation source following isotopes are used: Ir-192, Co-60, less Ra-226 and Cs-137 [Katunin (2015)]. Due to the disparity in absorption, density or thickness, the inspected part absorbs various amounts of the penetrating radiation. Thicker and more dense regions stop some X-rays or Gamma-rays, while in the thinner one they pass through. Radiation which passes through the material is exposed on the film, plate or photosensitive paper, which creates the shadowgraph. Darker areas indicate more exposure, which means higher intensity. In sequence, lighter areas mean lower exposure and consequently less radiation intensity. RT visualizes all defects in detail together with internal structures without necessity of pre-arrangement of tested parts [International Atomic Energy Agency (1999)]. Furthermore, it is very sensitive method, which is used to inspect hidden areas, since a direct access is not necessary in contrary to UT.

Nonetheless, RT has several disadvantages, e.g. hazard associated with radiation in old radiographic devices high cost of testing equipment, time-absorbing process due to its long duration of exposure. Moreover, depth of discontinuities is not measured and testing requires two-sided access to the component. RT remains insensitive if a direction of a damage is the same as the direction of penetrated radiation. The polymer matrix composite materials are weakly penetrated by some radioactive isotopes. Furthermore, due to the lack of changes in density, RT is not able to detect delamination. Thus, in aircraft inspection RT is not a common method. Nevertheless, these limitations can be overcomed by using special X-rays absorbent liquids, which allow to enhance a contrast between health and damaged regions of a tested structure [Baniukiewicz, Chady and Sikora (2014)].

Applicability of RT method includes various industry segments, e.g. medicine, security, art, automotive, ship-building, aircraft, etc. In medicine it is used for imaging condition of a human skeleton e.g. to see hallux valgus [Lee, Ahn, Chung et al. (2012)] or femur [Gamage, Xie, Delmas et al. (2010)]. RT is used to inspect condition of pipelines, e.g. under deep water offshore gas and oil pipelines [Moreira, Rabello, Pereira et al. (2010)]. It works well in verification of cargo containers [Tuszynski, Briggs and Kaufhold (2013)], in detecting smuggled nuclear materials like uranium [Gaukler, Li, Cannaday et al. (2011)]. Afterwards, parts manufactured by using die-casting are tested by RT for gas porosity in order to detect places with trapped gas [Hernández-Ortega, Zamora and López (2013)]. In civil engineering it can be used to study the effect of heat-driven water transport in bentonite-bonded molding sand [Schiebel, Jordan, Kaestner et al. (2018)]. RT is a common method in the field of cultural heritage, for conservation and for investigation as well [Impallaria, Evangelisti and Petrucci (2016)]. Moreover, it can be applied to determine characteristics as shape, material composition, structural integrity of car engines, thin plates in automotive industry [Hartman and Barzilov (2016); Kim, Kim and Kim (2014)] as well as condition of welded joints [Liao (1996, 1998)].

An improved version of a conventional RT method is X-ray Computed Tomography (CT), which provides a 3D image as a result of testing of a structure with a very high resolution. This 3D image is produced by two general steps. Firstly, collecting 2D cross-sections of the tested structure and afterwards reconstruction of them to 3D image. These 2D cross-sections are obtained by performing the scanning of a structure as the rotary table rotates around its axis, while X -ray source and detector remain stationary. There is also another solution, in which the tested element is stationary and the source-detector rotates around this element. Collimated X-ray bay passes through an element and is received by an array of the detectors on the opposite side.

The main strength of X-ray CT is a capability of volumetric representation of a tested element. Subsequently, a very high resolution of volumetric scans, which are obtained by some novel devices and techniques, e.g. nCT, µCT, ICT, allows the detection of meso-scale damage as well as the evaluation of the internal architecture of a structure even in a nano-scale. Their accuracy was already proven in several research papers [De Chiffre, Carmignato, Kruth et al. (2014); Carmignato (2012)].

Nevertheless, very high cost of inspection and limitations to laboratory conditions are crucial drawbacks for this technique. Moreover, there is no accepted test procedures and standards as well as results are often not traceable [De Chiffre, Carmignato, Kruth et al. (2014)].

The X-ray CT is applicable to evaluate delamination factors in CFRP laminates, woven glass reinforced polyamides [Kourra, Warnett, Attridge et al. (2015); Pomarède, Meraghni and Peltier (2018)]. Additionally, casting defects of aluminum parts are determined effectively [Li, Oberdorfer and Habe (2018)]. Its accuracy was already proven accuracy in aerospace and automotive industry during inspection of aircraft wings, turbine blades, manifolds or cast aluminum cylinders [De Chiffre, Carmignato, Kruth et al. (2014); Carmignato (2012)].

5 Infrared thermography

Infrared Thermography (IRT) is a method of obtaining an image of the heat distribution over the surface of an object. It gained popularity is due to its effectiveness, low cost and ability of performing in-field tests. IRT can be used to assess, predict the structure or behavior beneath the surface by measuring the distribution of infrared radiation and afterwards converting the measurements into a temperature scale caused by materials heat emission [Katunin (2015)] In the case of defect in tested structure, a thermal conductivity in these areas is different in contrary to healthy regions, which results in a local change of temperature in these regions.

Commonly, it uses a special camera together with an infrared sensitive IR (bolometric) detector and lens, which transmits infrared radiation.

Heat emitted by a tested element is captured by the optical system and proceeds it to detector, where is digitized and, as a result, a thermogram of a tested specimen is obtained. Such cameras can operate at normal video rates. Temperature variations in the subject are then displayed as shades of grey or can be converted into pseudo-color image [Hung, Chen, Ng et al. (2009)]. Temperature variations as small as 0.1°C can be detected. Thermographic images can also be obtained by coating the specimen surface with heat-sensitive (cholesteric) liquid crystals before applying the heat source to the opposite site. The IRT can be divided into two subgroups: passive (PIT) and active (AIT). PIT is commonly used for qualitative inspection to pinpoint the anomalies e.g. to analyze the heat distribution in hot objects such as furnace walls, insulated structures, electronic circuits. Nevertheless, abnormal temperature profiles indicate suspicious problem. Due to PIT limitation, AIT was developed to provide more accurate information by considering the amount of heat transfer and thermal radiation. A pulsed source of heat is put on one side of a specimen and the other side is examined for non-uniformities in infrared emission, which would correspond to internal inhomogeneities or large flaws. Moreover, AIT can be divided to next subgroup as follows: transient pulse, step heating, periodic heating (lock-in) and thermal mechanical vibration.

According to research papers, several more IRT methods can be distinguished, e.g. pulsed thermography [Fernandez, Ibarra-Castanedo, Zhang et al. (2015)], vibrothermography (ultrasound) [Fierro, Ginzburg, Ciampa et al. (2017); Balageas, Maldagne and Burleigh (2016)], line scan thermography [Khodayer, Lopez and Moldague (2018)], amplitude modulated thermography [Wu and Peters (2015)], square pulsed thermography [Zhang, Sfarra, Sarasimi et al. (2018)], high speed thermography [Wang, Dulieu-Barton and Thomsen (2015)], transmission thermography [Li, Sun, Tao et al. (2018)].

Applications of IRT covers a wide variety fields of industry. For example, in aerospace industry is used to evaluate condition of CFRP [Fernandes, Ibarra-Castanedo, Zhang et al. (2015); Ishikawa and Koyama (2018)], complex composite stiffener panels [Fierro, Ginzburg and Ciampa (2017)], adhesively bonded joints [Wu and Peters (2015)] or honeycomb structures [Balageas, Maldague, Burleigh et al. (2016)]. Subsequently, in automotive industry IRT inspects well condition of weld joints [Runnemalm, Ahlberg and Appelgren (2014)] as well as hybrid compounds, sandwich structures, aluminum thin plates for delaminations, engine blocks, steel parts for cracks or fatigue failures [Meola, Carlomagno, Squillace et al. (2006)]. Wind power industry uses this method to evaluate condition of turbine blades shells, webs [Wang, Dulieu-Barton and Thomsen (2015); Li, Sun, Tao et al. (2018]. IRT is treated as a common method for structural health monitoring (SHM) of windmills [Ciang, Lee and Bang (2008)]. Also in civil engineering it is used to localize and quantify voids, delaminations behind tiles [Hung, Chen, Ng et al. (2009)]. Moreover, it localizes delaminations of plaster at concrete and masonry or condition of sandstone columns [Weritz, Arndt and Röllig (2005)]. Additionally, by IRT evaluation of new materials is performed e.g. particleboard of sugarcane bagasse [Zhang, Sfarra, Sarasini et al. (2018)].

Nonetheless, IRT contains limitations like every NDT method. First, the references standards of materials are needed. Afterwards, infrared emission depends on the surface condition of the specimen (surface emissivity), and it requires highly trained operators.

6 Electronic speckle pattern interferometry

Interferometry is a measurement method using the phenomenon of interference of waves, which analysis may include certain characteristics of the waves themselves, as well as materials that the waves interact with. Modification of the classical interferometry is electronic speckle pattern interferometry (ESPI), a method using an electronic processing and data analysis for modal analysis measurement. ESPI is used to measure full-field deformations in real-time, where structures are subjected to various types of excitation. It is non-contact measurement used on optically rough surfaces [Ma and Huang (2002)]. Already this has been successfully used for measurement of the residual stresses [Hizli and Gür (2017)], since ESPI assures sensitivity of the fraction of the illumination wavelength. It means no requirement for any particular preparation of the surface. ESPI provides possibility of registering speckle pattern images by a video or digital camera, where random pattern of irregular or regular dots is observed [Meda (2003)]. As the object moves, the speckle patters changes. Subtraction of the deformed speckle pattern from the undeformed one provides correlation fringes, which depicts deformation of the tested object [Jang, Lee, Kim et al. (2001)]. Further analysis with data processing is performed with electronic methods. Measuring system consists of two parts: optical and electronic. The first one is a speckle interferometer, which commonly generates two beams. The beams generate a speckle pattern image, whereupon in the electronic part (CCD camera) it is converted to a digital data set. Further, correlograms are created from data and given to a digital analysis. The main task of it is to designate band of a derivate correlogram. Afterwards, results are given into qualitative and quantitative evaluation [Kowalewski, Dietrich, Kopeć et al. (2016); Patorski, Kujawińska and Sałbut (2005)]. In ESPI method, the same as in shearography, tested material must be excited statically or dynamically in order to depict deformations. Images are captured before and after stressing, whereupon they are together analyzed. Results obtained with ESPI are highly accurate in comparison to UT or RT. The described method is widely used in industries to all types of materials and structures.

During the fatigue analysis it allows to designate accumulation areas of strains due to the defects of the samples and allows for a precise location of the damage initiation [Butters (1977)]. In the field of aircraft is used to, e.g. evaluation of high-speed flywheels made of CFRP [Emerson and Bakis (2002)], microsatellite sandwich structures made of aluminum honeycomb core and aluminum skins [Caponero, Paolozzi and Pasqua (1998)]. Automotive industry uses this method to test aluminum plates, honeycomb sandwich panels [Dai, Shao, Geng et al. (2015)], investigate reliability and residual stresses of welded joints [Kim and Jung (2016)]. Additionally, is able evaluate results of brake sqeual mechanisms or sound quality of closing doors [Chen, Luo, Dale et al. (2003)]. ESPI is used successfully to evaluate residual stresses in the heat-treated carburized steels [Hizli and Gür (2017)], and low carbon steels [Petit, Montay and Francois (2018). Electronic industry inspects by ESPI flip-chip packages solder joints [Jang, Lee, Kim et al. (2001)], to resonant measurement of piezoelectric transducers [Ma and Huang (2002)]. Also in civil engineering is carried out to localize crack propagation in materials, e.g. Serena sandstone, which are very brittle materials [Meda (2003)], cracks in plain concrete [Chen, Chen, Su et al. (2017)]. Moreover, using ESPI one can obtain shear modulus of wood specimens and timber constructions [Müller, Ringhofer and Brandner (2015)]. In nuclear industry ESPI is used for evaluation of a condition of nuclear graphite cores [Tang, Zhang and Sun (2015)]. Manufacturing industry applies ESPI to calibration, validation and improvement of CAE models [Lianxiang, Lianqing, Sijin et al. (2014)].

ESPI method allows for monitoring deformation development until the sample is destroyed. It allows qualitative control of elements, e.g. pipes, covers, without retracting them from operation. Nonetheless, in contrary to other NDT method - shearography, ESPI is sensitive for accidental displacement of tested element or measuring system. Due to its complexity, it requires an experienced operator. Additionally, cost of the measuring system is much higher than cost of the traditional system to holographic interferometry or speckle photography.

7 Shearographic testing

Shearography, also known as shearing or shear interferometry is an NDT method alternative to ESPI. However, both of them belong to interferometric methods. The origins of this method can be found in a speckle interferometry made in early 1970s, which is closely associated with a holographic interferometry. The shearography is a full-field, high resolution optical method, used for measurement of structural response of beams, plates, subsequent damage localization [Minnini, Gabriele and Lopes (2016)]. It is based on a speckle phenomenon, which takes place when a rough diffuse surface is illuminated by a coherent light [Hung (1999)]. In many cases of this method, the coherent light uses one or more laser beams. Compared to ESPI, the shearography interferometer is less sensitive to accidental displacements of measuring system caused by vibrations or external perturbations [Yang and Hung (2004)]. Moreover, a rigid-body motion does not produce a strain, but displacements, what makes shearography insensitive to such motion [Araújo dos Santos and Lopes (2018)]. This is a relevant advantage in contrary to other NDT methods, because it distincts usefulness of this method in typical industry operations. Additionally, it is possible to use this method outside the laboratory conditions and implement to static or dynamic measurements [Hofmann, Pandarese, Revel et al. (2008)]. Strains in the shear interferometry can be directly obtained, because this method measures the gradient of displacements. That is why it is used as an NDT method since it was discovered [Hung and Ho (2005)]. Besides, shearing speckle modal slope shapes are compatible with theoretical derivations, which is usually shown at video framerate. As well as ESPI, the shearography measures displacement of gradients, which are excited thermally, acoustically, by performing partial vacuum loading or pressurization [Francis, Tatam and Groves (2010)]. Moreover, it is suitable for measurement of object slope, the derivative of shape as well as derivative of vibrational amplitudes of surfaces [Shang, Hung and Luo (2000)]. Two types of speckles in this method can be distinguished. The first one is objective and the second one is subjective. In objective speckle, there is no imaging system. Speckle dimension relies on the plane of observation and on the way how the illumination of the surface is carried out. However, in the subjective type, the speckle is formed by using imaging system dependent on the limit of diffraction of this system. Relevant issue of the speckle is its dimension, which is related to the amount of CCD or CMOS sensor pixels. Next essential issue of the shearography are phase maps, which are obtained from the speckle patterns [Araújo dos Santos and Lopes (2018)]. These maps contain information of displacement derivatives of a surface. In the aspect of a hardware, the shearography method consists of a digital camera, shearing unit and a laser device for illumination [Yang and Hung (2004)]. The output of a laser is expanded to illuminate the area of interest of the surface of an inspected object. Afterwards the scattered light forms a laser speckle pattern, which is recorded by the Michelson shearing interferometer onto a CCD or CMOS [Minnini, Gabriele and Lopes (2016)]. Shearing device divides image to two identical, but displaced images, which are recorded by camera. These two images combine coherently, what results in the interferometric speckle pattern at the sensor of the camera.

Shearography method is used with success to measure out-of-plane and in-plane displacements as well as measuring multi-components [Francis, Tatam and Groves (2010)] or creep compliance in elastomers [Pascual-Francisco, Barragán-Pèrez, Susarrey-Huerta et al. (2017)]. Common application of the shearography is an aerospace industry, where it is used for analysis of structural integrity of composite structures, fuselages, turbines blades, aircraft tyres or aircraft skins [Hung (1999); Růžek, Lohonka and Jironč (2005); Hung and Ho (2005)]. It is widely used in rubber industry for non-destructive inspection of tires in order to detect delamination along a steel-belt-edge on the interior of the tire [Hung, Chen, Ng et al. (2009)]. Next example is a preservation of artworks, where shearography and terahertz imaging evaluate wooden panel paintings to investigate surface and sub-surface defects [Tornari, Bonarou and Castellini (2001); Groves, Pradaruttu and Kouloumpi (2009)]. Moreover, the shear interferometry is widely used to determine the strains around welds in automotive industry e.g. for high-strength steels in car bodies [Völkers, Somonov and Böhm (2017)]. Next, investigation of objects over a small field of view in electronic industry, where components reliability is required as well as semiconductor industry to detect defections of unpolished silicon wafers [Hung, Chen, Ng et al. (2009)]. The shearography displacement derivative measurements have also been applied to the analysis of tissue phantom. This method is suitable to determine the derivative of vibrational amplitudes of surfaces, shapes, measurement of object slopes, surface displacements, strain distributions around cracks, curvatures and twists [Lopes, Ribeiro and Araújo dos Santos (2012)]. Nonetheless, limitations must be taken into consideration. The first one is shearing moment [Steinchen, Kupfer, Mäckel et al. (1998)]. Usually it is difficult for beginners to select a suitable shearing amount, which induces a small error but sufficient resolvable fringes. Next issue is an excitation, which must be applied on tested object. The shearography is limited to measurement only of the surface strain of object under investigation, due to the fact that bulk strain components do not contribute to this [Hofmann, Pandarese, Revel et al. (2008)]. Interpretation of result must be performed by experienced person due to its complexity. Moreover, it needs very good lighting over the probe to achieve suitable results.

8 Comparison and conclusions

In this paper six different NDT methods were discussed in detail, including functional principles, potential applications, advantages and limitations. From the obtained information can be undisputedly stated that there is no universal NDT method applicable to all existing defects in the structures.

VT is used in almost all industries as an initial testing approach, including hardly accessible areas. However, it is limited only to inspection of the surface damage. Moreover, the experience of the operator plays a crucial role in an appropriate evaluation of the carried inspection.

UT is the certified method in inspection of aerospace composite structures, portable and one-sided. Notwithstanding this fact, irregular shapes of the structures makes it hard to accurate inspection, especially when the orientation of defects is parallel to the sound wave. Moreover, in UT the coupling medium is needed to examine the structure.

Subsequently, RT method, does not need initial preparation of the inspected component. In contrary to UT, geometric variations have no influence on the results. Nevertheless, depth of discontinuities is not measured and a two-sided access to the component is required. For defects with the same direction as the penetrating radiation, RT remains insensitive. The polymer matrix composite materials are weakly penetrated by some radioactive isotopes as well as due to the lack of changes in density, it is incapable to detect delamination. Thus, RT is not a common method in aerospace industry.

Afterwards, a modification of a conventional RT method, CT, characterized by very high resolution of volumetric scale and the capability of defects detection, even in a nano-scale. In contrary to RT, it is capable of evaluation of delamination in polymer matrix composite materials. Awkwardly, the same as conventional RT, the cost of inspection is very high. Moreover, CT is limited to the laboratory conditions and has no accepted test procedures and standards.

IRT, often compared with shearography due to its effectiveness and high precision. It is non-contact method characterized by relatively low cost of performing tests as well as an ability of performing in-field tests. That is why it is common NDT method in wind power industry. Nonetheless, IRT contains several limitations. The reference standards of materials are needed, infrared emission depends on the surface condition of the specimen and, similarly as VT, requires highly experienced operator.

ESPI, the method widely used to measure residual stresses of all types of materials and structures. It is inexpensive, fast, non-contact and real-time. In spite of these advantages, inspection carried out by ESPI outside the laboratory conditions is difficult due to its sensitivity for accidental displacement. Also, this method needs imposing stresses on tested object, which other NDT methods, e.g. VT, UT, RT, do not need.

The last discussed in this paper NDT optical method is shearography. As well as ESPI, it is interferometric, full-field, non-contact, fast and applicable to all types of materials and structures method. Moreover, it is insensitive for accidental displacement and does not rely on the heat conduction as IRT. Already it is used as the major NDT method to evaluate condition of the aircraft tires. Nonetheless, similarly as ESPI, requires imposing excitation on tested component.

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