THERMAL MODAL ANALYSIS INSTRUMENTATION TO MEASURE BIOMATERIALS PHYSICAL CHARACTERISTICS

Camila Amorim Catalan, catalan@usp.br
Diana Rodrigues Frison, diana.frison@usp.br
Mara Talarito Meliani, meliani@fzea.usp.br
Marcia Regina Leite de Carvalho, macarvalho@usp.br
Tabatha Thayane Pereira dos Santos, tabatha.thaiane.santos@usp.br
Walter Ferreira Velloso Jr., velloso@usp.br

Faculdade de Zootecnia e Engenharia de Alimentos da Universidade de São Paulo.
Av. Duque de Caxias Norte, 225, Campus Universitário, Pirassununga , SP, Brasil

Abstract. *Modal analysis is a sophisticated method to measure physical characteristics of materials. Using this principle, a vibro-photo-acoustic set-up has been assembled in order to measure rheological and thermal characteristics of biomaterials, in particular foods and vegetables as the sugar cane (Saccharum officinarum) and the bamboo (Bambusa spp). The idea is to measure the physical properties in function of the vegetable growing phase. The method consists in construct a small vibrational module (a kind of resonator or tunnig fork) that can be loaded with a sample of the material to be analysed. Then, using the experimentally measured normal mode frequencies, it is possible to iterate with a Finite Element model in order to adjust the values of the physical characteristics involved in the process. A optimization program (using a linear programming method) is used to obtain the best values of these parameters. The same set-up could also be used to measure the physical characteristics of any other biomaterial as, for example, the hidroxiapatite in the dental tissues. In this work we explain the experimental set-up and the numerical methods used. The results of validation tests made with standard materials allow to say that the proposed method is adequate to the experimental purpose. Some preliminary values to bamboo and sugar cane are also discussed.*

Keywords*: modal analysis, finite element method, sugar cane, bamboo*

1. INTRODUCTION

The physical characteristics of materials (mechanic, thermal and electric) are important parameters in almost all fields of Research and Development in Sciences and Technologies, since they are crucial factors to design instruments, machines, experiments and in measuring methodology development. In general, these values are well known for homogeneous materials, as the main chemical elements, the metals (and their alloys) and the plastic materials. However, in the case of non homogeneous and/or composite materials (as the dental enamel which is a complex net of hidroxiapatite crystals) and/or biological tissues (as the bovine muscles that are composites of protein fibers, collagen and molecules of fat) or even in the case of the non-isotropic materials (as some crystals), the physical characteristics are hard to be determined since they are not constants. In fact, these values depend on chemical composition, on geometrical distribution of crystalline structure, on temperature and on time (specially for food).

It is necessary to use mean or typical values (Piovesana et al, 2006, Nogueira et al 2006) always these physical characteristics must to be applied. In technical literature (Rao et Rizvi, 1995; Verink, 1985) sometimes one get large standard deviations to the mean values or even discrepant.

These uncertainties affect some important activities, as the development of bone implants and prostheses or the theoretical thermal calculation on freezing or cooking food.

In general, the mechanical properties of biomaterials and food are much smaller when compared to industrial normal materials (metals and plastics, for example). This characteristic allows to define a new category of materials (including some liquid crystals, medicines, implants, etc) named “soft condensed matter”. The US National Research Council preview that that research on soft solids will be major factor of influence in the next decades, with positive effects and innovations in fields of Science (as Chemistry, Physics, Biology etc) and Technologies (bioengineering, dentistry and medical lasers, food engineering etc).

The microscopic structure of food materials affects in a significant way characteristics as the flavor liberation, texture and hardness. In the case of Food Engineering, the benefit of soft materials research will be a well knowing about the relationship between the microscopic structure properties and the macroscopic behavior of food materials with important consequences on the industrials procedures used to processing aliments.

The sugar cane (*Saccharum officinarum)* industry has a very important role in Brazilian economy. Only few years after the discovery (1500) the sugar cane began to be cultivate and since that time until the present days have a large and decisive influence on the economy and history of Brazilian society. The present Brazilian sugar cane production of about of 400 million of tons by year is still growing. The importance of ethanol on the energetic balance in Brazil is also growing (16 x10^9 litres in 2006). The sugar, a basic product in the Brazilians alimentary habits, is an important item in the exportation trades (1.3x 10^7 dollars in 2004).

The bamboo (Bambusa spp) is cultivated in almost all regions in Brazil, but the total area is still small, mainly considering the multiples possibilities to use of this vegetable. The economic importance of the bamboo could be greater since it has a large productivity (about 40 tons of stems by hectare) which could benefit the production of paper and cellulose and the use of the bamboo in buildings and in furniture industry, for example.

We explain in this work the experimental set-up and the numerical methods proposed to use in order to measure the physical characteristics of these vegetables. The experimental facility, acquired with grants from FAPESP (proc. N. 2006/04252), consists of a photo-vibro-acoustic set-up that allows excite the vibration normal modes of samples by using a pulsed laser beam or an electromechanical hammer and so measure the modal frequencies using a lock-in amplifier and a signal analyzer system. To determine the best values to the physical characteristics, we use a Finite Element model. Beginning with ad-hoc chosen tentative values for the model parameters, and by changing these parameters, we obtain a kind of meta model (a model to the model). These results make it possible to adjust a multi-dimensional polynomial to describe the model behavior in function of its parameters. Then, applying this polynomial in an iterative procedure of optimization (non-linear programming approach) until the simulation results agree, as better as possible, with the experimental data, we achieve the necessary corrections to apply to the characteristics values first proposed.

2. MATERIALS AND METHODS

The rheology is the study of object behavior (strain) when subjected to forces (stress). All the materials have characteristic rheological properties so is possible to use this kind of study in many fields (Geology, Aeronautics, Bioengineering, etc). In the case of Food Engineering the rheology (Costell et al, 1997) has been applied in order to study and design procedures of quality control, pumps, heat changers, and to understand the correlation between texture and sensorial data.

In general, the experimental determination of physical characteristics of the biomaterials and food needs sophisticated methods that involve industrial equipment of high technology (and high cost). These methods, however, do not determine directly the basic characteristics of the materials, but just global aspects such as “hardness”, “consistency”, “firmness”, etc. The basic characteristics (for example; modulus of elasticity, Poisson's ratio, tensions limits for rupture, etc) are rarely available (Rao, Delaney et Skinner, 1995; Rahman, 1995; Telis et al, 2005).

The use of the modal analysis (or acoustics spectroscopy) to get characteristics of food materials was used pioneering by Abbott et al (1968) and later by Finney (1972) and Hamann and Carroll (1971). The method consists in mechanically excite a sample of the material under analysis and measure the resultant vibrations. The analysis is based on experimental measures in which the foods, whole peaces or samples, were submitted directly to mechanical excitations and the dynamic response was measured directly by accelerometers (piezo-eletric ones) connected directly to the materials (Golias et al, 2003).

More modernly, Butz et al (2005) and Medendorp and Lodder (2006), respectively, had used the method to analyze the quality of vegetal foods and for the classification of medicines and foods in tablets.

We used an alternative approach, developed in the SIMFAB (Laboratory of Simulation and Physics Applied to Biomateriais, Food and Ambience of the FZEA-USP), that consists in use vibration modules (a kind of resonators) containing a sample of the material under analysis and then measure the normal frequencies of these modules that are affected by the presence of the sample.

The values of mode frequencies are determined also by the sample material , therefore generating a correspondent characteristic spectrum. In this way, measuring these normal modes (acoustically, using microphones, or electrically, using pieces of piezo-electric ceramics connected to the modules) it is possible to recognize the materials from their corresponding spectrum of normal modes. The comparison, between measured and numerical spectra, allows the adjustment of optimized physical parameters.

2.1. Apparatus for experimental analysis.

The figure 1 below represents the schematics of the structure mounted for the accomplishment of the experimental measures. The vibration module, in this case, is a type of metallic cup capable of vibrate with frequencies established by its dimensions and material. The sample presence inside of such cup modifies these frequencies and also adds new characteristic resonances depending on the geometrical shape (basically a cylinder in the case) and on the properties of the sample material

It is possible to induce vibrations in the module using two not mutually exclusive ways: a) by using a mechanical drive (using piezoelectric pieces or using a mechanical activator hammer); b) using a pulsed laser beam applied to the sample (in red in the figure) through a small glass window in the box of confinement.

In this second case, the sample heats (dilates) and cools (contracts) with the frequency of pulsation of the laser and, as a consequence, vibrates. The acoustic response, is measured using a microphone connected to the box of confinement where the structure of vibrational module is mounted. The proper vibrations of the cup also can be detected directly by a piezoeletric sensor (not shown in the figure to prevent interferences) connected directly on the metallic structure.

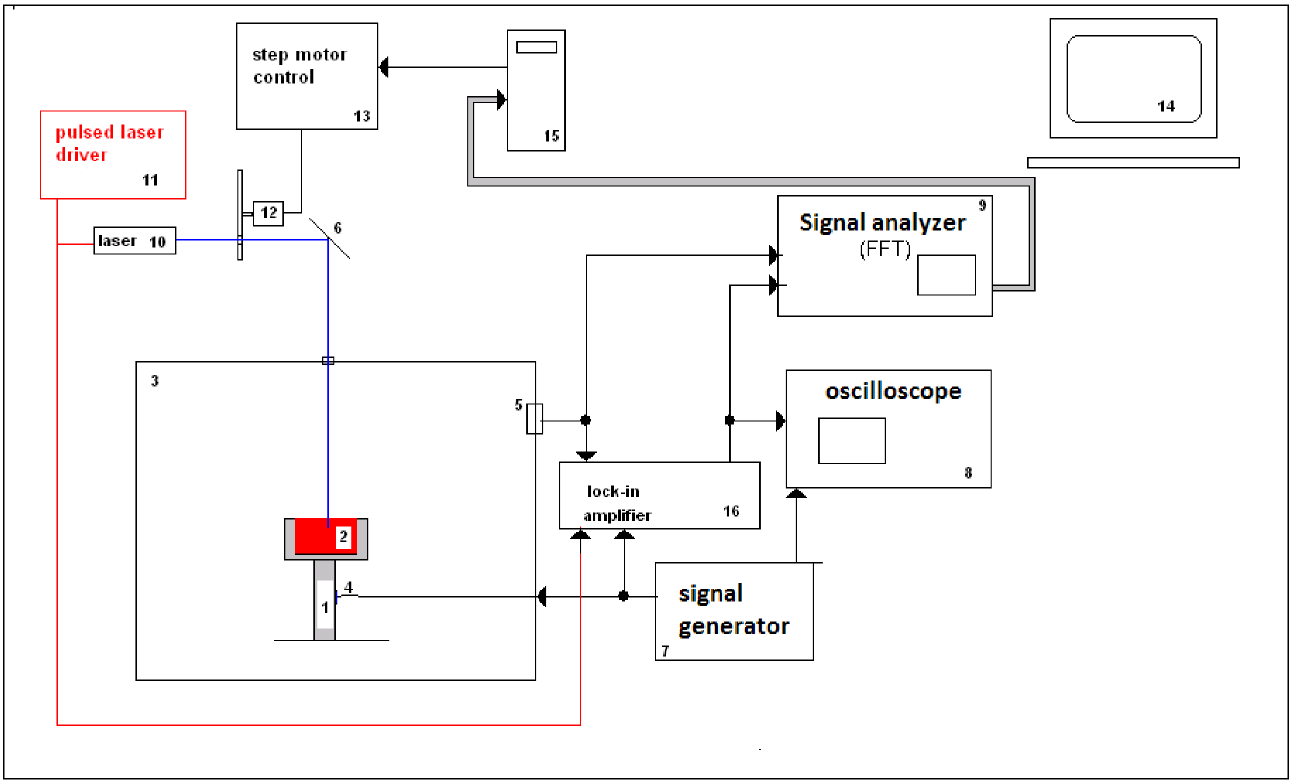

Figure 1: Experimental apparatus: (1) vibrational module, (2) sample, (3) acoustic chamber, (4) piezoeletric, (5) (microphone), (6) mirror, (7) signal generator, (8) oscilloscope, (9) signal analyzer, (10, 11) laser diode and its controller, (12, 13) step motor and its controller, (14) monitor, (15) microcomputer, (16) “Lock-in amplifier”.

Since biological materials, in general, present high damping coefficients, the signal amplitudes are very small and so it is necessary to pass the signals from the microphone by a pre-amplifier. After the amplification, the signal go to the oscilloscope (that allows the monitoring of the experiment and the determination of the phase between the excitation signal and the response of the system) and to the signal analyzer which will carry the transformation of the signal in its Fourier Spectrum (FFT). It is then possible to compare this measured spectrum with the numerically calculated theoretical one (see Fig.2).

2.2. Apparatus for numerical analysis.

The vibration modules are represented by a Finite Element model, in order to calculate the solutions of the dynamic equations and to obtain the normal mode frequencies and the frequency response in each in case, for each type of sample.

A simulation sequence procedure allows obtain optimized values to the parameters of the model (conductivity, specific heat, Young's modulus, density, Poisson's ratio, viscosity etc). By using the results of the successive calculations, it is possible to carry out statistical studies in order to consider, for example, the effect of the variation of the parameters of the model on the frequency of diverse normal modes of the structure. This procedure generates points in two-dimensional spaces (for example: specific heat versus Young's modulus). Statistic analysis allow to delimit the variation intervals in which the values of the physical characteristics of the sample is contained and, therefore, to find the optimum way where looking for the best configuration and to guide the successive iterations speeding up the convergence of the method.

The modeling and simulation were made using softwares of computer aided design (to draw the structures), and the “solvers” NASTRAN and ANSYS (to solve the mechanical systems equations and to analyze the solution). Presently, the SIMFAB counts on an educational version of the Nastran and on a partial version of the ANSYS, both of great use in the field of modal analysis.

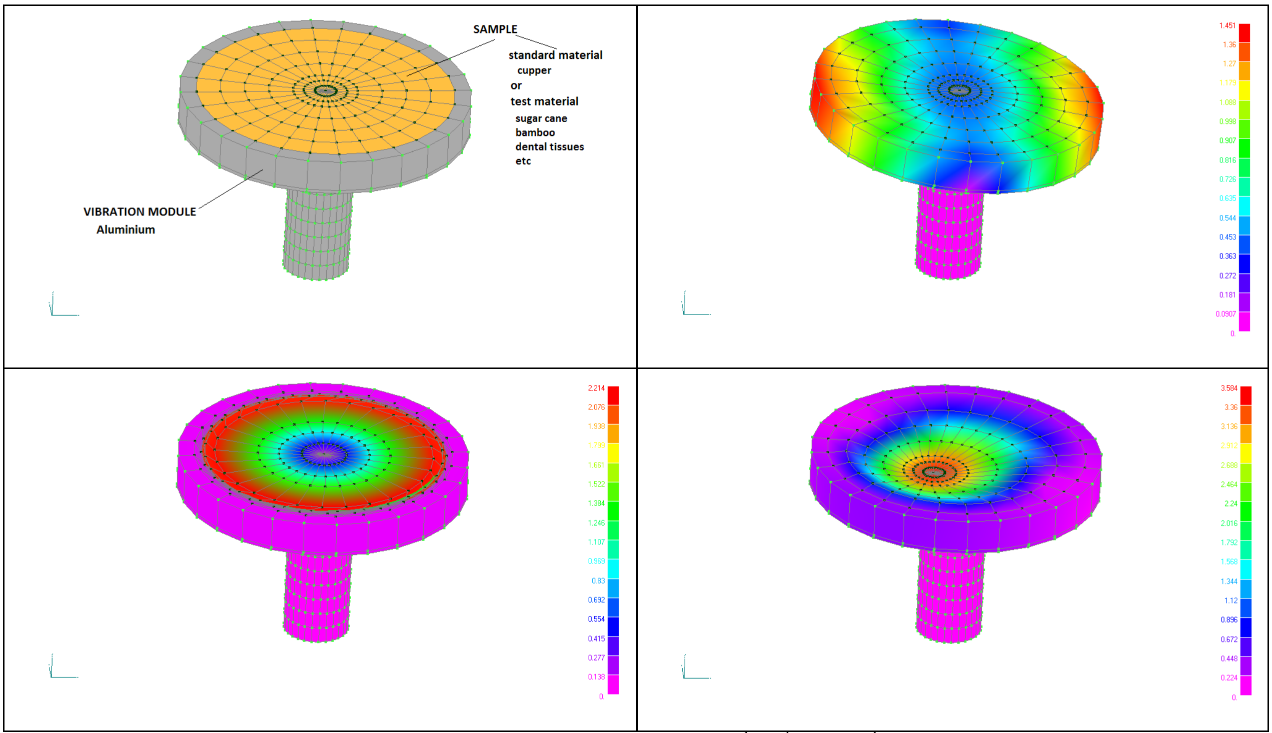

Figure 2. The FEM model and some normal modes shapes (1th, 3th and 5th) calculated for a vibration module containing a hypothetical material sample. In order to allow the visualization, we used enhanced magnitudes. Colors represent the real modes amplitudes in an arbitrary scale.

2.3. Strategy to implement the thermal analysis of the samples.

Once got the best values to the mechanical properties, the same experimental apparatus allows the determination of the sample thermal properties. The normal mode frequencies, of course, depend on the values of Young's modulus, density, Poisson's ratio for the vibration module and for the sample. The sample viscosity can be important, in some cases, too. However, these values change when the temperature changes. This temperature variation, by the way, depends on the thermal physical characteristics: specific heat, conductivity, expansion coefficient etc. So, these thermal properties can be determined by varying the temperature of the modules (there is the possibility for cooling or heating the acoustic chamber) while measuring the normal mode frequencies with the described apparatus.

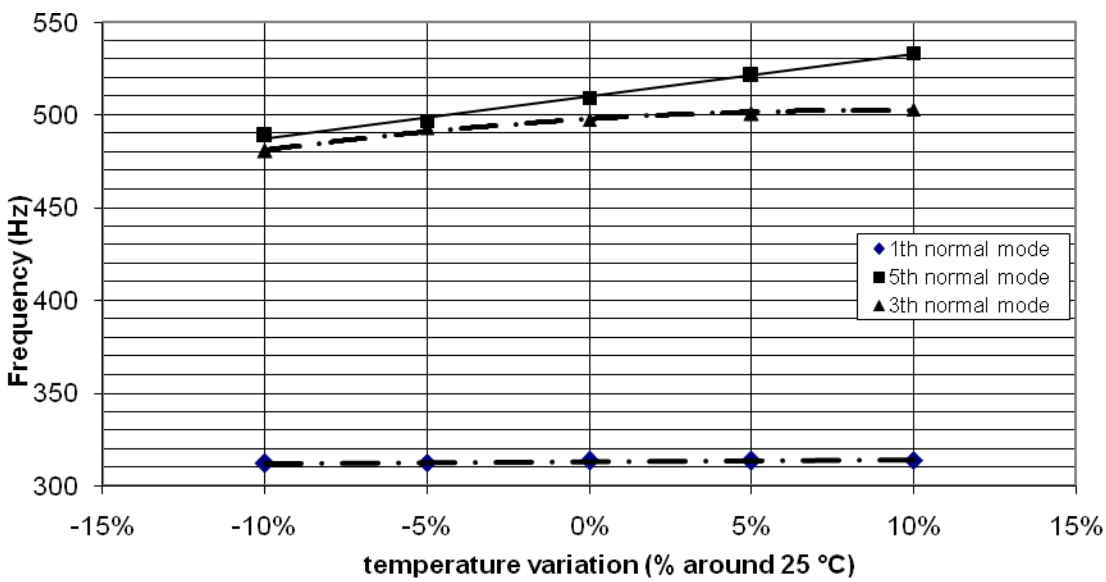

Figure 3. Temperature dependence of frequency for some normal modes. The first mode has an almost constant frequency. The third and the fifth modes frequencies changes in a significant way.

Figure 3 shows the calculated effect of temperature variation over the normal mode frequencies. The frequency of the first mode, which depends mainly on the vibration mode geometrical shape and material (see Fig.2), is almost constant (~ 1Hz) in this temperature range (22,5ºC – 27ºC). However, the frequencies of the 3th and of the 5th modes, which are determined also by the properties of sample material (see Fig.2 again), change in a significant and easy to measure way (~ 10 Hz).

It is possible to measure the temperature in the acoustic chamber using two thermocouples. One of them measures continually the temperature inside the chamber and the other measures directly the sample temperature. Running the numerical model and changing the values of thermal parameters, again it is possible to construct a bi-dimensional polynomial linking these values with the mode frequencies and, using the data showed in fig.3, for example, it is possible to relate these frequencies with the temperature. This strategy make it possible to determine these thermal properties for the sample material in function of temperature (in a restrict range, of course).

2. RESULTS AND DISCUSSION

In order to validate the method, we applied it to a vibration module made in Al (aluminium) alloy and as a standard material a piece of Cu(copper) alloy. The table 1 shows the results obtained. The data in 6th and 7th column correspond to the measured and calculated frequencies for the 10 first modes (for the module of Al plus the standard of Cu). The 8th column shows the differences. The calculated frequencies are really obtained from a two-dimensional adjust on data (3th column) from the model, changing two parameters (Young´s modulus and density; 1th and 2th columns) for the cupper around its standard published values. An optimization procedure, based on a linear programming iterative method, use these bi-dimensional equations to looking for the configuration that corresponds to the minimum value for the differences (8th column). The best result is represented by the values in columns 4 and 5 corresponds to the percentile correction to be applied to Young´s modulus and density values in order to minimize the data in the last row in the last column which contains the root mean square of data. The data in table 2 correspond to the results obtained for a module of AL and a standard sample of Cu. The 0.002 value, obtained for the root mean square for the differences between calculated and experimental data, is the minimum achieved. In the case showed, the optimization procedure result that the Young´s modulus and density values have to be corrected by the percentile factors showed in the 4th and 5th columns respectively.

Table 1: Results from the optimization procedure.

adjusted	polinomial	Frequency (Hz)	Young´s modulus correction	Density correction	Frequency(Hz)	Frequency(Hz)	differences	
F=f(E)	F=f(d)	From FEM model	Delta E	Delta d	Experimental	Adjusted	Exp. - Adj.	$(\text{Exp. - Adj.})^2$
2.4175	-7.4794	506.1624	3.64%	3.30%	501.0995	501.1004	-0.00096	9.3624E-07
8.2469	-5.0360	507.1634			510.3713	510.3743	-0.00305	9.3051E-06
9.5964	-8.0025	549.1910			550.7844	550.7849	-0.00052	2.8040E-07
9.8728	-8.2533	560.3152			561.9329	561.9347	-0.00186	3.4933E-06
10.4659	-8.7722	598.0370			599.7315	599.7308	0.00073	5.3557E-07
10.6140	-8.8655	606.0831			607.8346	607.8315	0.00302	9.1207E-06
10.6171	-8.8794	607.0818			608.8225	608.8195	0.00302	9.1713E-06
11.2136	-9.3653	638.0646			639.9134	639.9129	0.00058	3.3785E-07
11.2259	-9.3770	638.5355			640.3844	640.3844	6.4672E-05	4.1825E-09
11.1017	-9.2274	640.8480			642.7231	642.7223	0.00077	6.0547E-07
							Root mean square ➔	0.0018

These results show that the method we proposed is really capable to get a relatively precise experimental determination for the values of physical characteristics of materials. Both mechanical and thermal data can be obtained with similar proceedures. The thermal measurements depend on monitoring the temperature during the experiment. The necessary instrumentation is being implemented. We intend to use this instrumentation to determine physical characteristics of both sugar cane and bamboo in function of the growing phase and in function of the temperature. The same facility can also be used to measure characteristics of dental tissues (Esteves-Oliveiraeta al, 2008; da Ana, Velloso e Zezell, 2008) to analyse the effect of laser irradiation on the mechanical and thermal behavior (elasticity, hardness, specific heat etc) of the enamel.

3. ACKNOWLEDGEMENTS

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