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A METHOD OF INVESTIGATION OF MOISTURE MATERIALS USING FFT

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A method of investigation of moisture objects, made of porous materials, using Fast Fourier Transform (FFT) is presented. A sound signal, which is the response to the percussive force, is registered in a digital form by a given sampling frequency, and at further stages it is subjected to analysis in a frequency field in order to determine the main formant. It is proved that the main formant position, which is the response to the percussive force, is a function of moisture changes in the investigated object. An algorithm enabling analysis of the discussed phenomenon in the MATHCAD environment is presented. The following fields may be examples of the described method and programme applicability: i) testing of hygrometers used for moisture investigations of porous materials; ii) the program prepared by Professor Bogdan Skalmierski was used much earier in diagnosis of stringed musical instruments, where the dependence between the main formant position and stress states occurs.

Key words: formant, fft, humidity

1. Introduction

Objects made of porous materials, for example concrete, cement, gypsum, marble, limestone, dolomite, sandstone and wood are subjected to significant influences of changes in moisture. The use of experimental methods, under natural conditions, enables determination of the maximum absorbability of objects made of porous materials by measuring the quantity of water which the given material is able to absorb. One can assent that the maximum absorbability is the state in which water delivered to the object will not be further absorbed by caverns, pinholes and capillaries in the material. Since growth of moisture causes growth of object mass, it is possible to use the quotient of water mass m_w, which is absorbed by the material, and the object mass m_0 that is assumed as the initial state. As a result of percussive force action – a mechanical impact caused by a shock exciter – the object is stimulated to vibrations and emits a sound signal which may be recorded in a digital form. Recorded signals can be converted from the time field into frequency field by a measurement process of digital signals and analysis of its results (see References). This is data which includes the same information but in different forms. By carrying out measurements under the same conditions and by using the same device, it can be assumed that mean values of systematic errors formed as a result of the influence of the level signal to interference ratio, in the determination process of the main formant position of object response to the pulse force, are approximately constant – one can determine their value and then reduce their influence on final results by using a suitable filter at FFT stage. A suitable computational algorithm makes it possible to determine the frequency at which the measured response to the percussive force has the largest spectral power and this frequency is defined as the main formant (Skalmierski, 1986). The conversion of the signal, which is the object response to the percussive force, causes some problems but their negative effects can be eliminated. One of these methods is a technique that uses data windows in pulse testing – described inter alia in Kucharski (2002), Lyons (2000), Marven and Ewers (1999).

2. Aim and range of the study

The aim of the study is to determine the relationship between main formant position changes, emitted through an object stimulated to vibrations, and the degree of material moisture of an object. Vibrations of the object arise as a result of a percussive force. The object is made of a porous material. The result of the above relationship is a function that is a moisture frequency characteristic of the investigated object.

3. Description of the testing method

The measuring apparatus is a PC computer equipped with a 16-bit sound card and software which enables registration and digital analysis of recorded sound signals. The objects of investigations are plates with diversified thickness and dimensions in plane, made of porous materials and not resistant to moisture. The object is stimulated to vibrations with percussive force action as a result of a mechanical impact of a shock exciter at the object surface. The tip of the shock exciter is made of plastic which is resistant to moisture. The vibration pick-up is a microphone connected to the computer sound card and placed at a suitable distance from the investigated object on the opposite side to the exciter impact. The distance of the vibration pick-up is experimentally selected in such a way that a signal record of the object response to stroke pulse will not have amplitude clipping. The object is stimulated to vibrations several times at time intervals that ensure full response of the object to each percussive force. The value of the percussive force is variable and chosen so that the investigated object would not break down. The object is fastened to elastic pull rods. Object responses to the percussive force are recorded in a disk file format with "wav" extension. In the present study, the sampling frequency of $f_p = 44100\,\mathrm{Hz}$ and the length of analysed signal of 131072 samples are assumed. These values correspond to the record with time duration of about 2.972 seconds.

The object is moistened with water and weighed before each test. Assuming the following denotations:

m_0 – object mass in the initial state (aerial-dry),
m_n – mass of object partly moistened with water,
m_w – water mass in object material,

the moisture coefficient is established by the quotient equation

$$\frac{m_w}{m_0} = \frac{m_n - m_0}{m_0} \tag{3.1}$$

4. Applied computational algorithm

The analysis of formants distribution and identification of the main formant of the object response to the percussive force can be carried out in the MATHCAD environment by the use of the following computational algorithm (Paleczek, 2003):

— definition of the data initial index, data read in from the file with length of $L = 2^{17} = 131072$ samples, definition of data vector length, sampling frequency, FFT declaration and definition of vector transformation

$$\text{ORIGIN} \equiv 0$$
$$\begin{bmatrix} L \\ i \\ Z1 \\ Z2 \\ C1 \\ C2 \\ N \\ \Delta \\ j \end{bmatrix} := \begin{bmatrix} 131071 \\ 0,\ldots,L+1 \\ \text{READPRN("test1.prn")} \\ \text{READPRN("test2.prn")} \\ fft(Z1) \\ fft(Z2) \\ \text{last}(C1) \\ 1/44100 \\ 0,\ldots,N \end{bmatrix} \tag{4.1}$$

— declaration of parameters controlling density of spectral frequency band division

$$f_j := \frac{j}{L+1}44100 \tag{4.2}$$

— declaration of the signal power vector at individual frequencies

$$r := 0,\ldots,300$$
$$\begin{bmatrix} s_r \\ s2_r \end{bmatrix} := \begin{bmatrix} \sum_{j=200r}^{200(r+1)} (|C1_j|)^2 (f_j)^2 \\ \sum_{j=200r}^{200(r+1)} (|C2_j|)^2 (f_j)^2 \end{bmatrix} \tag{4.3}$$

— declaration of the expected frequency value vector

$$f_r := \frac{r}{L+1}8820000 \qquad F_r := \frac{f_r + f_{r+1}}{2} \tag{4.4}$$

— declaration of data ordering parameters for visualization of the results of analysis (in graphical and numerical forms)

$$q := \text{last}(F)$$
$$\begin{bmatrix} \sigma \\ F_q \\ Fs_r \end{bmatrix} := \begin{bmatrix} F_{q-1} - F_{q-2} \\ \sigma + F_{q-1} \\ F_r \end{bmatrix} \tag{4.5}$$
$$\begin{bmatrix} \alpha 1 \\ \alpha 2 \end{bmatrix} := \begin{bmatrix} 20 \\ 8000 \end{bmatrix}$$

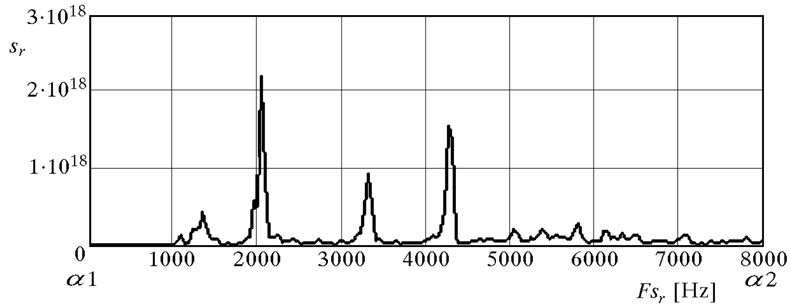

Fig. 1. Visualization of the signal spectrum in the frequency field of one of the investigated samples; the main formant occurs at a frequency of about 2050 Hz

The visualization of the signal spectrum in the frequency field of one of the investigated samples is shown in Fig. 1. It can be noticed that the main formant occurs at a frequency of about 2050 Hz.

The algorithm enables identification of the main formant as well as the formants distribution in the analysed signal. It is possible to compare two or more signals in one diagram modifying the algorithm by re-indexing of the declared variables.

5. Discussion of results of analysis

The use of the presented computational algorithm to determine the main formant position demonstrates a proof that the influence of a constant ratio of the signal level to interference is of little importance for interpretation of the results of analysis.

An example of an investigated signal showing the main formant position with a frequency of about 2100 Hz without- (broken line) and with the use of the background interference filter (full line) is presented in Fig. 2 in a form of one diagram. The filter with the following form was used in this case

$$C_j := \begin{cases} 0 & \text{if } \ |Cn_j| < \Psi \\ Cn_j & \text{otherwise} \end{cases} \tag{5.1}$$

in which Ψ denotes the average level of the signal background.

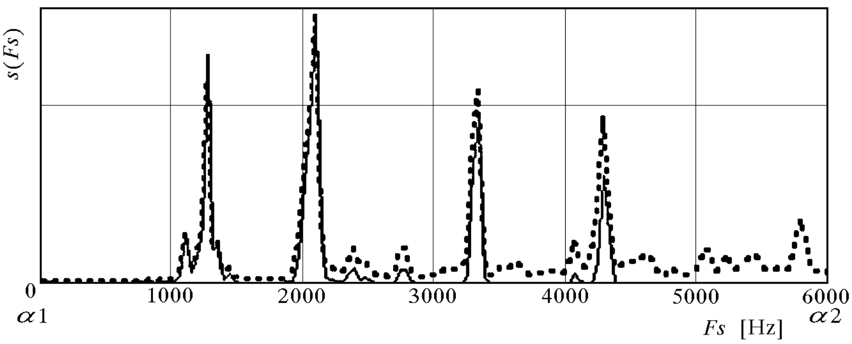

Fig. 2. An example of a signal spectrum with the use of a filter at the FFT stage (full line) as well as without the filter (broken line)

Calculation results are presented in diagrams that show the spectral frequency by which the signal, that is the object response to the percussive impulse, has the largest amplification. A diagram of all absolute values

$$|C_j| = \sqrt{\mathrm{Re}[fft(z_j)]^2 + \mathrm{Im}[fft(z_j)]^2}$$

directly obtained from FFT does not always enable implementation of the main formant identification because the signal also includes different frequencies whose absolute values, as a result of transformation, are shown equally as absolute values coming from responses of the object itself. The identification of the main formant by means of the proposed algorithm is considerably more comfortable than the identification obtained using the FFT procedure, and it enables simultaneous catching of various divergences which can appear during analyses. An illustration of such incompatibilities is presented in two examples: example I in Fig. 3 and example II in Fig. 4.

In example I (Fig. 3) it can be noticed that at a spectral frequency of about 1030 Hz the largest amplitude in the considered spectrum range (dotted line) occurs, however, near a frequency of about 2050 Hz (full line) the main formant of this signal occurs. Next, in example II (Fig. 4) one can see that at a spectral frequency of about 1100 Hz the largest amplitude in the studied spectrum range (dotted line) occurs, whereas near a frequency of about 1600 Hz (full line) the main formant of this signal occurs. The presented divergences may be caused by wrongly cutting the record window off and such results should be excluded from further analysis (Kucharski, 2002).

The influence of cutting the record off, on the main formant shift is shown in Fig. 5.

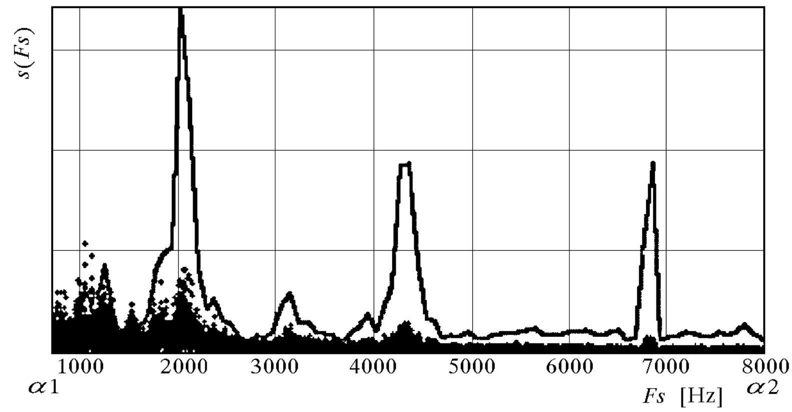

Fig. 3. Example I (described in the text)

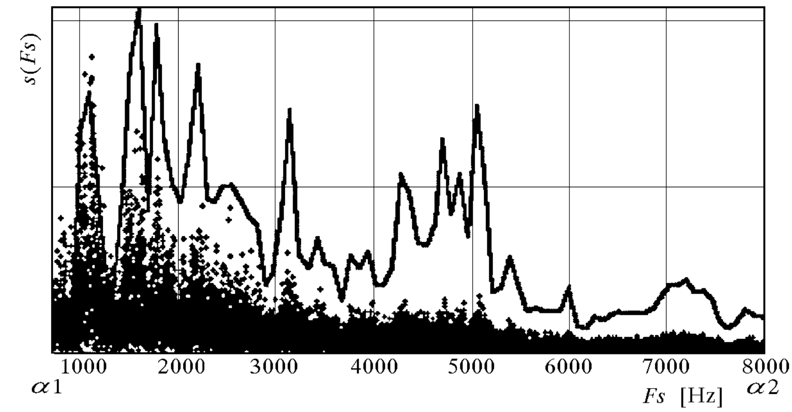

Fig. 4. Example II (described in the text)

The measurement of the object responses to the percussive force, carried out after each object is moistened with water, enables the determination of the change of the main formant position with the moisture change of the object.

The signal represented by the full line comes from the object with lower moisture, whereas the signal represented by the dashed line comes from the same object but with higher moisture. It is seen in this figure that the main formants lie in the same frequency range, i.e. about 2000 Hz. In order to identify more easily the frequency range, in which the main formant of both signals lies, a graph magnification was completed (see Fig. 6).

The exact readings of the main formants position frequencies from the range of 2000-2200 Hz, shown in Fig. 6, can be directly made out from diagrams and printouts in a MATHCAD® program.

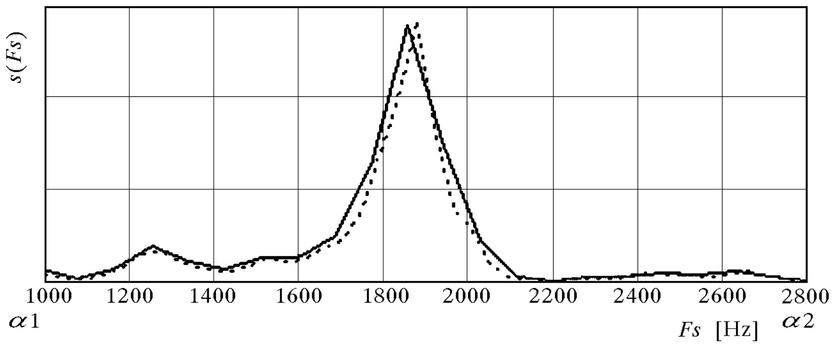

Fig. 5. Spectra of correctly – (full line) and wrongly cut off (broken line) signals – the main formant is shifted

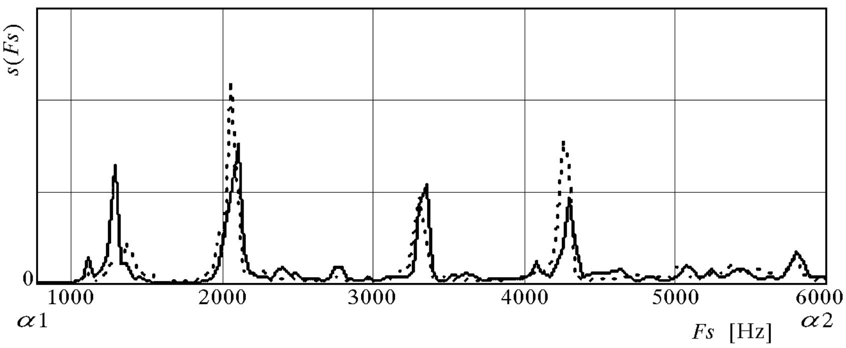

Fig. 6. A spectrum diagram of two signals of the object response to a percussive impulse – the object with different moisture

As the object moisture grows – the main formant shifts towards lower frequencies.

The relationship course of the m_w/m_o quotient on the main formant position for objects from two different materials (sandstone and cement) is presented in Fig. 7 and Fig. 8.

The moment at which the object percolation occurs is denoted in Fig. 7 and Fig. 8 with black filled points (the object material is completely moistened with water). The measurement points that are shown in the figures can be approximated by means of a smooth function. The analysis has shown that these points are well approximated by a second-degree polynomial, which makes an analogy with the guidelines of the ITB (Polish Building Research Institute) specification [13], which relates to supersonic measurement methods.

Fig. 7. A position characteristic of the main formants depending on the degree of material moisture – a sandstone plate

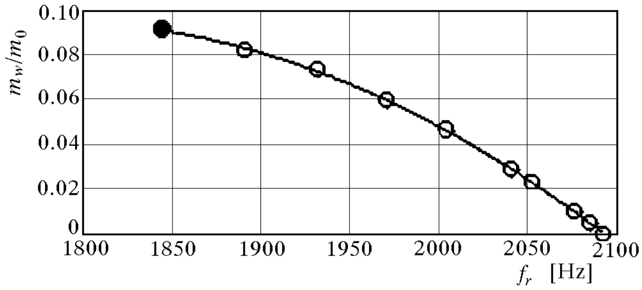

Fig. 8. A position characteristic of the main formants depending on the degree of material moisture – a cement plate

6. Conclusions

The approximation of points in the diagrams presenting the moisture dependence on the main formant position enables the determination of the function which can be identified with the frequency characteristic of the humidity of investigated objects. This means that the object feature, which is its moisture, can be described in the frequency field. This feature can be implemented in the testing of hygrometers that are used for moisture investigations of porous materials, as for example hygrometers for wood or concrete. The method and software were used much earlier by Professor Bogdan Skalmierski for diagnostics of the violin, where dependence between stress states of sound boards and the main formant position occurs. The presented measuring and computational method is much simpler and cheaper than the ultrasonic method.

Acknowledgement

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References

1. Bendat J.S., Piersol A.G., 1976, *Methods of Analysis and Measurement of Random Signals*, PWN, Warsaw (in Polish)
2. Cempel C., 1989, *Applied Vibroacoustics*, PWN, Warsaw (in Polish)
3. Chmielewski T., Zembaty Z., 1999, *The Elements of Building Dynamics*, Arkady, Warsaw (in Polish)
4. Kaliski S., 1986, *Vibrations and Waves*, PWN, Warsaw (in Polish)
5. Kucharski T., 2002, *The System of Mechanical Vibrations Measurement*, WNT, Warsaw (in Polish)
6. Lyons R.G., 2000, *Introduction to Digital Signal Processing*, WKiL, Warsaw (in Polish)
7. Marven C., Ewers G., 1999, *Outline of Digital Signal Processing*, WKiL, Warsaw (in Polish)
8. Nowacki W., 1972, *Dynamics of Buildings*, Arkady, Warsaw (in Polish)
9. Osiński Z., 1978, *Theory of Vibrations*, PWN, Warsaw (in Polish)
10. Paleczek W., 2003, *Mathcad 2001 Professional*, Akademicka Oficyna Wydawnicza EXIT, Warsaw (in Polish)
11. Skalmierski B., 1986, *Stress State in Sound Boards and the Quality of Instrument*, PWN, Warsaw (in Polish)
12. Skalmierski B., 2001, *Analytic Mechanics and Theory Vibrations*, Wydawnictwo Politechniki Częstochowskiej (in Polish)
13. ITB Specification No. 209: Use specification of supersonic method for nondestructive quality inspection of concrete in construction. ITB, Warsaw 1998 (in Polish)

Metoda badania wilgotności materiałów przy wykorzystaniu FFT

Streszczenie

Przedstawiono metodę badania wilgotności obiektów wykonanych z materiałów porowatych przy wykorzystaniu szybkiej transformacji Fouriera (FFT). Sygnał dźwiękowy, będący odpowiedzią na wymuszenie udarowe, rejestrowany jest w postaci cyfrowej, przy zadanej częstotliwości próbkowania i w dalszym etapie, w celu określenia formantu głównego, poddawany jest analizie w dziedzinie częstotliwości. Wykazano, że położenie formantu głównego, będącego odpowiedzią obiektu na wymuszenie udarowe, jest funkcją zmian wilgotności badanego obiektu. Zaprezentowano algorytm umożliwiający analizę omawianego zjawiska w środowisku MATHCAD. Przykładowy zakres stosowalności opisanej metody i programu: i) do testowania wilgotnościomierzy stosowanych w badaniu wilgotności materiałów porowatych; ii) przedstawiony algorytm opracowany przez Profesora Bogdana Skalmierskiego był przez Niego stosowany już wcześniej w diagnostyce instrumentów lutniczych, gdzie ujawnia się zależność pomiędzy położeniem formantu głównego a stanami naprężenia.

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