Piezoceramic linear parameters calculation from the Thickness Extensional mode of, thickness poled, thin plates or thin disks

Introduction

For the fundamentals and definitions of the resonance method for piezoceramic characterization in the linear range the user of this software is addressed to the standards in the matter: “IEEE Standard on piezoelectricity”. ANSI/IEEE Std. 176-1987, and “Piezoelectric properties of ceramic materials and components. Part 2: methods of measurement – Low power”. European Standard CENELEC, EN 50324-2.

This software offers a solution to the limitations of the standard calculation method concerning characterization in the linear range of high loss and low sensitivity ferro-piezoelectric ceramic materials. It has been tested throughout in the past years for a wide number of ceramics at ICMM-CSIC.

This software allows determining a number of material coefficients in complex form, thus including losses, from the measurement of the frequency dependence of the complex impedance or admittance at the thickness extensional electromechanical resonance mode of thin plates or disks, poled and excited along its thickness.

In the first stage of the program, it creates the needed file for the calculation, which will be stored with the extension “xxx.ESP”, that the program will recognize in future calculations as appropriated.
This file is created from density and dimensions of the sample and from a file of the measured complex admittance ($Y^* = /Y/\cos\theta + i\,/Y/\sin\theta$) with the format:
frequency_1(kHz), $/Y_1/$(Siemen), θ_1(rad)
frequency_2, $/Y_2/$, θ_2
etc., where a point is used to separate decimals.

The calculation

The material data is here determined by solving a set of non-linear equations that results when experimental impedance data at a number of frequencies are introduced into the appropriate analytical solution of the wave equation. This set of equations is established for as many frequencies, which are automatically selected by the program, as unknown coefficients.

Solution is carried out by an iterative numerical method, fully automatic, described in: C. Alemany, L. Pardo, B. Jiménez, F. Carmona, J. Mendiola and A.M. González. "*Automatic iterative evaluation of complex material constants in piezoelectric ceramics*". J. Phys. D: Appl. Phys. 27, 148-155 (1994).

This software solves for the **thickness extensional mode of a, thickness poled, thin plate or thin disk** the following analytical solution:

$$Z = R + iX = -i\frac{t}{2\pi f S \varepsilon_{33}^{S}} + i\frac{h_{33}^{2}}{2\pi^{2} S f^{2} c_{33}^{D}\sqrt{\frac{\rho}{c_{33}^{D}}}}\tan\left(\pi f t\sqrt{\frac{\rho}{c_{33}^{D}}}\right)$$

Where ρ is the ceramic density, t is the thickness (dimension of the sample parallel to the electric field on poling and, also, to the a.c. field for the electromechanical excitation) and S is the area of the electroded surface.

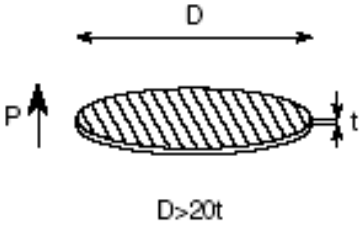

Fig. 1. Thickness poled thin disk.

Such analytical solution is valid for a thin plate or thin disk with given aspect ratios, which allows exciting uncoupled modes, as stated in the standards mentioned above. For a thin disk, the needed aspect ratio is D>20t.

Regular sample geometries are recommended for the use of this characterization method (rectangular plates or disks) and accurate measurement of the dimensions and density of the samples are required for the accurate determination of the complex material parameters. For error sensitivity calculations, see: M. Algueró, C. Alemany, L. Pardo and A.M.Gonzalez. "*Method for obtaining the full set of linear electric, mechanical and electromechanical coefficients and all related losses of a piezoelectric ceramic*". J. Am. Ceram. Soc. 87(2) 209 (2004).

In order to test the frequency dependence of the material parameters, this software allows calculation of the coefficients, not only for the fundamental resonance, but also for the overtones, taking place at odd multiples of the fundamental frequency (A.M. Gonzalez and C. Alemany."*Determination of the frequency dependence of characteristic constants in lossy piezoelectric materials*". J. Phys. D: Appl.Phys. 29, 2476-2482 (1996)). To do so, information on the measured overtone is asked when the data file used for the calculation is created.

Directly and indirectly calculated material properties

The **directly calculated parameters** for this mode are: the elastic stiffness, at constant D, $\mathbf{c^{D}_{33}}$, the dielectric permittivity $\boldsymbol{\varepsilon^{S}_{33}}$ and the direct piezoelectric coefficient $\mathbf{h_{33}}$.

This program uses the following relations that allows, additionally, the indirect calculation of other interesting parameters of the material:

the direct piezoelectric coefficient e_{33} $\quad e_{33} = h_{33}\varepsilon_{33}^{S}$

the elastic stiffness, at constant E, c^{E}_{33} $\quad c_{33}^{E} = c_{33}^{D} - h_{33}e_{33}$

A loss factor is calculated and displayed for each material complex parameter $P^{*}=P' - i\,P''$, defined as $Q_i(P) = P'/P''$(i=p for piezoelectric, i=m for elastic and i=e for dielectric coefficients).

This software also carries on the reconstruction of the spectra (R and G versus frequency curves, where Y=G+iB=1/Z) using the above mentioned analytical expression and the material parameters obtained. Reconstructed curves are plotted together with the measured ones as an accuracy test of the final set of calculated coefficients. This accuracy is also quantitatively characterized by the regression factor (R^2) of such reconstruction.

Values of the relative width of the peak at half-height ($Q=f/\Delta f$) are provided for the G and R peaks, Q_s and Q_p, respectively, from both the experimental data and reconstructed spectra.

Finally, the following two parameters, useful in many engineering connections, are also calculated:
the thickness electromechanical coupling factor k_t (ratio between converted and input energies)

$$k_t^2 = \frac{\varepsilon_{33}^S h_{33}^2}{c_{33}^D}$$

and the frequency number $N_t = t(mm).f_s\ (kHz)$
where f_s is the frequency for the G_{max}.

Practical notes on the software

The LabView window
On the top of the LabView Window there are two buttons. Use the red button to stop the program at any point and the arrow to re-start it.

The button "Readme first"
The button "Readme first" will automatically open this information file.

The button "GENERATE FILE TO CALCULATE"
Any measurement file can be converted into a file for calculation using the button "GENERATE FILE TO CALCULATE" of the software when the corresponding density, distance in between electrodes, surface of these and if the measurement corresponds to the fundamental mode or to a given overtone is known. This is possible provided that the file has the correct format.

As an exercise, you can convert the file "raw_data.txt" that is provided here and contains in the correct format the measurement of the fundamental mode of a PZ27ceramic disk that has a distance between electrodes=0,76 mm, electrode area=1128 mm^2 and density of 7, 70 $g.cm^{-2}$.
This is the same measurement as the one in the calculation file "PZ27.ESP", also provided here to exercise the use of the program. If the generated file from "raw-data.txt" file is done correctly, the results of calculations from both files must be identical.

Note that, when creating the calculation file, a comma is used to separate decimals for all the inputs. Use 0 to identify the fundamental mode measurement and 1 for the first overtone (3^{rd} harmonic), 2 for the second (5^{th} harmonic) and so on.

The file to convert will be shown in three columns at the right window of this page in the same way as the calculation program will read it. Only those files that can be correctly shown here will give place to correct calculations.

Pressing the "GENERATE" button will allow you to provide the calculation file name and choose the folder to save it. Then the software will create the file and automatically bring you to the "CALCULATE WITH EXISTING FILE" page. The software adds the correct extension to the typed calculation file name.

The original programs in which the present ones are based were designed to be used while the measurement of the admittance took place. At each iteration of the calculation, the program asked the measuring equipment to measure the admittance at two auxiliary frequencies, that may be far away from the narrow interval of the resonance (away from f_s or f_p).

Note, also, that, when calculations are done with this software from a formatted measurement file, the measured interval must be wide enough to contain the experimental data that the program will ask for. It is suggested to take data in an interval that covers at least $5(f_p-f_s)$. If the calculation program needs data at a frequency outside the measured interval it will stop and an error message explaining this will appear in the screen.

The button "CALCULATE WITH EXISTING FILE"

The calculation window will open when pressing the button "CALCULATE WITH EXISTING FILE".
First, navigate in your folders to choose the "File to open". This is the formatted file including the information on the sample density, dimensions, complex admittance measurement and overtone.

When the file is open, you must "PLOT", by pressing the corresponding button, the measured resonance spectrum. This will appear, as R and G peaks, plotted in the window "Experimental data". In the right upper corner of this there are some utilities that can be used to see sections of the plot in detail. Full use of the utilities is obtained from the menus that you can get by the right-click of the mouse when the cursor is on the graphic area.

Press the "CALCULATE" button to carry out the calculation. Results of the calculus will appear in the right part of the window. The reconstructed spectra after calculation will be now plotted together with the experimental data in the window re-named as "Final result".

Calculations are carried out from the complete experimental data contained in the file and are independent of the previously chosen view of the Experimental data selected with the plot utilities.

After calculation, the program stores the four following files:
"xxx.DAT"= G(Siemens) and R(Ohms) experimental data vs. frequency (calculated from the measured Y*),
"xxx.DAR"= " " reconstructed " " . These can be used to create plots.
"xxx.txt" = text file with the results of the calculation, and
"xxx.html" = html " " " . These can be used to create tables of calculated coefficients.
Plots and tables are useful when writing reports or manuscripts, create presentations etc.
This files are saved by default in the same folder and with the same name (just with a change of the extension) as the calculation file.
The "SAVE RESULTS" button will open a window that will allow you to rename these files and store them in the folder of your choice. At the same time, the previous files are erased.

On the calculations from overtones

Calculations from measurements at the overtones are done in the same way as those at the fundamental resonance. The information on this is part of the formatted file. As mentioned above, when creating a calculation file you must correctly identify the measurement.

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