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Multi-element capacitive sensor for non-destructive measurement of the dielectric permittivity and thickness of dielectric plates and shells

Imants Matiss [1]

Riga Technical University, 1 Kalku Street, Riga, LV-1658, Latvia

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ABSTRACT

Results of original research aimed at increasing the accuracy and applicability of capacitance testing techniques are presented. The essence of this innovation consists of the utilisation of multi-parameter capacitance testing based on scanning the test item by using an electric field of different topography. This approach enables to design a comparatively simple and reliable capacitance testing hardware and software for unilateral measurement of the thickness of dielectric plates, shells and layers with compensation of its dielectric properties. The design of the sensor consists of an array of coplanar electrodes adapted to the profile of the surface of the test piece with the possibility to change the potential distribution on the electrodes.

1. Introduction

Capacitance measurement techniques that enable the possibility to perform tests in a non-destructive manner have found applications in a wide range of different branches of industry related to testing the parameters of geometry and physical properties [1]. However, these capacitance measurement techniques are being replaced by techniques based on application of other physical principles (ultrasonic, radiation, radio wave, etc.); this reduced use of capacitance measurement techniques is due to the presence of several sources of measurement uncertainties specific to capacitance techniques, for example variable dielectric properties of the test item. Such uncertainties affect the measurement of the geometric configuration of objects (shape, thickness, displacement). Whereas test results of the dielectric parameters depend on the presence of factors of geometric character (configuration, structure, surface condition). Traditional approaches to solve this problem involve the introduction of corrections during the measurement, taking into account the relevant influencing factors. In the case of a thickness measurement, the type of material of the test item is observed manually or automatically. Such an approach justifies itself if the dielectric properties of the test item are well known or might be controlled.

On the other hand, it is possible to convert the defect into an effect, which, in the case of capacitance thickness meters, expresses itself as independent measurement of both the thickness and dielectric properties of the test item, i.e., to measure the thickness while compensating for the influence of variable properties. The goal of the present article is to demonstrate a new approach to capacitance techniques in the area of geometric and property measurements using theoretical justification and a realistic design of particular test arrangements. The essence of this innovation consists in the application of multi-parameter capacitance testing based on scanning the test item by using an electric field of different topography [2,3]. In this paper, the field topography refers to the distribution of the electric-field intensity in the test object. This multidimensional scanning approach results to comparatively simple; however, reliable capacitance testing hardware and software for the unilateral measurement of the thickness of dielectric plates, shell and layers with compensation of its dielectric properties. For example, applicability to test the thickness of a wide range of objects produced by materials of different types or of inconsistent properties. The principles applied to the thickness measurement may be generalised for other combinations of two input parameters, where one of them is a measurand and the second is under compensation mode, for example testing the dielectric permittivity (in general a complex quantity) and a geometry parameter (linear or angular displacement, thickness of coatings, surface roughness, etc.). Essential novelty is design of the sensor, which comprises an array of

E-mail address: certcn@latnet.lv

[1] *Permanent address*: 1 Akademijas laukums, Riga, LV-1050, Latvia. Tel./fax: +371 67212807.

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coplanar electrodes adapted to the profile of surface of the test piece, with possibility to change the potential distribution on the electrodes and thus to obtain the necessary configuration of the electric-field topography in the active area of the sensor.

When taking into account that a number of advanced materials, such as composites, ceramics, polymers, resins, the testing results indicated that these advanced materials can be represented as a non-metallic or a semiconductor medium; these new qualities of the capacitance testing technique may be of interest to the testing community.

2. Research methods and procedures

The primary component of any measurement system is a sensor. Capacitance techniques usually are related to indirect measurements, i.e., the sensor fulfils twofold functions—it is a source of electric field for scanning the test item and a source of information about the properties under examination. To provide multiparameter tests, the sensor should to acquire a third function—the ability to vary field topography in the sensing area. This ability is new for capacitance techniques and is based on the novel approach for scanning the test item and consequently using data processing of the correspondent response. The design and development of such sensors in this particular research was performed using the methods of electric field theory and mathematical physics. Due to the multidimensional nature of the feed back received from the test item, processing of such information consists of array processing. For this purpose, methods of algebraic transformations are applied.

Finally, all theoretical assumptions are investigated by mathematical modelling. There are several considerations speaking in favour of the modelling approach. First, labour and time-consuming facilities are considerably greater for full-scale physical experiments. Second, measurement standards and reference materials shall be available in this case, for example, standards of irregular geometry of the test item or its surface roughness. Therefore, the substitution of real measurement situations by equivalent models could considerably contribute cost effective studies. Third, approximate solutions offered by mathematical models would be quite acceptable for conceptual studies, a comparison of optional solutions and the assessment of its strengths and weaknesses.

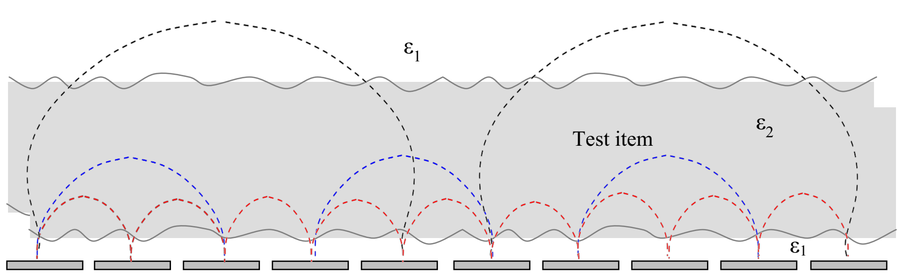
3. Basic principles of multidimensional scanning of the test item

By changing the field topography, it is possible to concentrate field energy at different locations of the sensing area and thus to obtain feedback from the test item of the properties of special interest, for example, the surface condition, displacement, and structure. Such an approach may be categorised as multi-parameter control to emphasise the dimensions of the measurement. In contrast, traditional capacitance techniques utilise individual capacitance sensors and therefore may be referred to as single parameter tests. Only the heterogeneity of the test medium and the possibility to vary the topography of the field source are the prerequisites for the application of multidimensional measurements. The term "multidimensional scanning field" here and hereafter should be understood to depend on the situation because the components of the field are generated step-by-step and not simultaneously, and the multidimensional field itself is a scalar quantity. Each component of the multidimensional electrical field corresponds to one unique field topography in the test item and thus should to detect only one input parameter. However, such favourable conditions of selectivity cannot be provided in a real sensors design. In fact, the topography of each field consists of contributions from all the input parameters, but with different levels of contribution of the constituents of the input. This difference has to be exploited to separate the input into its constituents by using the appropriate data processing. In theory, the dimension of the multi-parameter control is not limited, although independent measurement of over three parameters is not practically feasible, due to the selectivity reasons mentioned above [4].

Looking for a prototype of this approach, there is similarity with tomography methods, which scan the test item by utilising penetrating waves from multiple directions. The projection data gathered during the exposure are processed by tomography reconstruction software. Direct transfer of this principle to capacitance methods is not acceptable, due to the one-sided approach of the surface scanning. Therefore, the only means for obtaining "projections" is variation of the depth of the scanning field and thus to "palpate" each layer of the test item under study one-by-one.

4. Underlying principles for the modelling of the capacitance sensors

A schematic design of the array electrodes' with variable electric field topography, which is intended for tests of flat surface



0	1	0	1	0	1	0	1	0	1
Distribution of potentials with sign change of each next electrode (lowest penetration)									
0	0	1	1	0	0	1	1	0	0
Distribution of potentials with sign change after each third electrode (medium penetration)									
0	0	0	0	1	1	0	0	0	0
Combination of potentials, with forms three electrode system (highest penetration)									

Fig. 1. Schematic design of the array of electrodes for variable field topography: ε_1 and ε_2 are the dielectric permeability of air space and test item, respectively; sign alternate (0 and 1) potential distribution on the electrodes correspondent to three combinations of the field penetration: field lines of the lowest, medium and highest level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)