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CAPACITANCE MEASUREMENTS AT ULTRA-ACOUSTIC FREQUENCY: FIRST EXPERIMENTS AT IEN

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Abstract – The Istituto Elettrotecnico Nazionale Galileo Ferraris (IEN), the Primary Metrological Institute for electrical quantities in Italy, started efforts toward traceable measurements of impedance standards at ultra-acoustic frequencies (up to 10 MHz). We report on the implementation of a calibration method for capacitance standards, first described by K. Suzuki. The method, starting from one-port impedance spectra measured with a commercial automatic network analyzer, predicts the frequency dependence of the corresponding four terminal-pair impedance for the same standard, impossible to measure directly in a traceable way.

First measurements on commercial capacitance standards (nominal value 100 and 1000 pF), suited for high-frequency measurements and employed for calibration of commercial RLC bridges, have been carried out. The results are compared with published data from implementations of the same method.

Keywords: capacitor stray impedance, dissipation factor, four terminal pair capacitor.

1. INTRODUCTION

Recent years have seen the appearance of commercial automatic impedance RLC bridges with extended ranges of frequency and magnitude (see e.g. Quadtech 7600 works up to a frequency of 2 MHz and Agilent 4294A up to 110 MHz)[1].

National Metrology Institutes are challenged by the extension of impedance traceability to bridge the gap between "acoustic-frequency" impedance metrology, (i.e. in the frequency range covered by high-precision coaxial transformer bridges), and "microwave" impedance metrology, (in frequency domains typical of a wave description of the electrical signals and the employment of network analyzers).

First research efforts toward this problem have been made at IEN.

In particular, the present paper describes the implementation of a calibration method given by K. Suzuki [2]. Very simple modelling of the obtained data is carried out. The measurement results are compared with those of more refined implementations of other Institutes [3-7], as a starting point toward more competitive efforts in the future.

2. SUZUKI METHOD

The “acoustic” and “microwave” frequency domains for impedance metrology differ not only in the measurement methods and instrumentation employed, but also in the very definition of the impedance standard. Whereas for microwave frequencies the impedance standards are defined as one-port standards, several definitions may occur to acoustic frequencies. Among these latter, the most complete definition, suitable for highest accuracy levels, is the *four terminal-pair* (or equivalently, four-port) definition given by Cutkosky [4]. Thus, any attempt to relate acoustic and microwave impedance measurements must deal with the problem of converting between these different impedance definitions. In particular, measurements with microwave impedance analyzers (one-port) have to be converted to Cutkosky four-port definition to be of any sense also at acoustic frequency.

A method to make this definition transformation has been developed by K. Suzuki [6, 7] by mathematical calculations. Here a brief description of the method is reported.

The four terminal-pair impedance (Z_{4TP}) is defined as

$$Z_{4TP} = \frac{V_2}{I_4} \quad \text{when} \quad I_2 = 0, I_3 = 0 \quad \text{and} \quad V_3 = 0 \tag{1}$$

where V_2 is the voltage at the Hpot terminal-pair, and I_4 is the current flowing from the Lcur terminal-pair. I_2 and I_3 are the currents respectively at the Hpot and Lpot terminals and V_3 is the voltage at Lpot terminal.

We can regard the four terminal-pair system as a black box. If the system is *linear*, as can be safely assumed for impedance standards, the relation among voltage V_i and current I_i appearing on each terminal-pair i can be written introducing a transimpedance matrix Z_{ij} as follows

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \tag{2}$$

where each Z_{ij} is defined as

$$Z_{ij} = \frac{V_i}{I_j} \quad \text{when} \quad I_{i \neq j} = 0 \tag{3}$$

It is easy now to show that the four terminal-pair impedance can be written as

$$Z_{4TP} = \frac{Z_{21}Z_{34} - Z_{31}Z_{24}}{Z_{31}} \tag{4}$$

If the four terminal pair system is *reciprocal* as well as *linear*, then $Z_{ij} = Z_{ji}$. It is possible to show (demonstration omitted) that

$$Z_{ij} = Z_{ji} = -\sqrt{Z_{jj} \cdot (Z_{ii} - Z_{iisj})} \tag{5}$$

where a new set of transimpedance elements Z_{iisj} have been introduced, i.e. the one-port impedance measured at port i by shorting out port j (with the ports $j \neq i$ left open).

By substitution of (5) in (4), we obtain

$$Z_{4TP} = \sqrt{\frac{Z_{22}}{Z_{11} - Z_{11s3}}} \cdot \left[\sqrt{(Z_{11} - Z_{11s2}) \cdot (Z_{44} - Z_{44s3})} - \sqrt{(Z_{11} - Z_{11s3}) \cdot (Z_{44} - Z_{44s2})}\right] \tag{6}$$

We call (6) the *Suzuki* equation, which computes the four-port impedance Z_{4TP} of a given standard, from a set of one-port impedance measurements, Z_{ii} and Z_{iisj}, a set which can be measured directly with an automatic network analyzer (ANA).

In principle both the measurement and computation could be made just at the frequency of interest. In practice, because of the limited intrinsic accuracy of ANAs, it is necessary to measure $Z_{ii}(f)$ and $Z_{iisi}(f)$ frequency *spectra* on a large bandwidth (up to 300 MHz) and do some fits on the spectra, in order to extrapolate ANA measurements on the frequency range of interest.

Such extrapolation starts from physical assumptions on the behavior of the standard: all models developed until now, for example, are suited for gas-dielectric capacitors where the frequency dependence of the permettivity and losses of the dielectric can be considered negligible [5].

At present, the models considered in literature [3, 6] are complex networks of frequency-independent, lumped stray impedances, constructed analyzing the actual physical structure of a particular standard.

3. EXPERIMENTAL

We conducted first experiments at IEN to test the Suzuki method, using a Agilent 4395A vector ANA. In the impedance analyzer configuration (using Option 010), the bandwidth of the instrument is 100 kHz - 500 MHz.

We followed this measurement procedure:

1) raw measurements on all ports to fix the frequency range and the conditions of interest;
2) open-short-load calibration of the impedance analyzer at the input port of Option 010 using Agilent 909C short and 11512A 50 Ω load;
3) connection of a flexible N-N cable and a N-BNC adapter
4) compensation of the analyzer at the BNC end of the adapter, with a home-made impedance set (BNC short, BPO MUSA 75 Ω termination and the corresponding adapter);
5) measurement of the seven one-port impedance spectra (Z_{11}, Z_{11s2}, Z_{11s3}, Z_{22}, Z_{44}, Z_{44s2} and Z_{44s3}), the input quantities of (6), with sweep averaging. Quantities which are subtracted from one another in (6), like (Z_{44} - Z_{44s2}), have been measured in strict sequence, to minimise possible effects of analyzer drifts.

The computation of Suzuki equation (6), and simple polynomial fits to the obtained Y_{4TP} spectra, have been straigthforwardly implemented in a MATLAB® script.

4. RESULTS

In the following we show the results of measurements on two Hewlett-Packard (now Agilent Technologies) gas-dielectric capacitance standards: HP16384A (nominal value 1000 pF) and HP16383A (100 pF). Both standards are configured as four-port standards with male BNC coaxial connectors. Measurements are done in the frequency range of 100 kHz to 300 MHz, with a source power of -20 dBm (≈ 22 mV on 50 Ω load), with 300 Hz detection bandwidth, and by averaging 4 spectra to smooth out the noise.

Fig. 1 and Fig. 2 display the same data: the results of a typical measurement set, the seven impedance spectra to be entered in (6). For simplicity, only the magnitudes of each complex-value spectra are shown.

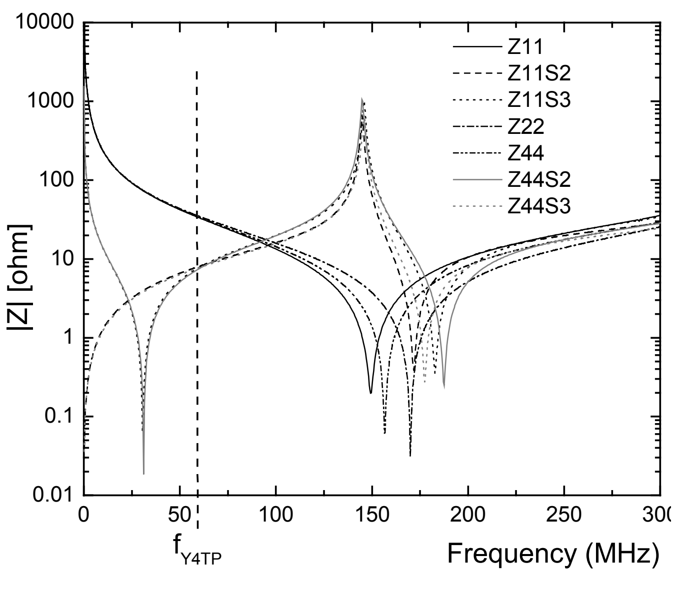

Fig. 1. An example of an original dataset. The impedance magnitudes $|Z_{11}|$, $|Z_{11s2}|$, $|Z_{11s3}|$, $|Z_{22}|$, $|Z_{44}|$, $|Z_{44s2}|$ and $|Z_{44s3}|$ for the 1000 pF capacitance standard HP16384A are shown.

Equation (6) generates the four-port Y_{4TP} admittance spectrum. Fig. 2 and 3 both show the computed four terminal-pair admittance Y_{4TP}, computed from the measurements in Fig. 1 (an admittance representation has been chosen because it is more visually related to four-port capacitance). Fig. 2 shows the real (conductance) and imaginary (susceptance) parts of Y_{4TP}; Fig. 3 shows $|Y_{4TP}|$ in a semilog scale.

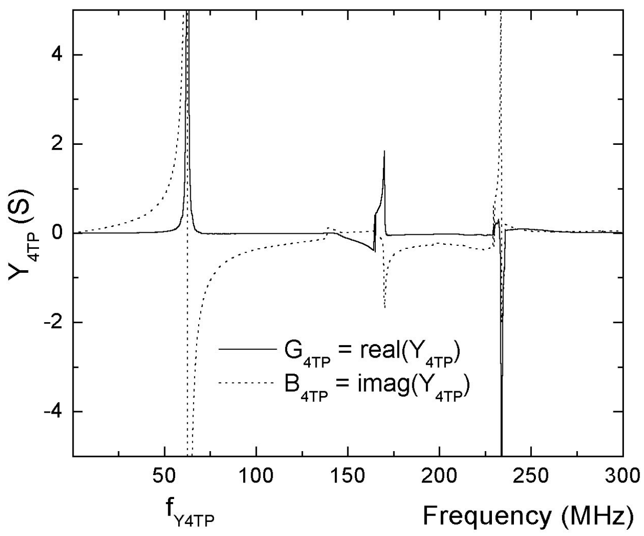

Fig. 2. Real (conductance) and imaginary (susceptance) parts of the admittance Y_{4TP}, obtained from the computation of Suzuki equation, starting from impedance spectra shown in Fig. 1.

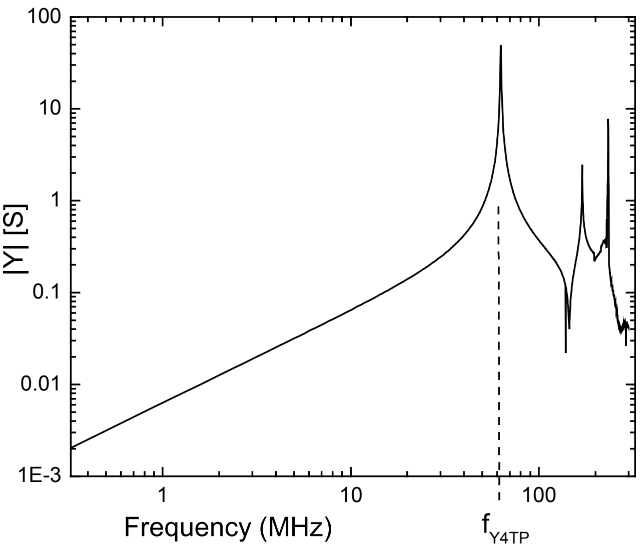

Fig. 3. Same data of Fig. 2. The magnitude of the computed $|Y_{4TP}|$ is shown.

It is worth noting that the strong resonance of Y_{4TP} in Fig. 3, marked as f_{Y4TP}, does not correspond to any apparent resonance, zero-crossing, or particular feature in the spectra of Fig. 1 but emerges only after calculation.

The capacitance *C*(*f*) and dissipation factor *D*(*f*) dependence on frequency have been extracted from computed Y_{4TP} with a simple fit of the data in the frequency range 1 MHz - 20 MHz, assuming a quadratic dependence $C(f) = c{\cdot}f^2$ for capacitance [5] and a linear dependence $D(f) = c{\cdot}f$ for the dissipation factor. Fig. 4 shows the *C*(*f*) curves for the two capacitors and the corresponding fits. Fig. 5 shows the *D*(*f*) curves for the two capacitors.

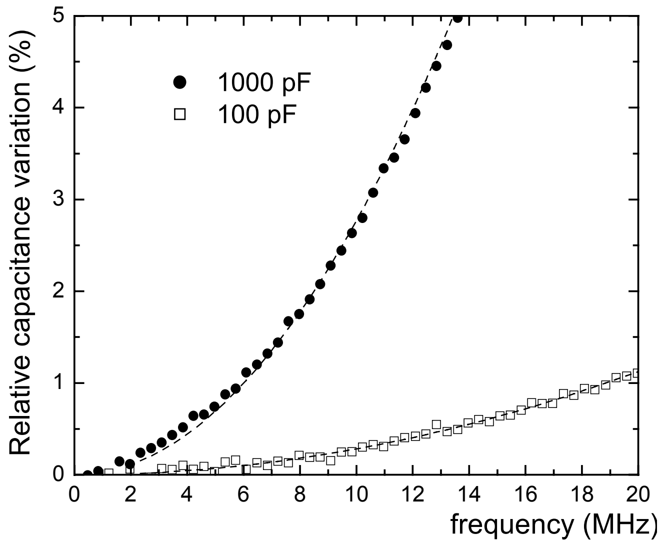

Fig. 4. Relative capacitance variation versus frequency for the two capacitors. (solid circles) results from Y_{4TP} of Fig. 2 and 3, 1000 pF capacitance standard, and corresponding quadratic fit. (open squares) Same for 100 pF capacitance standard.

std	f	ΔC (IEN)	ΔC [6]	u(ΔC) [6]
100 pF	1 MHz	+28 ppm	+30 ppm	200 ppm
	10 MHz	+0.281%	+0.27%	0.25%
1000 pF	1 MHz	+277 ppm	+250 ppm	200 ppm
	10 MHz	+2.77%	+2.6%	0.9%

Tab. 1. Comparison of IEN results with published data. (first column) *ΔC* results, present paper. (second and third columns) Results after Ref. [6], and stated uncertainties.

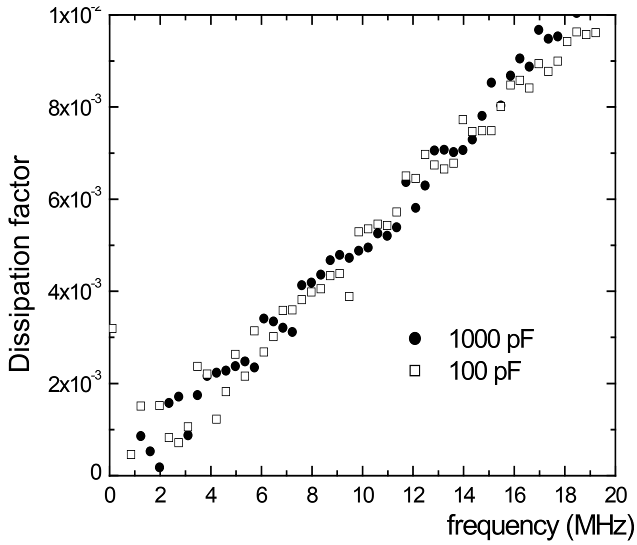

Fig. 5. Dissipation factor versus frequency. (solid circles) 1000 pF standard. (open squares) 100 pF standard.

Table 1 shows the same results of Fig. 4 for *C*(*f*), computed at two particular frequencies, 1 MHz and 10 MHz, and compares them with published data [6] on capacitors of the same model. The data of [6] have been obtained with a much more refined and complicated fit of the analyzer data on a lumped parameter model of the capacitor. It is premature to state any uncertainty for our data.

std	f	***D*** **(IEN)**	***D*** **[6]**	**u(*D*) [6]**
100 pF	1 MHz	$5{\cdot}10^{-4}$	$< 10^{-5}$	10^{-5}
	10 MHz	$5{\cdot}10^{-3}$	$6{\cdot}10^{-5}$	$2{\cdot}10^{-4}$
1000 pF	1 MHz	$5{\cdot}10^{-4}$	$< 10^{-5}$	$7{\cdot}10^{-5}$
	10 MHz	$5{\cdot}10^{-3}$	$7{\cdot}10^{-5}$	$2.1{\cdot}10^{-3}$

Tab. 2. Comparison of IEN results with published data. (first column) *D* results, present paper. (second and third columns) Results after Ref. [6], and stated uncertainties [6,8].

Table 2 does the same comparison for the dissipation factor *D*(*f*) (Fig. 5).

It is apparent that if the capacitance dependence versus frequency of our measurements is in good agreement with published data [6], the dissipation factor appear instead significantly different, even considering stated uncertainties of [6], also reported in Tables 2.

3. CONCLUSIONS

We implemented at IEN the Suzuki technique together with a very simple data analysis. Comparison of results on two gas-dielectric capacitance standards with published data shows good agreement for measured capacitance and some inconsistencies for the dissipation factors. Further work will be devoted to solve this problem, and to define the uncertainty of the implementation.

4. ACKWNOLEDGMENTS

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