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Electrical Measuring Techniques – Expectations for Increasing Accuracy

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Abstract. **Multi parameter testing by Calibrated Disturbing Factors (CDF) methodology may present interest as more sophisticated mean for increasing metrological qualities of electrical testing techniques. Detailed analysis of a set of validation parameters, such as thickness and dielectric permeability of plates, demonstrates advantage of this approach in comparison with single parameter tests.**

Keywords: **calibrated disturbing factors, dielectric permeability, non-destructive testing, thickness of films**

I. Introduction

Electrical measuring techniques, in some sources called as capacitance techniques directly may be applied for testing a variety of geometrical and structure characters, such as shaft angle or linear position, motion, chemical composition, electric properties [1]. Indirectly these techniques can measure many other variables, which could be converted into motion or dielectric permittivity, for example pressure, acceleration, fluid level, moisture, aging and polymerisation degree [2]. Special interest is testing geometry and structure properties of dielectric objects including advanced materials. Due to merging important properties as low conductivity of electricity, heat and noise reduction, high specific mechanical resistance, these materials (composites, polymers, ceramics) have found application in high responsible structures and thus needs relevant testing means [3,4].

Electrical measuring techniques are based on scanning of the test item by electric field of a condenser, employed as a probe of a measuring system as well. Recording and data processing response created by the test item to the source of the field implies unexplored potential for further improvement of these techniques.

Simplicity and reliability of construction, high sensitivity to heterogeneity of test environment, and possibility to carry out non contact tests with unilateral access to testing surface are benefits of this testing technique. However, non-destructive testing (NDT) in general and electrical techniques as well possess number of undesirable features practically without any means to eliminate its influence. First, presence of new sources of measurement uncertainty, such as less accuracy and resolution makes these techniques non-competitive in comparison with laboratory testing facility, where all testing conditions are provided for the most favourable metrological qualities. Second, there are no possibilities to adapt the test item for testing, for example by changing its shape (specimen) and treating surface. Third, there are limited possibilities for controlling ambient environment more beneficial for testing.

II. Basics of multidimensional testing

During the measuring process, input characters of the capacitance probe are transformed into output characteristics. In other words, transformations of measurement dimensions are taking place. Under input characters should be understood all parameters under examination as well all influencing factors, although undesirable. The most applied approach for elimination of undesirable influence is to put the most critical influencing factors under control. It means introduction of additional testing channels by independent measuring devices.

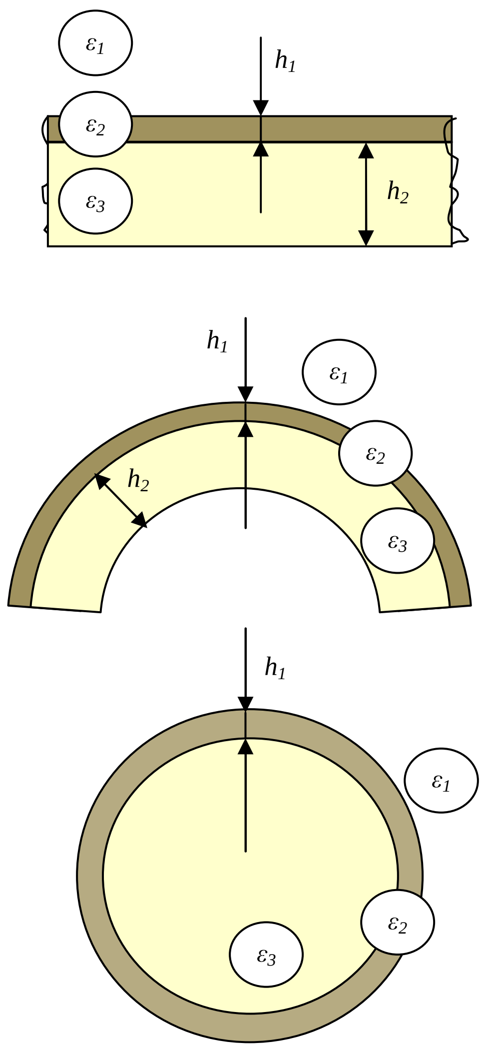

Fig.1. Range of testing assignments solved by capacitance NDT, presented in a way of three laminar structures: plates (a); films (b) and coating (c).

Actually, approach proposed in this study is based on the same principles, however distinctive in such way that all testing channels are formed by the same physical field, particularly electric field, generated by several or to commutable single capacitor. Such scanning signal comprises several components in this study denominated as multidimensional signal. Obviously, dimension of the signal should correspond to total number of input parameters (measurable and influenced). Multidimensional scanning signal is generated by a capacitance probe with variation of topography of the electric field according dimension of the input parameters.

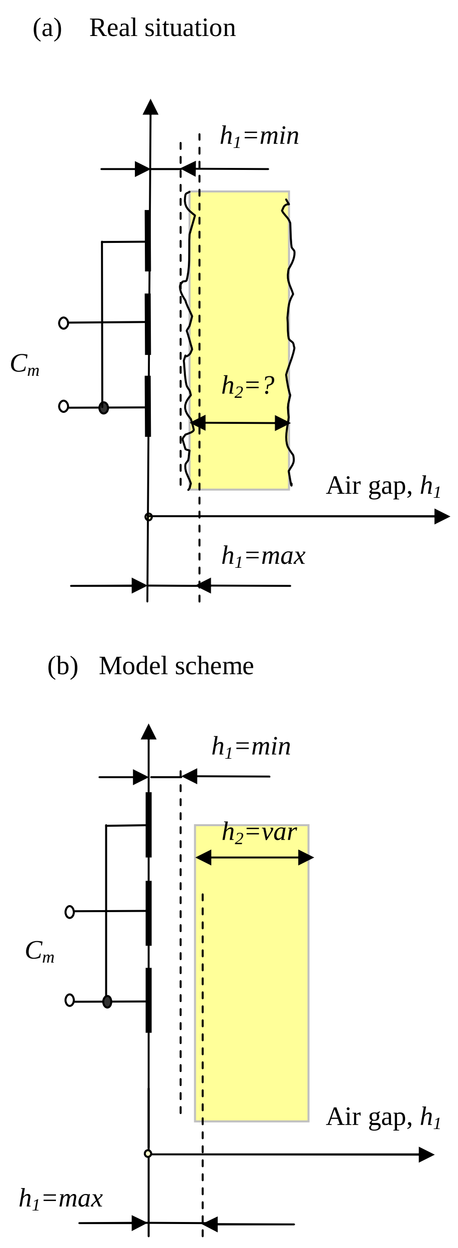

Fig.2. Evolution of the model for testing thickness of a plate by capacitance probe.

Calibration is necessary in each measurement system, including multidimensional. In this particular study, each component of the scanning signal is calibrated in metrological adequate conditions with subsequent transposition of obtained calibrated reference scales to the real testing range. All components of the scanning signals are in active phase, while one of them is in measurement process, other operate in compensation mode. This testing approach, designated as Calibrated Disturbing Factors (CDF) offers simultaneous information about all input parameters with suppressed disturbing influences. Additional benefit is cost effective calibration resources [5]. Metrological qualities of these techniques are validated in accordance with International standards [6]. In this particular case study test task is thickness measurement of dielectric plates and shells (Fig.1). Evolution of disturbing factors in this instance is illustrated in (Fig.2).

First, presence of surface roughness prevaricates to define a distance between the probe and the test piece. Second, uneven thickness of a layer or coating raises a question – how to define thickness? Therefore real situation (Fig.2a) should be transformed into model in order to define input parameters. Solution proposed in this study provides substitution of surface roughness by equivalent distance between the probe and the test piece. In the same way, inconsistent thickness of the layer or its surface curvature may be substituted by average thickness (Fig.2b). Another essential concern is changeable properties of the test item, which may be presented through dielectric permittivity. The last correlates with several composition and structure parameters, such as polymerisation and aging degree of plastics, moisture and density of substances, etc.

Therefore, assignment of thickness measurement corresponds to three parameter independent control of input parameters. These parameters are: thickness of the plate, transposition of the test item and its dielectric permittivity.

This task may be solved in three different ways depending on measurement interests. In other words, which input parameter is in status of a measurable – thickness, displacement or dielectric permittivity? Continuation of the study relates to thickness measurement with compensation both - the test item's displacement (surface roughness) and its dielectric permeability variation.

Mathematical modelling of the unilateral capacitance probe was carried out in order to validate metrological parameters of CDF technique applied for this particular testing assignment [7]. The probe comprises a number of electrodes deployed on surface of the test item represented as a three layer structure. Three dimensional scanning fields may be generated by three autonomous unilateral capacitors or by a set of electrodes attaining potential distribution in three different combinations (Fig.3).

Response obtained as result of the measuring process is three readings of capacitance. Data processing in algebraic representation corresponds to solution of system of three equations. As the first approximation, linear interpretation may be utilised:

$$\begin{cases} h_{21k} = h_{21m} + k_{11}\Delta h_{21}^{h1} + k_{21}\Delta h_{21}^{\varepsilon}; \\ h_{22k} = h_{22m} + k_{12}\Delta h_{22}^{h1} + k_{22}\Delta h_{22}^{\varepsilon}; \\ h_{23k} = h_{23m} + k_{13}\Delta h_{23}^{h1} + k_{23}\Delta h_{23}^{\varepsilon}; \end{cases} \quad (1)$$

where:

- h_{inm} are readings of the thickness meter in all three measurement channels correspondingly;
- index "*k*" relates to corrected values obtained by relevant data processing;
- the second lower index indicates number of the measurement channel (probe);
- the upper index indicates the compensation parameter (h_1– displacement, ε – dielectric permeability)
- Δh_{2i}^{h1} *and* $\Delta h_{2i}^{\varepsilon}$ $i = 1,2,3$ - corrections of maximal influence of the corresponding disturbing factor (*h* or ε);
- k_{1i} and k_{2i} (*i*=1,2,3) – iteration coefficients.

The first iteration intends:

$$k_{11} = k_{12} = k_{13} = k_1$$
$$k_{21} = k_{22} = k_{23} = k_2 \quad (2)$$

Its means solving (1) in respect to corrected thickness values:

$$h_{2k} = B/A; \quad (3)$$

where:

$$A = \Delta h_{21}^{\varepsilon}(\Delta h_{23}^{h1} - \Delta h_{22}^{h1}) - \Delta h_{22}^{\varepsilon}(\Delta h_{21}^{h1} - \Delta h_{23}^{h1}) - - \Delta h_{23}^{\varepsilon}(\Delta h_{22}^{h1} - \Delta h_{21}^{h1});$$

$$B = \Delta h_{21}^{\varepsilon}(h_{23m}\Delta h_{22}^{h1} - h_{22m}\Delta h_{23}^{h1}) - - \Delta h_{22}^{\varepsilon}(h_{21m}\Delta h_{23}^{h1}) - \Delta h_{23}^{\varepsilon}(h_{22m}\Delta h_{21}^{h1} - h_{21m}\Delta h_{22}^{h1}).$$

Transfer functions, which characterises abilities to transform input (thickness, displacement and dielectric permeability) into output (capacitance) of the probe are presented in Fig. 4.

Two dimensional dependences are presented on the Fig.4 for all probes in three modes: nominal mode, which means ideal calibration curve without any disturbing influence and combination of less favourable measurement conditions caused by disturbing factors. Abbreviation "*Minmin*" relates utmost deviation of measurement readings downward (dielectric permittivity of minimal value, displacement of maximal value); abbreviation "*Maxmax*" relates to utmost deviation of measurement readings upward (dielectric permittivity of maximal value, displacement of minimal value). Curves *"Close max"* and *"Close min"* relate to utmost deviation only of dielectric permittivity correspondingly upward or downward.

As it can be seen from the Fig.4:

1) Influence of only one disturbing factor – displacement causes not acceptable deviation of the calibration curve (quantitative figures are given below);
2) Transfer functions are quite non-linear, which jeopardize linear approximation according (1).

Consequently more radical means should be applied for solution of (1) by refusal of (2) and introducing correction for coefficients k_{ji}. System (1) may be transformed into actually non-linear equations:

$$\begin{cases} h_{21k} = h_{21m} + k_{11}(R_{11})\Delta h_{21}^{h} + k_{21}(R_{21})\Delta h_{21}^{\varepsilon}; \\ h_{22k} = h_{22m} + k_{12}(R_{12})\Delta h_{22}^{h} + k_{22}(R_{12})\Delta h_{22}^{\varepsilon}; \\ h_{23k} = h_{23m} + k_{13}(R_{13})\Delta h_{23}^{h} + k_{23}(R_{13})\Delta h_{23}^{\varepsilon}; \end{cases} \quad (4)$$

where R_{ji} are additional weight functions or coefficients, which should be identified during optimisation or iteration process.

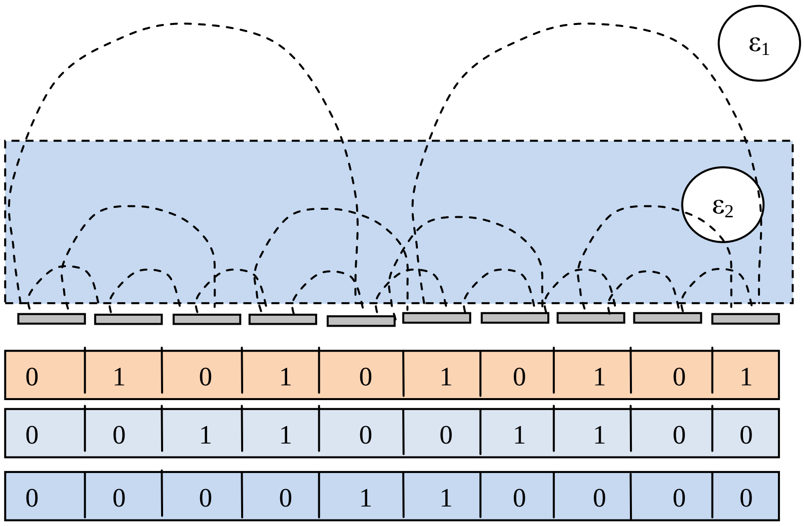

Fig.3. Design of the capacitance probe for three dimensional scanning of the test item: ε_1 and ε_2 dielectric permeability of air space and test item correspondingly

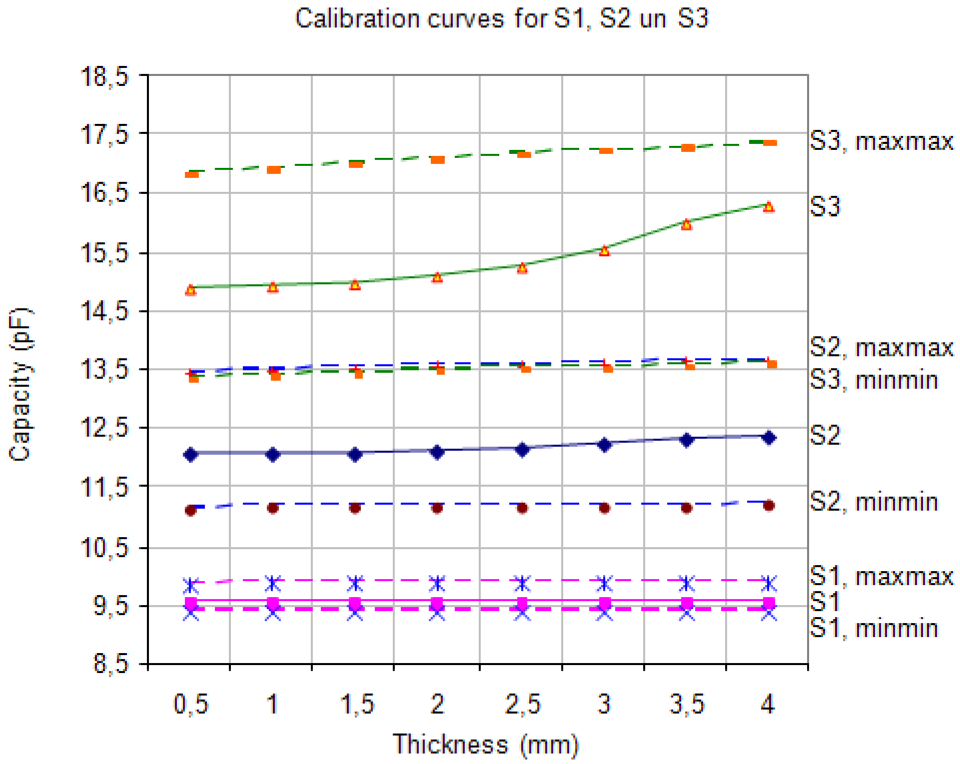

Fig. 4. Transfer functions of sensors S_1 S_2 and S_3 for single parameter testing: capacitance as function of thickness and displacement: solid lines for nominal mode (no disturbing influence); dashed lines for upper and lower limit of influence by disturbing influence. The probe S1 characterizes with shallow penetration of electric field, S2 with medium and S3 with deep-penetrated field.

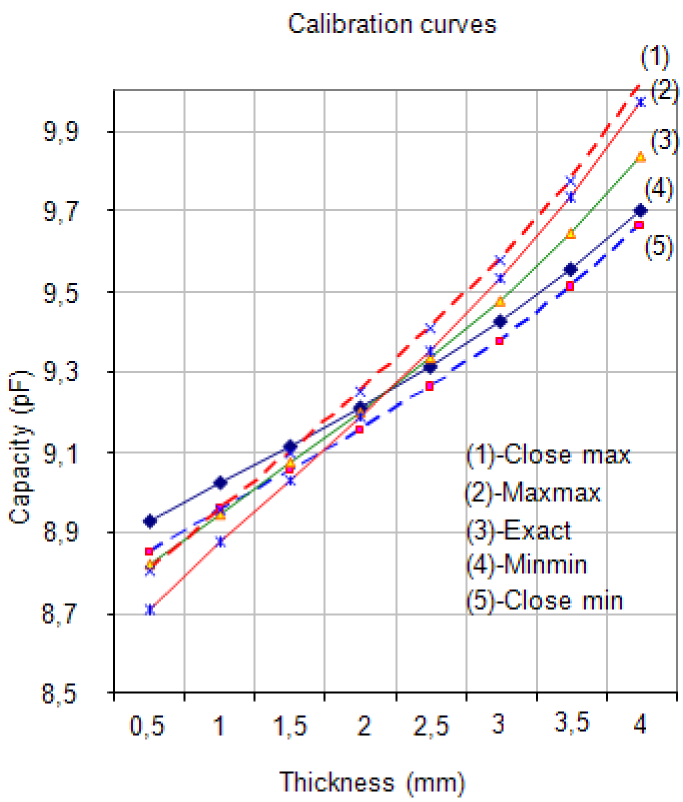

Fig. 5. Transfer functions of input parameters (thickness, displacement and dielectric permittivity) into the probe's capacity obtained by CDF methodology.

Transfer functions calculated according (4) by tabular weight functions R_{ji} are mapped in Fig. 5, which demonstrates that transfer functions are more linear in comparison with single parameter tests and congruence is more convincing. However, only expression of these arguments in quantitative format could give scrupulous representations. For that purpose, the following metrological characters [6] are introduced.

Taking into account that the main metrological quality of the data processing algorithm is its capability to compensate undesirable influence of main disturbing influences leading to measurement uncertainty, priority has been given to the compensation **error**. This parameter is defined as relative error (%) of influenced measurements in respect to ideal measurements obtained without any influence. Distribution of compensation errors of the best single parameter probe (S1) and measurements obtained by CDF technology is presented in Fig. 6. Designation *the best* to the probe S1 is granted quite conditionally, only from the point of view of reducing influence of disturbing factors. In this regard, this probe is in better position in comparison with other single parameter probes (S2 and S2). Smooth distribution of errors of the probe S1 in full measurement range seems also acceptable. However, more detailed examination of metrological capabilities of single parameter measurements disclosed deficiencies of such approach for characterizing metrological qualities. Actually assumed advantages of compensation capacities of the probe S1 is result of low sensitivity to the measurable – thickness of plates or coatings (see transfer functions in Fig. 4). So, there is no need for high compensation capabilities, if the main function - measurement of plate thickness does not meet requirements.

As it follows from Fig. 6, CDF measurement technology demonstrates quite different character of error distribution. Presence of sign reversed functions of compensation errors, which tends to zero at calibration base (values of measurable by which disturbing influences have been calibrated) may be considered as evidence that compensation of disturbing influences is taking place.

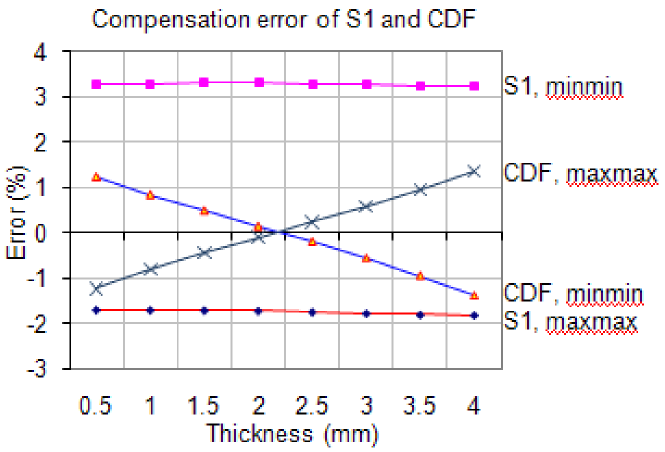

Fig. 6. Distribution of compensation errors of single parameter and CDF measurements technologies.

Concluding considerations how to assess new measurement technologies, necessity of additional criteria for appraising metrological qualities is evident. Helpful in this regard would requirements of corresponding International standards, which require that all non standard methods should be validated in order to confirm its suitability for intended use [6]. These requirements may be applied in full to multidimensional measurement techniques, particularly thickness measurement based on CDF. Therefore, the following additional criteria for assessment of metrological capabilities of proposed CDF technologies have been introduced:

- **Sensitivity or resolution** of the measurement system – ratio of the probe's output (capacity) over input (thickness), dimension pF/mm;
- **Robustness** (in some sources selectivity) is defined as ability of the measurement system to perceive only the measurable but to be immune in respect to influencing parameters. In this study - ratio of the compensation error over sensitivity, dimension [%·mm/pF];
- **Linearity** – ratio of the first part of the scale over the second part of the scale, dimension - decimal fraction.

All these metrological parameters for validation purposes were applied to single parameter test results, as well as to results attained by CDF methodology. Summary of the validation results are presented in the Table I. Favourable tendencies of metrological parameters are as follows: compensation error - the less error the better performance; the more sensitivity the better performance and the less robustness indicator the better capability.

As it follows form Table I, compensation error is not the only character of metrological quality. For example, CDF and single parameter tests by the probe S1 seems competitive regarding this character, however low values of sensitivity make it not applicable in respect to robustness of measurements. Taking into account results of all validation parameters, CDF methodology has no competitors among single measurement operators.

TABLE I

METROLOGICAL CAPABILITIES OF SINGLE AND MULTI PARAMETER TESTING OF THICKNESS

Metrological parameters for ideal and influenced calibration curves	**Method**			
	CDF	**S1**	**S2**	**S3**
Compensation error at min influence [%]	0.1469	-1.7143	-7.9135	-10.640
Compensation error at max influence [%]	-0.0971	3.2995	11.751	13.167
Sensitivity of calibration curve [pF/mm]	0.2914	0.4765	0.3608	0.1974
Sensitivity at min influence [pF/mm]	0.2214	0.0008	0.0153	0.0599
Sensitivity at max influence [pF/mm]	0.3606	0.0032	0.0562	0.1593
Selectivity at min influence [%mm/pF]	0.6633	-1921.2	-514.87	-177.38
Selectivity at max influence [%mm/pF]	-0.2692	1021.1	208.92	82.645
Linearity of ideal curve	0.7490	0.4765	0.3608	0.1974
Linearity at min influence	0.7317	1.4104	1.3305	1.1843
Linearity at max influence	0.7744	1.6809	1.4374	1.1894

CONCLUSIONS

1. Assessing applicability of solving testing tasks by different means the most serious disturbing factors as potential sources of measurement uncertainty should be taken into account.
2. Validation of new testing techniques by one parameter is not effective and is not capable to present full scale justification of selected testing approach.
3. Multi parameter testing by CDF methodology may present interest as more sophisticated mean for increasing metrological qualities of electrical testing techniques. Detailed analysis of a set of validation parameters demonstrates advantage of this approach in comparison with single parameter tests.
4. Approach employed for thickness measurement of dielectric plates and films may be applied for testing other input parameters of the same testing assignment (disposition, dielectric permittivity).
5. Results obtained by electrical testing techniques may be summarised to other, so called near field testing methods, particularly, conductance, electromagnetic, thermal.

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