Non-destructive Methods For Composite Materials Anisotropy Evaluation

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Introduction

The control of sheet materials (paper, fiberboard and other) anisotropy is actual nowadays. To control mechanical sheet materials anisotropy Lamb waves are used. Materials can have mechanical as well as electric anisotropy, which is characteristic only to dielectric materials. Electric anisotropy can be evaluated by measuring permittivity in various directions. The objective of this work is to create methods and equipment for measuring permittivity anisotropy and to check assumptions of existing connections between electric and mechanical sheet materials anisotropy.

Theory

Composite materials consist of fiber (coal, wood, glass and other fiber) and filling. Usually fiber and filling have different permittivity. In some materials fiber arrangement is chaotic, in other ones fiber has prevalent direction. If the material permittivity of fiber and filling are different, and fiber has prevalent direction, such materials have dielectric anisotropy.

Electric capacitance forming between two electrodes can be expressed in different ways:

1. $$C = \varepsilon_0 \varepsilon_r \frac{S}{d} \quad ; \qquad (1)$$

here: ε_0=8.854187817 10^{-21} F/m – electric constant; ε_r – relative permittivity; *S* – overlapping areas between electrodes; d- distance between electrodes.

2. $$C = \frac{Q}{U} \quad ; \qquad (2)$$

here: *U* – voltage between electrodes; Q – difference of charge between electrodes.

$$Q = \varepsilon_0 \varepsilon_r \int\int\int \overline{E}(\overline{r}) dA \qquad (3)$$

3. $$C = 2\frac{W}{U^2} \quad ; \qquad (4)$$

here: *W* – potential electric energy between electrodes.

$$Q = \frac{1}{2}\varepsilon_0 \int\int\int \varepsilon_r(\overline{r})\left(\overline{E}(\overline{r})\right)^2 dV \qquad (5)$$

It can be seen that in all expressions capacitance depends on permittivity.

If permittivity is different in different directions and we want the chose one, according to formula (5) the biggest dependence of energy (and capacitance as well) on permittivity in a chosen direction will be the biggest when the direction of electric field will coincide with a chosen permittivity direction.

Electric field near electrode surface places itself perpendicular to the surface of the electrode. Receding from the surface of the electrode the direction of the electric field depends on the electrodes nearby and the permittivity of the surrounding.

The best way to evaluate electric anisotropy is to use two parallel electrodes and place a sample of tested material between them. Then the main components of electric field will locate in straight direction between electrodes and thus the maximum of electric capacitance dependence on permittivity in a measured direction. But this method is destructive – in order to place electrodes in the tested material, material must be broken.

Electrodes can be put to the tested material in several ways for non-destructive testing. We have just one suitable method. Electrodes have to be placed on the surface of the tested material.

After choosing the form and arrangement of electrodes the maximum proportion of *ΔC/C* can be obtained

$$\frac{\Delta C}{C} = \frac{C_x - C_y}{C_x + C_y} \quad . \qquad (6)$$

here: C_x – is the capacitance when electrodes are placed in the direction *x*; C_y – is capacitance when electrodes are put in the direction *y*.

Then permittivity anisotropy is

$$\frac{\Delta \varepsilon}{\varepsilon} = \frac{\varepsilon_x - \varepsilon_y}{\varepsilon_x + \varepsilon_y} = K \frac{\Delta C}{C} \quad , \qquad (7)$$

here ε_x is permittivity in the direction *x*; ε_y is permittivity in the direction *Y*; *K* is a coefficient, which depends on the parameters of electrodes.

If electrodes were placed parallel and the tested material was put between them, then the coefficient *K* would be close to 1. Electrodes are on the surface and *K* will be significantly smaller than the *1*. Our task is to find the optimal placing of electrodes to have the maximum coefficient *K*.

Theoretical investigation – modeling

In order to evaluate electric anisotropy, anisotropic electric field has to be created. For this reason, electrodes of comb type will be used, when the length of electrodes is much bigger than other parameters (fig.1).

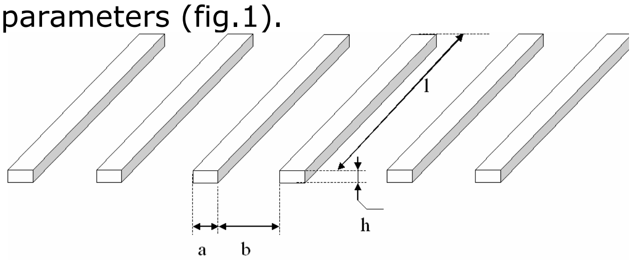

Fig.1 **Electrodes:** a – the width of electrodes; b – the distance between electrodes; h – the thickness of electrodes.

In order to optimize electrodes and find the maximum parameter *K* we will use the method of finite elements. We use Ansys program for finite element modeling, and capacitance between electrodes we calculate using "Capacitance Matrix" function.

In our case the thickness, the width of electrodes and the distance between them can be changed. We change relative permittivity of tested material also.

Dielectric material covered with copper was used for practical production of electrodes. In order to receive modeling results as close to the field experiment as possible a dielectric material model was used in the modeling too.

The modeling was performed with the 0,5 mm wide electrodes having distance between them 4,5 mm, thickness of electrodes was 0,1 mm and relative permittivity of test material was 50. The electric field potential is shown in figure 2.

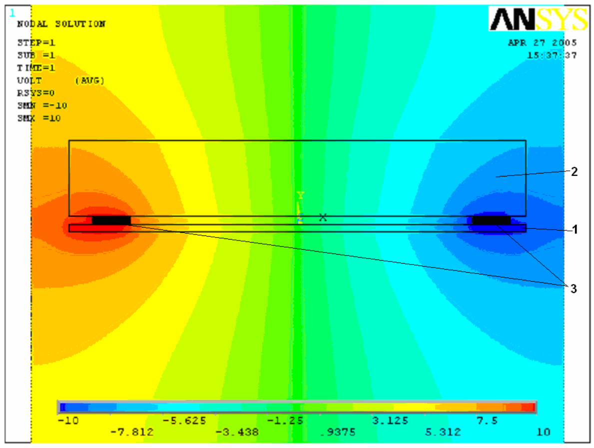

Fig. 2. **Electric potential between two electrodes, when** 1 – test material; 2 – dielectric material, with ε_r=2; 3 - electrodes;

The dependence coefficient *K* on permittivity of tested material was investigated. The modeling was performed with the 2,5 mm wide electrodes having distance between them 2,5 mm and 0,1 mm thickness of electrodes. The dependence coefficient *K* on permittivity of tested material is shown in figure 3.

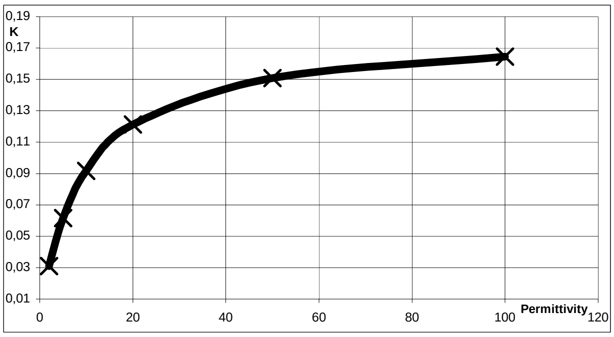

Fig.3 **The dependence of *K* on tested material relative permittivity ε_r**

It can be seen from figure 3, that the coefficient *K* is bigger when relative permittivity of testing material is bigger. This happens because electric flux density in tested material increases, when relative permittivity of testing material is bigger. Electric flux density is shown in figure 4.

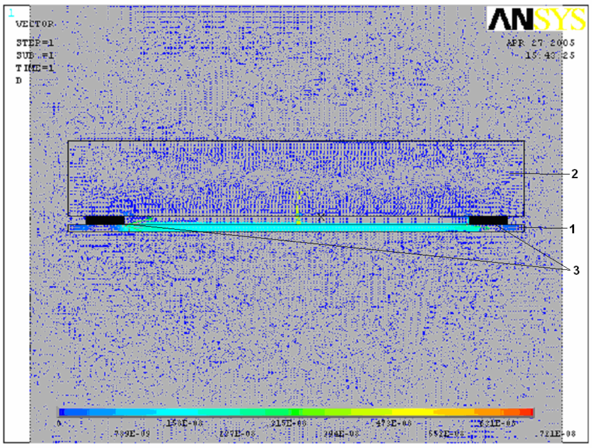

Fig. 4 **Electric flux density, when**: 1 – test material; 2 – dielectric material, with ε_r=2; 3 - electrodes;

Two cases of modeling were performed. In the first case electrodes were placed to the tested material through 1 mm thick dielectric material, which relative permittivity is ε_r=2. In the second case electrodes were put to the tested material directly. In both cases the results showed the dependence of coefficient *K* on the proportion *a/b*, when the thickness of electrodes is *h* = 0,1 mm. Both dependences are shown in figures 5 and 6.

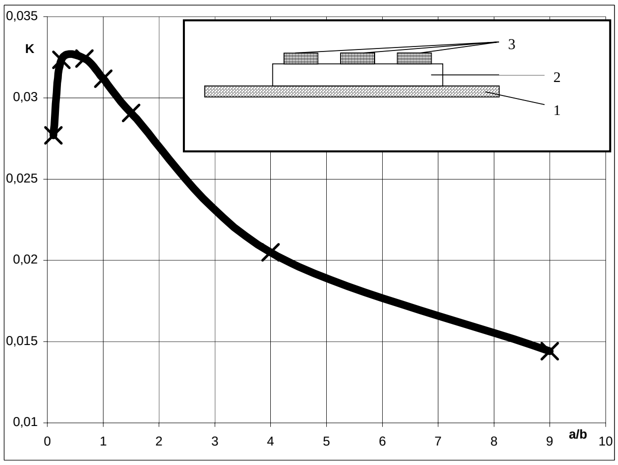

Fig.5 **The dependence of *K* on *a/b*, when**: 1 – test material; 2 – dielectric material, with ε_r=2; 3 - electrodes;

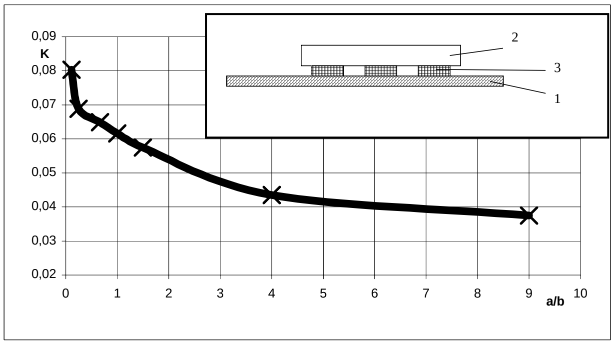

Fig.6 **The dependence of *K* on *a/b*, when**: 1 – test material; 2 – dielectric material, with ε_r=2; 3 - electrodes;

It can be seen from figures 5 and 6 that the proportion *ΔC/C* and the coefficient *K* are bigger when electrodes are placed directly to the tested object. As it is shown in figure 5, when the proportion *a/b* decreases, the proportion *a/b* is increasing to the limit *a/b* = 0,667. When proportion *a/b* is smaller than 0,667, the proportion *ΔC/C* and coefficient *K* decreases. This happens because electric field lines close in dielectric material no.2 and only a small part of them reaches the tested material.

When electrodes are placed directly to the tested material the proportion *ΔC/C* as well as the coefficient *K* increase and the proportion *a/b* is decreasing. This modeling clearly shows that:

1. It is necessary to place electrodes directly to the tested object;
2. The smaller is the proportion between the width of electrodes and the

distance between them, the bigger is the proportion *ΔC/C*, as well as the coefficient *K*.

Also theoretical dependence of the *K* on the thickness of electrodes was investigated. The modeling was performed with the 2,5 mm wide electrodes having the distance between them 2,5 mm. The dependence of the *K* on the thickness of electrodes is shown in figure 7.

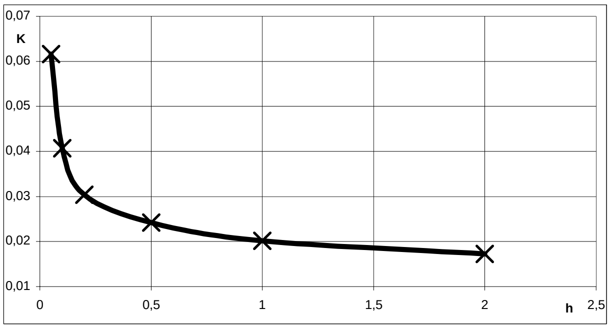

Fig.7 **The dependence of *K* on *h***

As it can be seen in figure 7, it is advisable to use thinner electrodes. The thinner are the electrodes, the bigger is the proportion *ΔC/C* and the coefficient *K*.

After several modeling procedures the following conclusions were drawn:

1. Electrodes have to be placed to the tested material directly;
2. The width of electrodes a and the thickness of electrodes h have to be as small as possible;
3. The distance between electrodes has to be as big as possible.
4. Common permittivity of tested material has to be estimated.

The capacitance of about 0,6pF forms between two electrodes with the length of 45 mm, the thickness *h* = 0,1 mm, the width *a* = 0,5 mm, and the distance between the electrodes is *b* = 4,5 mm. In order to increase the capacitance more electrodes were placed together. In this way an electrode comb, called a capacitance comb, was made. Increasing a number of electrodes, the electric capacitance *C* as well as the difference between capacitances *ΔC* increase. Therefore the proportion *ΔC/C* and the coefficient *K* stay unchanged.

Experimental research / investigation

A special capacitance comb shown in figure 8 was made for experimental materials testing.

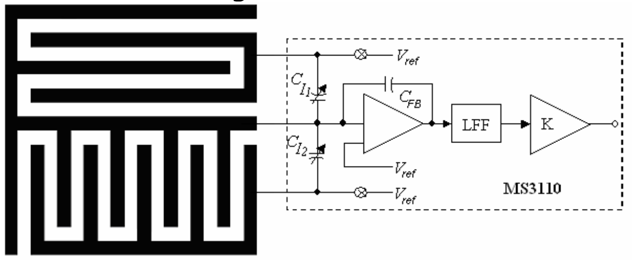

Fig.8 **A special capacitance comb for permittivity anisotropy estimation with MS3110 [6]**

This transducer evaluates two capacitances at once: one capacitance reflects the permittivity ε_x in the direction x, another capacitance reflects permittivity ε_y in the direction y.

The microchip MS3110 was used for capacitance measurement (This microchip is made by "Micro-sensors", capacitance measurement resolution 4aF/rtHz) [6]. RLC measurement instrument "Instec LRC – 819" was used for calibration.

The experiments were carried out with paper and fiberboard. In order to minimize the influence of surrounding factors, all the system was not moved during the experiment and only the tested material – paper and fiberboard was rotated. The material with low permittivity was used to ensure paper pressing. To reduce the influence of the pressing material it was in a fixed position – its position towards the position of the capacitance comb did not change.

In order to compare electric and mechanical anisotropy, ultrasonic anisotropy testing was performed. Measurement of Lamb waves propagation velocity was measured with "Hardboard Strength Meter" [4].

The results of paper anisotropy measurement using electric and Lamb wave methods [5,6] are shown in fig 9(a). The results of fiberboard anisotropy measurement using electric and Lamb wave methods are shown in fig 9(b). Measurement were performed every 10 degrees of circle perimeter.

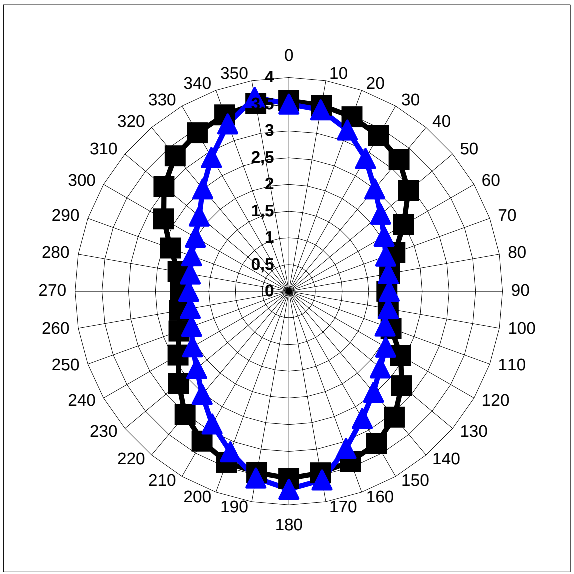

Fig.9 a) **The dependence of paper properties on direction:** —▲— - Lamb waves velocity in kilometers per second; —■— - change of electric capacitance in 0,1 Pico farads minus 7 pF.

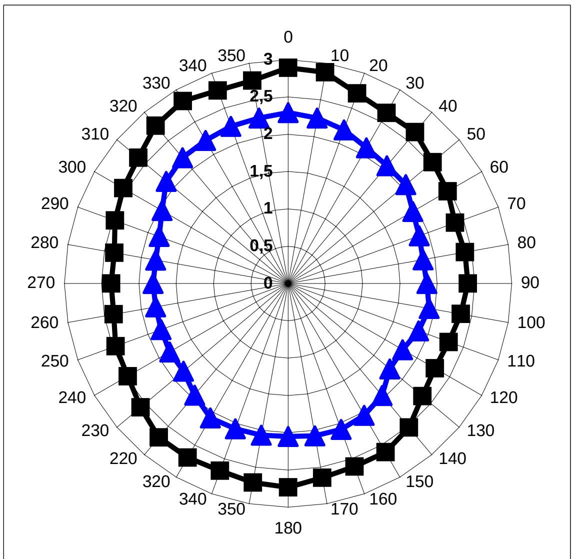

Fig.9 b) **The dependence of fiberboard properties on direction:** —▲— - Lamb waves velocity in kilometers per second; —■— - change of electric capacitance in 0,1 pF minus 7 pF.

Two lines are shown in fig.9. One marked with triangles (—▲—), shows the dependence of Lamb waves velocity on direction in kilometers per second. The other one marked with squares (—■—) shows the change of electric capacitance dependence on direction in 0,1 Pico farads minus 7 pF.

In paper, fiber arrangement has strong prevalent direction – it is proven by both electric and ultrasonic methods.

In fiberboard fiber arrangement is more chaotic – it is confirmed by the results of both electric and ultrasonic methods.

The results of experiments show that the both paper and fiberboard properties can be evaluated ultrasonic as well as electrical method.

Common permittivity of tested material has to be estimated. In order to estimate common permittivity and permittivity anisotropy, special capacitance transducer was created. Schematic of this transducer is shown in figure 10.

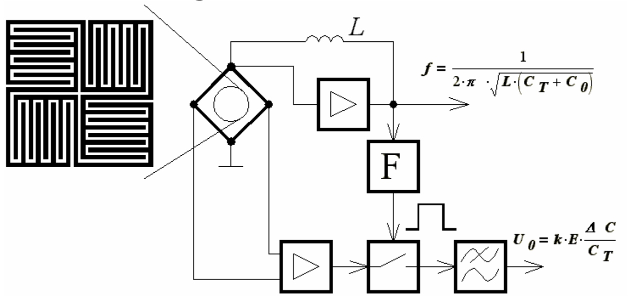

Fig.10 **Capacitance comb for Common permittivity and permittivity anisotropy estimation**

This type of capacitance transducer has two valuable signals – output frequency and output voltage. Frequency is proportional to common capacitance and voltage is proportional to change of capacitance. Common permittivity and permittivity anisotropy can be estimated using this equipment.

Conclusion

- The experiments show that paper and fiberboard properties can be evaluated by using both ultrasonic and electrical methods;
- Electrodes have to be placed as close to the tested materials as possible.
- Electrodes have to be as thin and narrow as possible.
- Common permittivity of tested material has to be estimated

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Nondestructive methods for composite materials anisotropy testing

Summary

Composite materials are widely used nowadays. These materials usually have various anisotropical properties because of fiber in them.

This article presents two nondestructive anisotropy evaluation methods: electrical and ultrasonic. Ultrasonic method is based on precision Lamb wave velocity measurement. Electric method is based on permittivity measurement, using special capacitance transducers.

It was found, that experimental results of both methods strongly correlated with results of known strength determination methods.

These methods can be used for anisotropy evaluation of fiberboard, paper and other composite materials. In addition, both methods can be implemented in production line

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