Accurate Assessment of CMUT Devices Through Precise Electrical Impedance Measurement in Air

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***Abstract*— This paper reports a technique to exploit results from electrical impedance measurement of cMUT devices in air. An analytical 1D model has been used as a fitting function. The accuracy of this model has been theoretically analysed.**

***Index Terms*— cMUT, characterization, impedance, 1D model**

I. INTRODUCTION

Electrical impedance measurement in air is an important element-scale characterisation method for transducers of any technological family. Piezoelectric transducers can be evaluated using impedance measurement followed by fitting the results with an analytical model of the thickness resonance mode [1]. For cMUT technology, electrical impedance characterisation is an important tool for batch-to-batch, wafer-to-wafer, design-to-design comparison. These devices have to be polarised for receiving and emitting acoustic waves. An adequate evaluation tool must render not only the dynamic parameters but also their dependence to bias voltage. In this paper, based on simple 1D model, we propose to extract equivalent parameters of cMUT devices from a set of data impedance versus frequency and polarisation voltage $Z_{Vdc}(\omega)$. In the first part, the 1D model is briefly recalled and equivalence domain with exact models is discussed. The second part described the fitting procedure, where stability of output parameters is discussed as a function of the number of Z_{Vdc} data used. Finally, experimental validation is performed, with two devices which the same shape and membrane structure, but two different thicknesses.

II. EQUIVALENCE BETWEEN DISTRIBUTED AND LUMPED MODELS

Electrostatic terms

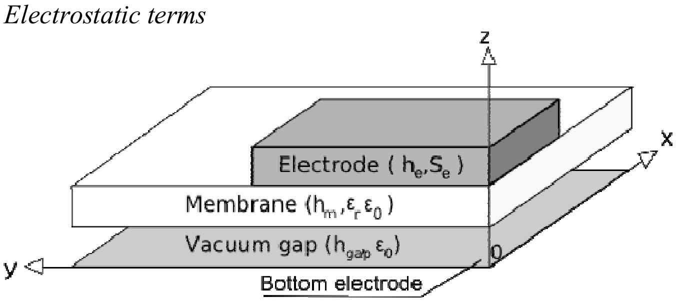

Figure 1 : Schematic representation of a cMUT element

Figure 1 show a generic cMUT cell. xOz and yOz are symmetry planes. The typical geometry of a membrane displays small vertical and comparatively large horizontal dimensions, allowing the use of Timoshenko's [2] thin plate relations.

If the position z (vertical deflection compared to position at rest) of all points of the membrane is represented by a vector $\{z_{eq}\}$, the linear mechanics of the membrane can be written as a matrix {K} with the mechanical reaction of the membrane to a deformation equal to :

$$\{P\} = \{K\}\{z\} \quad (.1)$$

The electrostatic pressure, assuming vertical field lines, writes as :

$$P_e(x, y) = \frac{V^2\varepsilon_0}{(h_{eq} + z)^2} \quad (.2)$$

Where V is the applied voltage, and h_{eq} is the equivalent gap (gap height and membrane thickness normalized by the relative permittivity).

The 1D model for electrostatic actuation ([3],[4]) represents the cell as a capacitor made of two flat parallel plates, one of which is mobile with linear mechanical properties (mass, stiffness, damping factor). This model has a single degree of freedom, the distance between those plates. This model can be completely studied analytically, extending to the expression of impedance for any bias voltage (up to collapse) and frequency.

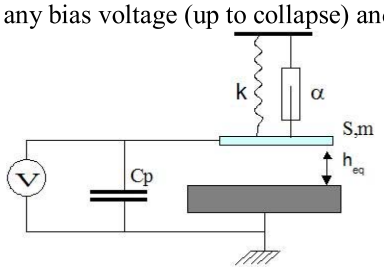

Figure 2 : Elements of 1D model

Figure 2 shows the elements of the 1D model. For a given bias voltage V_0, the static solution is the equilibrium between mechanical and electrostatic forces. The dynamic problem is given by linearization around the equilibrium position and results in the following equivalent scheme:

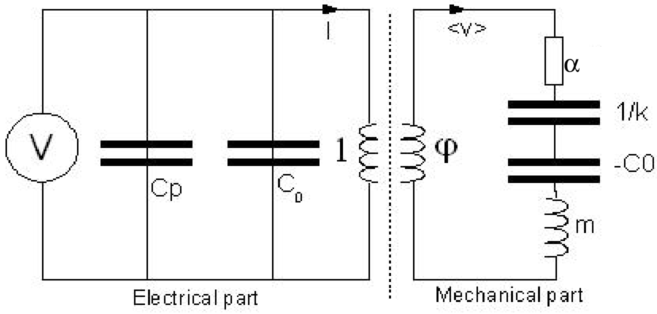

Figure 3 : Dynamic equivalent scheme

φ is the electromechanical conversion factor. The term in the right part corresponds to the average particular velocity of the metallised area (electrode) of the membrane. An additional conversion factor could be used to connect the scheme with the displacement of the complete membrane. The negative capacitance on the right correspond to the *spring softening effect*, that makes the series resonance frequency change downward when bias voltage is increased. The parallel resonance frequency is constant at $2\pi^{-1}\sqrt{km^{-1}}$ if Cp = 0, and goes down with polarisation if Cp>0. φ and C0 are functions of V_0.

While the impedance of the system at a fixed bias voltage can be studied as any electromechanical oscillator (with the same equivalent circuit that a piezoelectric layer in its thickness mode), a set of impedance data including several values of polarisation voltage is more complex to analyse, as it encompass both static and dynamic relations, which gives access to more information. The use of parameter variations with Vdc allows to separate the determination of the mean mechanical stiffness of the membrane from its mean mass density. Thus, we can extract without any ambiguity mean mechanical stiffness of the plate.

Validity of the model

It is mandatory to theoretically analyse how accurately a 1D system can simulate the electrical impedance of a real cMUT. In a distributed model (Analytical models [5], finite difference method [6] or Finite elements tools [7]), the dynamic current in the cell writes as:

$$I = j\omega C_0 \, v_1 - \int_{S_e} \frac{V_0\,\varepsilon_0\,dS}{\left(heq + z(x,y)\right)^2} . u_1(x,y) \qquad (.3)$$

Where:
V_0 is the static bias voltage
v_1 is the excitation (dynamic) voltage
C0 is the static capacitance of the cell
S_e is the electrode area
$u_1(x,y)$ is the dynamic displacement field

An equivalent 1D system is characterised by:

- A passive capacitance Cp^{1D} (which may be null)
- An equivalent active electrode of area S^{1D}

The first necessary condition to equalise the dynamic current of 1D system with the distributed system is to obtain the same static capacitance, so that the first term of (.3) is equivalent. Thus the position z_{eq}^{1D}(V0) is defined to verify :

$$Cp^{1D} + \frac{S^{1D}\varepsilon_0}{Z_{eq}^{1D}(V_0)} = \iint_{S_e} \frac{\varepsilon_0}{Z_{eq}(V_0,x,y)} dS \qquad (.4)$$

The electromechanical driving term for the two models, integrated on the whole electrode, is :

$$\varphi = \iint_{S_e} \frac{V_0\varepsilon_0 dS}{Z^2{}_{eq}(V_0,x,y)} \;, \varphi^{1D} = \frac{V_0\varepsilon_0 S^{1D}}{(Z_{eq}^{1D}(V_0))^2} \qquad (.5)$$

Mathematically, z_{eq}^{1D} can not fulfil (.4) and yet ensure the equality between φ and φ^{1D}. However, as the bending of the electrode is moderate, the error is very small.

Similarly, the softening term can not be strictly equal in both models.

$$k_{sof} = \iint_{S_e} \frac{V_0^2\varepsilon_0 dS}{Z^3{}_{eq}(V_0,x,y)} \;, k_{sof}^{1D} = \frac{V_0^2\varepsilon_0 S^{1D}}{(Z_{eq}^{1D}(V_0))^3} \qquad (.6)$$

Figure 4 shows the errors in both terms for z_{eq} calculated according to with Cp^{1D}=0.

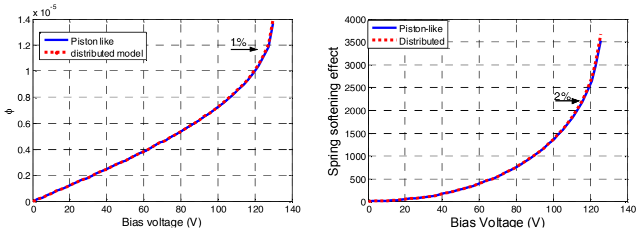

Figure 4 : Error due to flat electrode approximation

As a conclusion, we can approximate the real cell by a flat vibrating electrode with minimal error on the scheme's terms.

Mechanical softening effect

Due to the bending of the electrode, and the $1/z_{eq}^2$ dependence of the electrostatic pressure, the distribution of it changes with the polarisation.

Figure 5 illustrates the repartition of electrostatic force for low and high bias voltage.

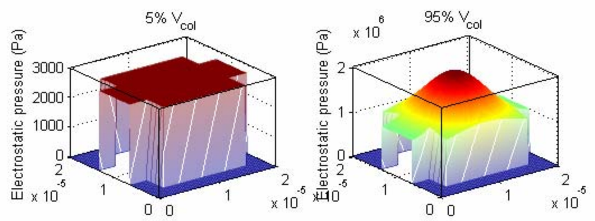

Figure 5 Distribution of P_e for low and high bias voltage

The mechanical stiffness is herein defined as:

$$k_m = \frac{\left\langle z_{eq}(x,y) - z_{eq}^0(x,y)\right\rangle}{\iint P_e(x,y)dS} \qquad (.7)$$

Where $z_{eq}^0(x,y)$ is the position of the membrane at rest, and < > denotes the averaging on an area of interest (total membrane area or electrode only depending of chosen definitions).

An elementary force deflects the membrane more efficiently if applied near the centre. As a result, k_m will be lower for a pressure field that is more concentrated on the centre of the cell, i.e. for high bias voltage. For low bias voltage, the pressure is uniform on the metallised area, unless the membrane initially bent because of thermal stress induced in the process [8].

This created a divergence with ideal 1D model, where the mechanical stiffness is assumed to be constant. This applied in both static and dynamic regimes, and results in a alteration of master curves, and, in particular, a slight shift in anti resonance frequency.

III. FIT PROCEDURE AND VALIDATION

Principle

The model used for fitting is a usual 1D model, with an added parasitic (passive) capacitor. Its impedance at any bias voltage and frequency is determined by five independent parameters (compared to four at a fixed bias voltage). A convenient choice of parameters is Cp (parasitic capacitance), ksi (friction term), heq (equivalent gap), k (mechanical stiffness) and m (mobile mass), heq, k and m being all normalised for a fixed active electrode area.

Those parameters are initialised using very simple inputs (such as peak position and average capacitance) then optimised using a simplex algorithm to fit input data.

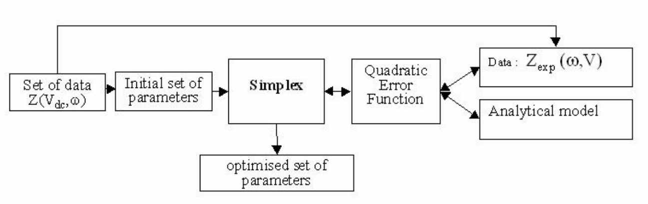

Figure 6 : Mechanism of the fit

Choice of voltage values

To apply the fitting procedure, a set of voltage values have to be chosen. It is necessary to check how the values can be chosen without affecting the results. In that end, a set of impedance data have been calculated for a simulated square cell, with a metallisation rate of 50%. The impedance has been computed for 0, 2, 4… 98% of the collapse voltage, which is calculated at 129 Volts using finite difference approach.

The fitting procedure is used for five regularly spaced voltage values between 2% of Vc and a variable maximum. In Figure 7 the collapse voltage and initial active capacitance of the 1D system that results from the fit are displayed as indicators of the stability of results. Values are stable unless voltages above 80% of Vc are used.

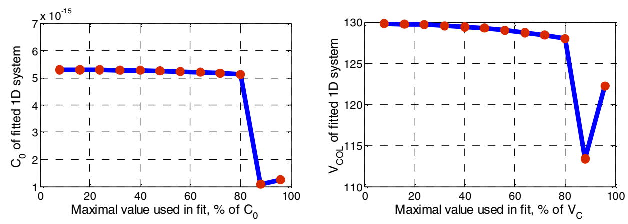

Figure 7 : Stability of fit results

Accurate results are obtained even using only low bias voltage impedance data. When applied to experimental results (performed on transducer arrays typically including hundreds of elementary cMUT's), this is an interesting property, as high voltage measurements are often affected by the dispersion between cells. Very low bias voltage measurements are not experimentally usable either, as the resonance peak are very small and can be masked by the noise.

In the next sections, it has been chosen to use five values with the maximum around 50% of Vc.

Influence of metallisation rate

Three elementary cells are simulated using the distributed model. These cells are square with 20x20 µm horizontal dimension. They differ by their metallisation ratio: 25, 50 and 75%.

The fitting procedure is applied in each case, using the same range of bias voltage values (relatively to V_C) : 0 to 50%.

Table 1: Results according to metallisation rate

Metal Rate	Finite difference results	Fitting 1D model	
	Vc	Vc^{1D}	Cp/C0
25%	132	133	0.04%
50%	126	129	7.9%
75%	112	116	37%

With 25% metallisation rate the cell is extremely close to a flat electrode mass-spring system. Increasing metallisation rate distances the system from perfect 1D model by amplifying the aforementioned effect, which is fitted by converting part of the cell's capacitance into parasitic capacitance.

For a whole cmut array, that also includes *physical* parasitic capacitance (corresponding mainly to interconnection strips), those two forms of parasitic capacitance are added and can't be distinguished using impedance measurement.

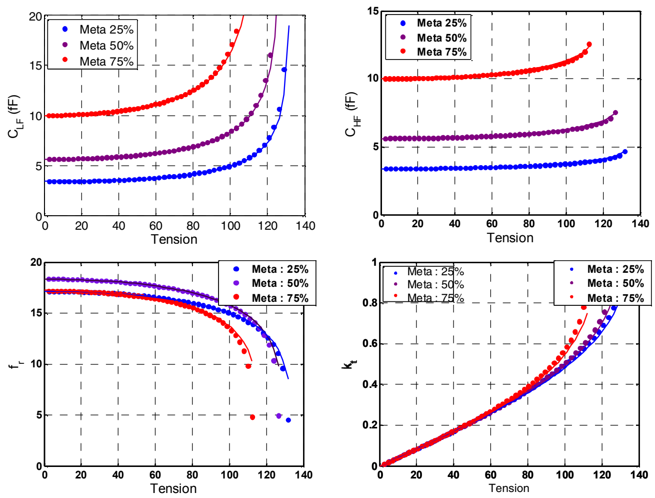

Figure 8 : Results for three metallisation rates
Dots are FD results, lines are fitted 1D models

IV. EXPERIMENTAL EXPLOITATION

Measurement protocol

Measurements are performed using an Agilent 4294A impedance analyser through a RC coupling circuit necessary for DC polarisation. The only treatment between the measures and the input data of the fit procedure is the substraction of the real part of impedance measured for zero polarisation from all other measurements. This subtracted part mainly corresponds to the resistivity of the ground electrode. The measurement frequency range stretches from 0.5 to 70 MHz.

Example of result

Some experimental results are exposed on the next two figures. The measures have been performed with 0.5 volts pitch from 0 to 120, but only 5 values (from 10 to 50 volts) were used in the fit. Figure 9 shows a subset of the measured admittance, and corresponding values for the fitted 1D system.

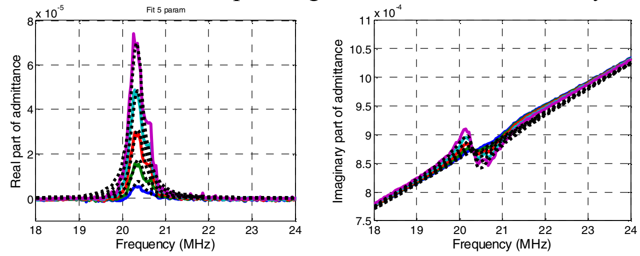

Figure 9 : Fit applied on a measurement. Fitted model is displayed in black dashes.

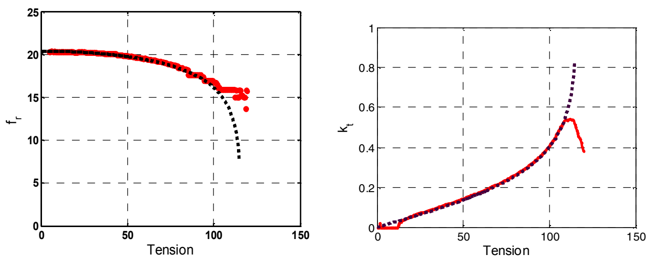

Figure 10 : Resonance frequency and kt from measurements (red) and fitted 1D system (black).

Confrontation of two samples

To validate this technique, two samples of identical design but different by the membrane thickness were measured and compared. The ratio between the two thicknesses was 1.45.

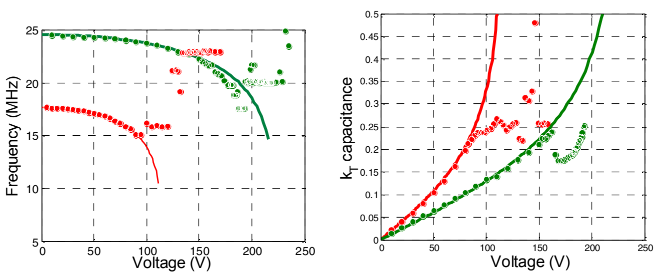

Figure 11 : kt and frequency of the two measured samples (dots) and the fitted 1D systems.

The two designs being identical, we can assume the equality of active surfaces. Thus the fit results can be normalised by active surface to compare the two samples. The ratios between their respective equivalent stiffness and mass are reported in the table bellow. They almost perfectly match those obtained using FD model of both cells.

Table 2: Ratios between values of "thick' and "thin" membranes

	Finite difference results	Fitting 1D model
Stiffness	2.65	2.64
Mass	1.33	1.34

V. CONCLUSION

An approach to extract simple parameters from impedance measurement data of a cMUT array has been developed. The 1D model has been used as an analytic model to fit the total impedance of a real cMUT, either at single cell or complete element scale. Moreover, the mechanical stiffness of the plate can be determined independently of the mass thanks to the combined analysis of static and dynamic behaviour. A few low-bias voltage measurements have been shown to provide enough information to describe the complete static and dynamic behaviour of the system. The existence of some parasitic capacitance in the equivalent model of a single cell without obvious passive metallisation has been explained as an expression of non constant mechanical behaviour of the membrane due to changing force distribution.

VI. ACKNOWLEDGEMENTS

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