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► **To cite this version:**

Houssein Ibrahim, Géraldine Villain, Xavier Dérobert, Jean Paul Balayssac, Sérgio Palma Lopes, et al.. Calibration procedure for the development of an embedded capacitive sensor. 25e Congrès Français de Mécanique, Nantes, 29 août-2 septembre 2022, Aug 2022, Nantes, France. hal-04280177

HAL Id: hal-04280177

<https://hal.science/hal-04280177>

Submitted on 13 Nov 2023

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Calibration procedure for the development of an embedded capacitive sensor

Houssein Ibrahim^{a,b}, Géraldine Villain^a, Jean-Paul Balayssac^b, Xavier Dérobert^c, Sérgio Palma Lopes^c, Thibaud Devie^c

a. Univ Gustave Eiffel, MAST-LAMES, Campus de Nantes, F-44344 Bouguenais, France, houssein.ibrahim@univ-eiffel.fr, geraldine.villain@univ-eiffel.fr ;

b. Université de Toulouse, LMDC, F-31077 Toulouse, France, balayssa@insa-toulouse.fr ;

c. Univ Gustave Eiffel, GERS-GeoEND, Campus de Nantes, F-44344 Bouguenais, xavier.derobert@univ-eiffel.fr, sergio.palma-lopes@univ-eiffel.fr, thibaud.devie@univ-eiffel.fr

Résumé :

La notion de durabilité d'un ouvrage se traduit par un ensemble de spécifications techniques basées sur des méthodes d'essais directes (destructives) ou indirectes (non destructives). Dans cet article, on s'intéresse au développement d'un capteur capacitif à noyer dans une structure en béton armé afin de déterminer les gradients de teneur en eau, information essentielle vis-à-vis du développement de la plupart des pathologies, en particulier la corrosion des armatures. Il s'agit ainsi de concevoir un capteur ponctuel pour suivre la teneur en eau en mesurant la permittivité diélectrique au cours du temps. En effet, des études précédentes [1,2] ont montré que la permittivité est linéairement dépendante de la teneur en eau volumique, mais un étalonnage préalable est nécessaire pour relier la permittivité du milieu à la mesure du capteur. Des liquides étalons ont été sélectionnés pour leurs permittivités diélectriques qui couvrent la gamme de variation de la permittivité des bétons sains ou dégradés, secs ou saturés. Une étude numérique a permis le dimensionnement de la géométrie des électrodes du capteur. Les premiers résultats des essais d'étalonnage dans des liquides avec trois géométries d'électrodes sélectionnées sont cohérents avec les données de la littérature. Ces courbes, dans les liquides étalons dont on connaît la permittivité, constituent une base de calibration qui sera ensuite exploitée et étendue pour les mesures dans du béton.

Abstract:

Durability of a structure is defined in a set of technical specifications based on direct or indirect test methods. In this article, we are interested in the development of a capacitive sensor to be embedded in a reinforced concrete structure in order to obtain water content gradients, as very important indicator for the development of most pathologies, in particular the corrosion of reinforcements. This involves designing a punctual sensor to track water content by measuring dielectric permittivity over time. Indeed, previous studies [1,2] showed that permittivity is linearly dependent on water content, but prior calibration is required to relate the permittivity of the medium to the measurement of the sensor. Standard liquids have been selected for their dielectric permittivity values that cover the range of permittivity values of intact or degraded, dry or saturated concretes. A numerical study allowed the sizing of the geometry of the sensor's electrodes. The first results of calibration tests in liquids with three selected electrode geometries are consistent with the data in the literature. These curves, in standard liquids of which permittivity values are well known, constitute a calibration basis that will then be exploited and extended for measurements in concrete.

Keywords: Monitoring, Capacitive sensor, Calibration, standard liquids

1 Introduction

The determination of the water content of concrete using non-destructive methods (ND) has been the subject of numerous studies cited by [3]. Among these ND methods, we will focus on capacitive electromagnetic techniques that are sensitive to the water content and the presence of ions in the interstitial solution.

Capacitive surface measurements have been studied by [1,2,4]. Those surface measurements are sometimes insufficient because of the low resolution on one hand and the limitation of the depth of investigation on the other hand. In our work that is part of the French ANR-SCaNING project, we are interested in developing a new embedded capacitive sensor for the monitoring of concrete structures, which is better than surface measurements in cost, resolution and by limiting human intervention. Sensor developed could be embedded in old structures or easier in new structures during concrete pouring. Many studies have been carried out in resistive and capacitive embedded sensors domain, such as Multi-ring electrodes placed in fresh concrete [5], wire network electrodes [6], ladder-shaped PCB sensor [7]. However, despite those studies, the field of embedded capacitive sensors remains limited.

The first objective of this article is to establish electrodes dimensions by a parametric study. The design was performed by means of a simulation software based on the finite element method. The second objective is to make a calibration in solutions of known permittivities. So materials defined in section 4 will be used to calibrate our electrodes. Several mixtures of these materials were prepared in various proportions in order to obtain liquids of real permittivity values ϵ' close to those of concrete ($2 < \epsilon' < 30$) at frequencies close to 33 MHz.

2 Materials and methods

In the field of NDT, capacitive techniques are used for the detection of motion, thickness measurement, saturation assessment and other applications cited by [2].

The capacitive method principle consists in applying an alternating current between two electrodes placed on the surface of a sample and measuring the frequency of resonance of the electrode-concrete system. The circuit oscillates at a frequency close to 33 MHz in order to minimize the influence of temperature and ion conduction [1]. For surface measurements on reinforced concretes structure, many probes with capacitive plates have been used (figure 1).



Figure 1: Capacitive plates and instrument developed by [8] and used for surface capacitive measurements.

Probes are a combination of metal plate electrodes and Plexiglas® holder; they are connected to an RLC-circuit apparatus called “SYMECC”. Several plate geometries have been developed by [2,8]. The difference between them is their number as well as their dimensions and spacing which makes their depths of investigation different [2]. Tests were done to detect the range of capacity measured by the SYMECC apparatus. The minimum limit found is 1 pF, the maximum limit 55 pF.

3 Numerical study

3.1. Numerical approach

Numerical modeling was carried out in order to understand the effect of the different geometrical parameters. The numerical study was performed on Comsol Multiphysics® software. This commercial simulation software is based on the finite element method.

Knowing that our capacitive measurement method uses a circuit that oscillate at 33 MHz, even though it was shown that we can study capacitive phenomena in the electrostatic domain. This is why, in the AC/DC module of the software, we select a stationary study with direct (or pseudo-direct) electric current. Essentially the equation governing the physics here is the Poisson equation (equation 1) and the potential drop between the electrodes is 1 V.

$$\vec{\nabla} \cdot (\epsilon \vec{\nabla} V) = 0 \quad (1)$$

We then define the input parameters: the geometry of the model, materials (concrete, air, stainless steel for electrodes) and the mesh. The latter was selected in order to ensure the convergence of the solution and a compromise between the accuracy and the time of the calculations executed. An analytical validation of the numerical approach used (equations to represent the physical problem, boundary conditions, mesh sizing, etc.) was made by modeling the case of a planar capacitor, a difference of 1.19% was estimated between the analytical solution based on the equation $C = \epsilon_0 \cdot \epsilon_r \cdot S/d$ and the Comsol result. Calibration in standard materials will be required for the next step.

3.2. Geometrical parameters influence

In order to study the influence of different parameters, we first show a scheme to present the studied parameters (Figure 2).

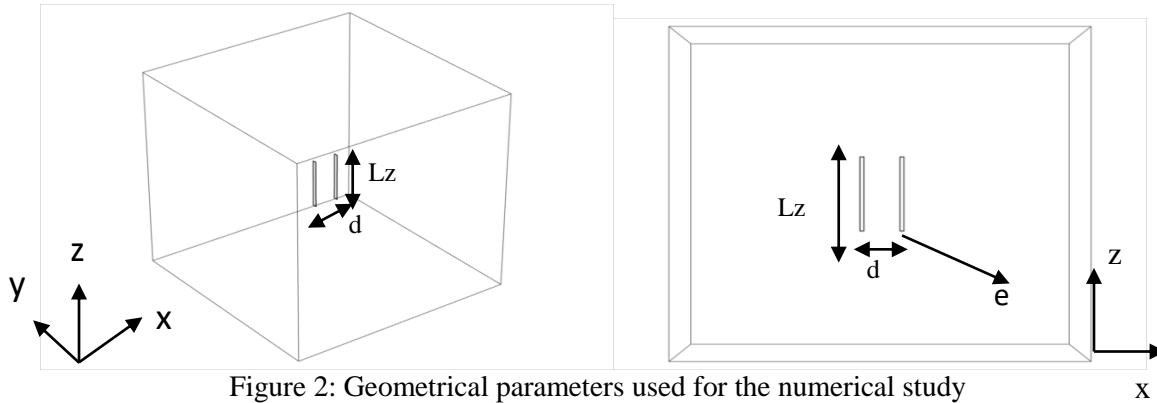


Figure 2: Geometrical parameters used for the numerical study

where d is the spacing between electrodes, e the electrodes thickness, Lz the length within Z axis.

We show next the influence of three different geometrical parameters: the electrode thickness e , their surface S and the length Lz , in two different cases: square faces and rectangular faces electrodes.

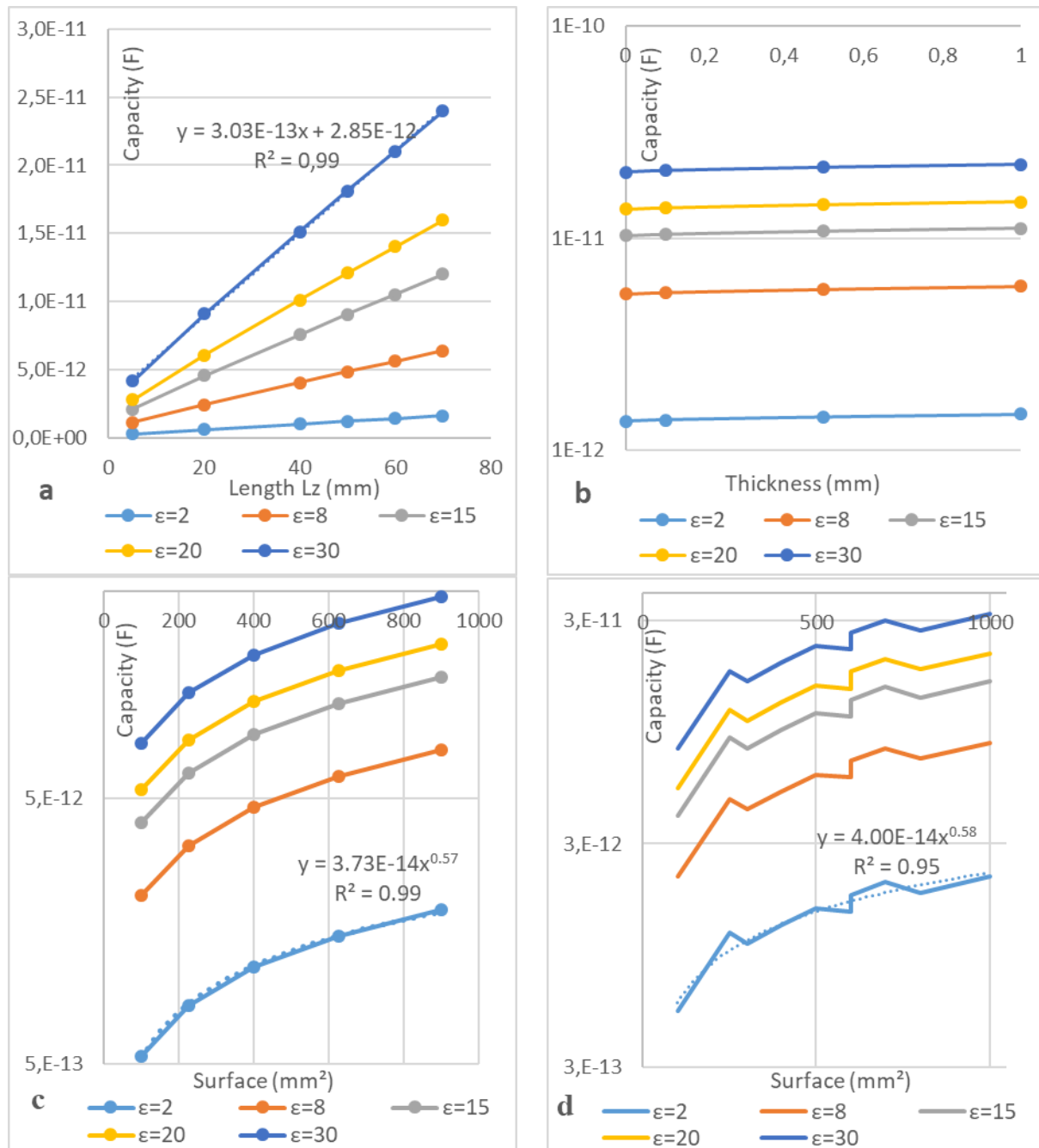


Figure 3: Geometrical parameters influence, where the numerically simulated capacity of the system is plotted versus: a. Thickness effect b. Length L_z effect c. surface effect (square case) d. surface effect (rectangular case)

It can be deduced from the parametric study that the sensitivity of the capacity measurement increases:

- in a negligible way with the increase in thickness of the electrodes (figure 3.a),
- in a linear manner with lengths of the electrodes (figure 3.b),
- according to a power function with the surface area of the electrodes (figure 3.c and 3.d).

After studying the influence of these geometrical parameters, three different surface geometries ($S=50 \times 5=250$, $S=30 \times 10=300$ and $S=30 \times 20=600$ mm^2) were selected for the experimental work. Calibration in standard materials will be required for the next step.

4. Calibration

4.1. Standard liquids selection

Several solid standard materials were already used (Teflon, PVC...) to calibrate the surface capacitive probes [2]. In our case, we are working with sensors to be embedded in concrete, thus this calibration procedure needs to be adapted. The idea proposed is to first drown the sensor in liquids or gels with known relative permittivity values in the range of concrete ones ($2 < \epsilon' < 30$) at frequencies around 33 MHz. Our search for gels or liquids is summarized in the following table:

Material	Reference	Frequency	ϵ'	ϵ''	T (°C)
Methanol	[9]	0 to 100 MHz	32	1	22
Ethanol	[9]	0 to 100 MHz	24	0 to 1	22
Liquid Paraffin	[10]	38 MHz	2.7		?
Acetone	[11]	0 to 2 GHz	20.5		20
Amyl Alcohol	[12]	DC to 5 GHz	15.152		20

Table 1: Standard liquids real and imaginary dielectric permittivity values

4.2. Calibration campaign

We now proceed to the calibration procedure with the different selected standard liquids, and a methanol-ethanol product mixture (50-50 proportion to obtain $\epsilon'=28$). The three electrode geometries selected 30×10 , 30×20 , 50×5 mm² were then fixed by a PVC holder in two orientations: face-to-face spaced 10 mm, coplanar spaced 10 mm.

To minimize and quantify errors, a strict protocol was defined. First of all, we select the geometry, spacing and orientation needed. We then start with measurements in the air. The average of the frequencies of the air is recorded. Successively a dozen measurements are made in each of the product tested (figure 4). After each calibration, the system is thoroughly cleaned and wiped before moving on to the next product.

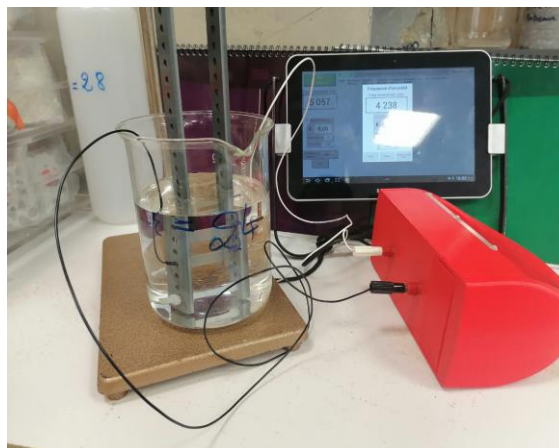


Figure 4 : Tests of coplanar electrodes in Ethanol

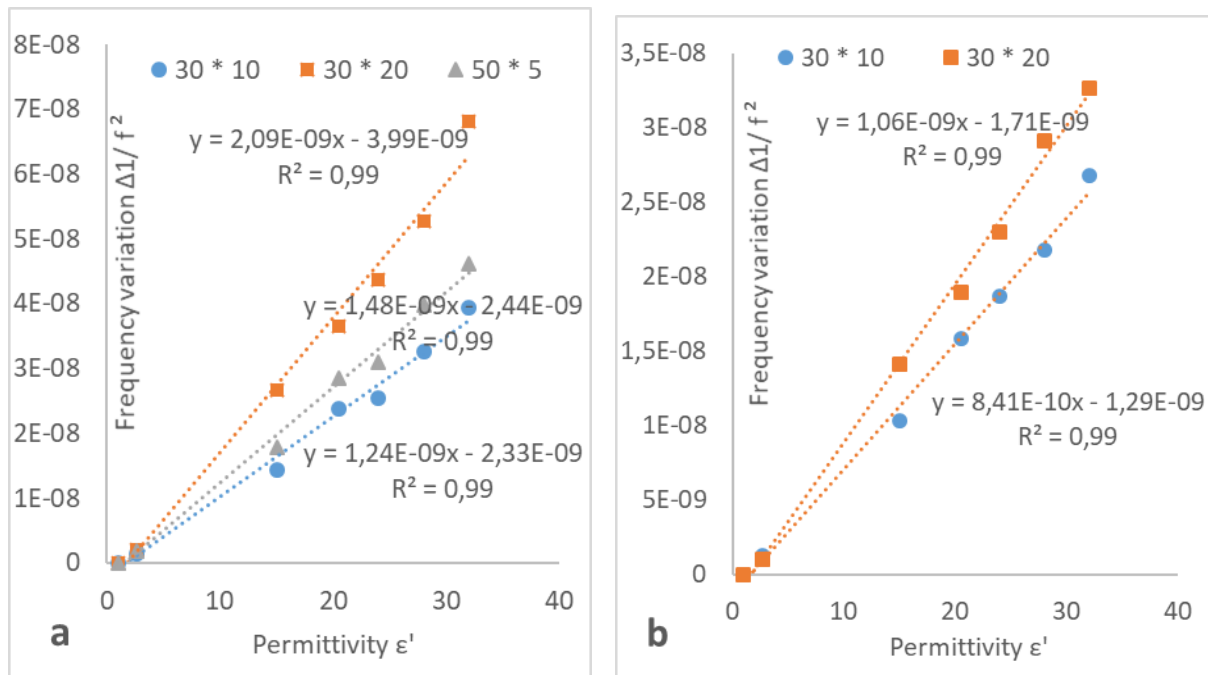


Figure 5: Calibration results : a. Face-to-face electrodes 10 mm spaced b. Coplanar electrodes spaced by d=10 mm

In order to relate measured frequencies to permittivity of standard liquids, the curves of frequency variation ($\Delta \frac{1}{f^2} = \frac{1}{f_{mat}^2} - \frac{1}{f_{air}^2}$) function of permittivity (ϵ') was plotted (figure 5). Other calibrations with different orientations were also performed. The results showed that the relationship between the frequency variation $\Delta 1/f^2$ and the permittivity ϵ' is linear for all orientations and for different spacings. Results found are in agreement with those in the literature [1,2].

5. Conclusion

This study aimed to design and test electrode geometries of a capacitive system that will be embedded in concrete to monitor water content over time. To do this, we started by a numerical study. Our numerical work allowed us to choose three electrode geometries (50×5, 30×10 and 30×20 mm²). Then electrodes with latter geometries were immersed in different standard mixtures chosen for their suitable permittivity values. Results obtained ($\Delta 1/f^2$ function of ϵ') confirm the relation between the measured resonance frequencies and the dielectric permittivity found by [1,2]. For the rest of the measurements will be launched in concrete to test the validity of the sensor in specimens as well as in reinforced concrete structures.

Acknowledgements

The authors would like to thank the French Agence Nationale de la Recherche for the financial support of the project ANR-2020-CE22-015 ScaNING. We would like to thank also Jean-Luc Geffard (MAST-LAMES laboratory) for his significant contribution in the experimental campaign.

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