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Method of Estimation of the Tension Wave Propagation Velocity in Flat Textile Products

Abstract
When considering the anti-impact applications of flat textile products, we must take account of the effect of a tension wave on the product's structure. Such a wave forces the creation of fast-changing deformations and active tensions. An example of anti-impact applications of flat textile products are ballistic textile barriers, in which deformations and tensions are generated by the stroke of a projectile moving at a very high velocity, in the range of 50-1600 m/s. The total time of duration of the phenomena acting in the product is often not longer than 5-50 μs. The quality of transmission of this type of impulse load through flat textile products depends on many factors, such as raw material and the geometrical structure of the product, as well as the dynamic of dissipation of the tension wave pulse energy. This latter, in turn, is connected with the propagation velocity in the medium under consideration. Estimating this feature of a flat textile product yields information which can be used firstly for optimal designing of the product considering its ability to absorption the pulse energy. This article presents a research method for estimating the tension wave propagation velocity by means of an optoelectronic transducer. Preliminary research tests carried out with the application of the presented m ethod are also described.

Key words: *flat textile products, tension wave, propagation velocity, wave propagation velocity, wave propagation medium, optoelectronic transducer.*

Introduction

The impulse input function acting on a flat textile product is characterised, at the first moment of action, by a jump-like displacement increase in those elements of this product which are connected with the source of generation. The energy of the tension wave created by this means is dissipated over the pulse duration by displacement of the subsequent material points lying in the plane of the 2D-product [1]. The increase with time in the area which dissipates the wave energy longitudinally in the plane of the product depends on the propagation velocity in the given direction of the product's medium. The propagation velocity is a parameter characteristic for each medium, and its limited value will cause the phenomenon of the so-called transport delay of the tension wave.

In the case of a one-dimensional textile object (yarns, monofilaments, filament fibres etc.), the mechanism of the pulse wave propagation is already familiar from many research works (mostly experimental) which have been carried out. Investigations into the propagation velocity of a longitudinal tension pulse in linear textile products have been carried out by Czołczyński, Szosland, and Stempień [1-3] among others. The experimentally obtained propagation velocities of tension pulses in threads manufactured from different raw materials, and their dependence on the preliminary thread tension, have been described by the above-mentioned authors. The values of the pulse propagation velocity have been included within the following ranges: from over 1000 m/s for wool, from 2000 m/s to 3000 m/s for cotton, and up to 5000 m/s for synthetic multifilaments.

In the case of a two-dimensional structure, the phenomenon of tension wave generation has been analysed predominantly during the mutual interaction of a flat textile barrier with a penetrator moving at great velocity within the range from 50m/s to 1400 m/s. Such a penetrator can be a projectile, the splinters of high-explosive shells, as well as fragments which break away from machines working at high rotational or linear velocities. This latter case can occur, for example, in jet engines, in which textile barriers are used as a kind of anti-splinter protective casing. The purpose of a flat textile anti-splinter protective barrier is to absorb the whole energy of the moving penetrator. The total destruction or degradation of the barrier depends on the amount of energy absorbed, as does its piercing or increased deflection, which may cause a harmful impact on the user's body in the case of personal protective barriers. The energy absorption by a flat textile barrier depends principally on the strength properties of the raw material, but the propagation velocity of the tension wave can have significant importance, as it determines the area of non-zero tensions in the barrier as a function of time. Thus, the need arises to measure this parameter in real flat textile products which are structurally differentiated (Figure 1).

A textile barrier in the form of a woven fabric has an orthogonal character with two directions predominating. In the investigations previously carried out, especially in those based on modelling, the wave propagation velocity is accepted as a constant, similar to those of an isotropic material [4-6]. In such a case, the wave propagation velocity can be determined from the equation:

$$c = \sqrt{\frac{E}{\rho}} \tag{1}$$

where:
- c - the wave propagation velocity in the plane of a flat isotropic product,
- E - the modulus of elasticity determined experimentally at different deformation velocities,
- ρ - the density of the wave propagation medium.

Roylance et al. [7] assume that the wave velocity in a plain fabric can be estimated on the basis of the following equation:

$$c_f = c\sqrt{2} \tag{2}$$

where:
- c_f - the wave propagation velocity of a plain fabric,
- c - the wave propagation velocity expected for the single fibre.

Considering the anisotropy of the product's medium, the tension wave propagation velocity depends on the properties of the medium (the woven fabric) in the giv-

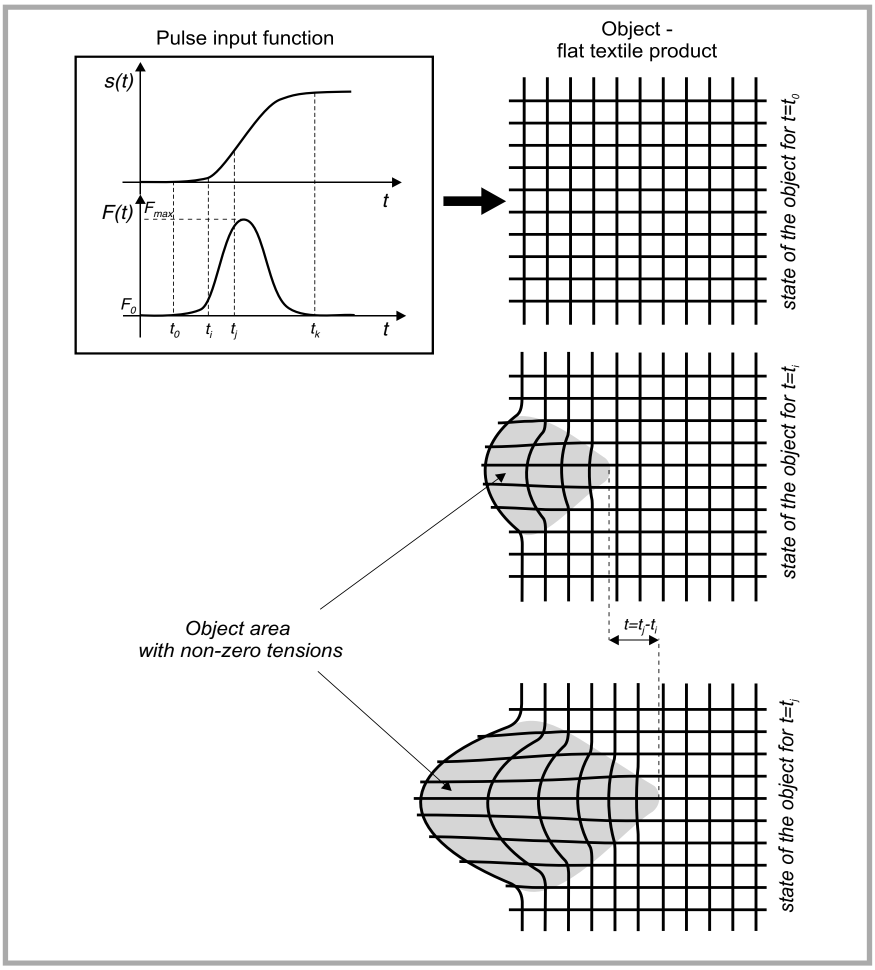


Figure 1. Model of action of a one-directional tension wave on the woven fabric.

en direction φ of wave propagation. The geometrical differentiation of the media at selected angles of wave displacement in the range of one report of the woven fabric is presented for the two analysed fabrics in Figures 4 and 5. The analysis of the particular cross-sections allow us to draw the following conclusions:

- the density of the material considered is different for the particular directions ρ=ρ(φ);
- the material continuity of the medium (the textile fabric) is ensured practically exclusively in the directions of warp and weft (φ=0° and φ=90°); the medium structure is discontinuous in all other directions;
- the medium geometry for the given direction depends on the product structure (in this case, on the weave);
- the modulus of elasticity depends on the direction φ considered; for the continuous medium structure (warp and weft directions) the material deformations are dominant; for the discontinuous medium, deformations of shape are significant.

On the basis of the above-mentioned conclusions, Equation (1) describing the tension wave propagation velocity can be presented in the following form for the flat textile structures:

$$c(\varphi)=\sqrt{\frac{E(\varphi)}{\rho(\varphi)}} \tag{3}$$

where:

c(φ) - the wave propagation velocity in the φ direction of the flat textile product,

E(φ) - the modulus of elasticity in φ direction,

ρ*(φ)* - the density in φ direction.

Flat textile products are in reality characterised by anisotropy of their properties, firstly as the result of the orthogonal character of textile products. The results of the impact of an penetrator (a bullet) on woven fabrics with different weaves are presented in Figures 2 and 3. Figure 2 shows a woven fabric with a 1/1 plain weave, whereas Figure 3 presents a woven fabric with a 2/2 twill weave. The moduli of elasticity and the specific densities of textile products do not have constant values as for isotropy bodies, but are functions of the φ parameter. Thus, the wave propagation velocity, which characterises the displacement in time of the non-zero tensions in the flat textile product will be advantageously determined directly, and not on the basis of the moduli of elasticity measurements. This is the reason that this stage of the investigation was devoted to developing an

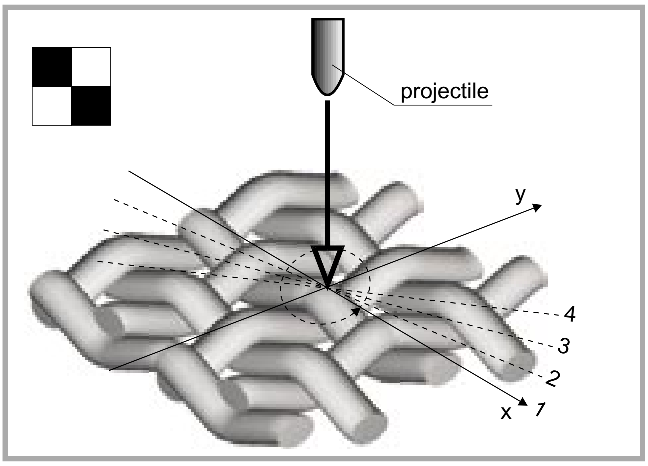


Figure 2. *Model of a woven fabric with 1/1 plain weave; 1 - φ=0°, 2 - φ=15°,3 - φ=30°,4 - φ=45°.*

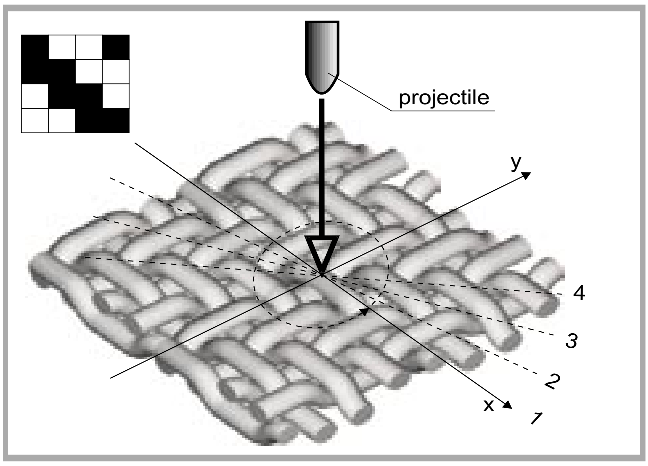


Figure 3. *Model of a woven fabric with 2/2 plain weave; 1 - φ=0°, 2 - φ=15°,3 - φ=30°,4 - φ=45°.*

effective method of measuring the wave propagation velocity in differentiated flat textile products.

Research Stand

The research stand for measuring the wave tension velocity is composed of two parts: a tension wave generation system, and the measurement system for assessing the displacements of selected points in the plane of the fabric. A scheme of the stand is presented in Figure 6.

The tension wave generation consists in the release of the potential energy accumulated in an elastic element, which in our system takes the form of an elastomer surrounded by a polyester braid (12). The object tested, a woven fabric of a given weave (1), is connected with the point of the tension wave generation by a segment of the monofilament (2). A static force F_p is applied to an auxiliary strand (15) fastened to the half-loop (12) at the point B of the elastomer immediately before releasing the tension impulse. The elastomer is stretched, and by the same action the point B is displaced to the moment, as the force components in both ends of the half-loop achieve a value which equals half of the sum of the forces F_p and F_w (F_w being the preliminary tension in the object tested). The value of displacement of the point B, in the state after loading the elastomer by the force F_p, determines the amplitude value of the step unit. A releasing system, which includes a resistor wire, a power transistor working in a keying circuit, and a direct current supply, is used for releasing the tension impulse. The auxiliary strand (15) is in direct contact with the resistance wire which is connected in the circuit of the power transistor. At the moment when the transistor is saturated, the resistance wire is dynamically heated and causes the auxiliary strand, manufactured from a polyamide monofilament of 0.3 mm diameter, to burn out. At this time, the action of the force F_p is cut off from the point B of the half-loop. The point B is displaced at the value s_p, and returns to its primary position. The tension in the particular ends of the half-loop at the primary position is selected in such a way that the value s_0 equals zero, with the aim of obtaining an intimate contact of point B of the elastomer with the barrier (10, 11). This condition must be fulfilled, even though a preliminary tension exists in the object tested, and a tension excess exists which is caused by the propagation of the tension wave. The parameters and character of the impulse

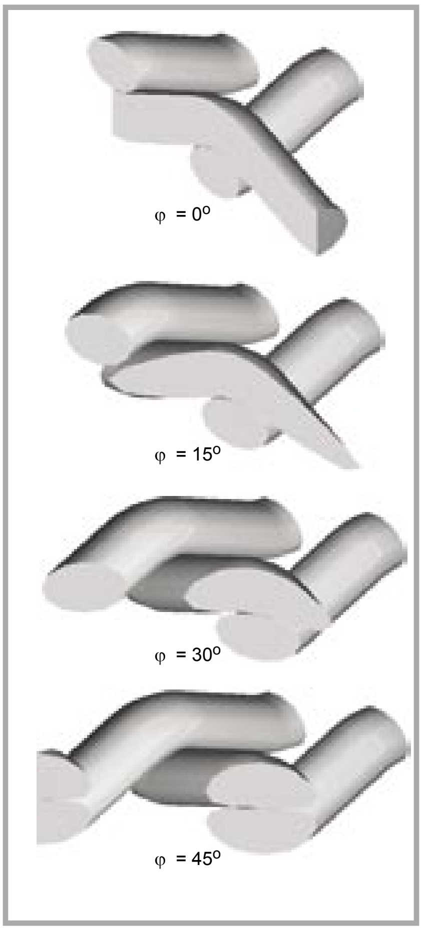


Figure 4. *Geometrical structure of the wave propagation medium, the woven fabric with plain weave, for different angles of wave propagation.*

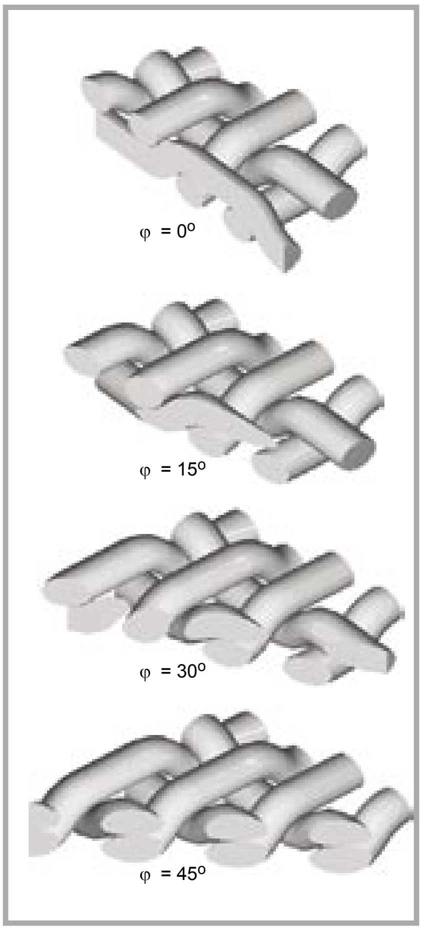


Figure 5. *Geometrical structure of the wave propagation medium, the woven fabric with twill weave, for different angles of wave propagation.*

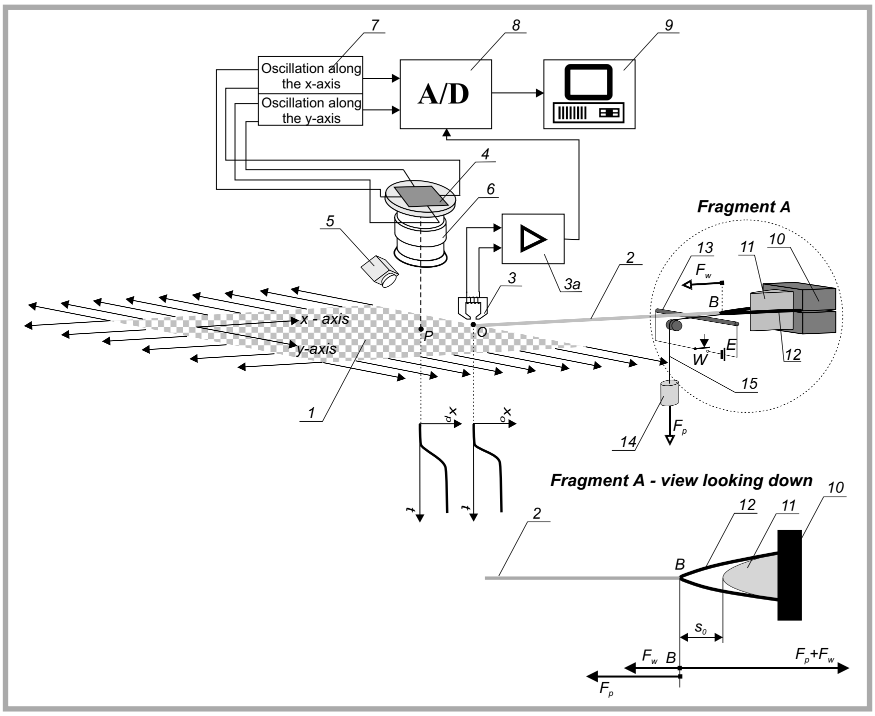


Figure 6. *Scheme of the research stand: 1 - object tested, 2 - monofilament, 3, 3a - inductive detector of the wave front, 4 - PSD transducer (detector), 5 - light source (illuminator), 6 - object lens, 7 - current amplifier, 8 - A/D transducer, 9 - computer, 10 - non-transitive barrier, 11 - buffer, 12 - elastomer, 13 - releasing system, 14 - stretch force, 15 - auxiliary strand.*

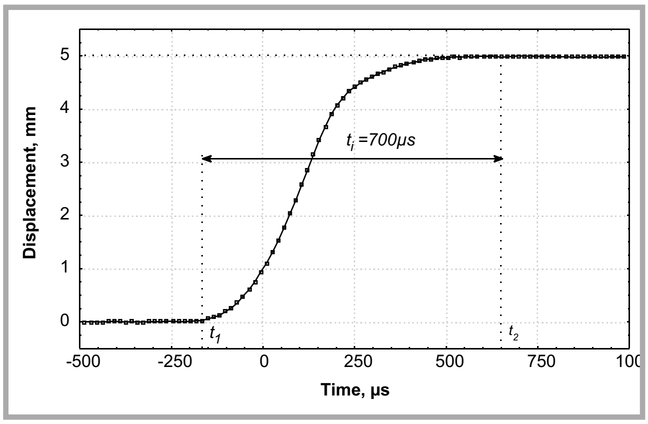
input function (the displacement of point B) are shown in Figure 7. The maximum increase velocity of the displacement equals 15 m/s; this is a velocity sufficient to create an impulse tension wave in the system, which is dislocated through the medium.

A PSD optoelectronic transducer (Position Sensitive Detector) is the main element (4) of the measurement system. It enables the displacements of selected points of the woven fabric in its 2D-plane to be recorded. The main static and dynamic metrological parameters of the transducer are listed below:
- the area of the photo-sensitive surface: 13×13 mm,
- resolution: 10 µm,
- photo sensitivity (λ=900nm): 0.6 A/W,
- rise time: 1.5 µs,
- electric current generated at light intensity which equals zero (dark current): 20 nA,
- the size of the light spot has no influence on the correct determination of the spot co-ordinates,
- the intensity of the falling light forming the spot has no influence on the correct determination of the spot coordinates, but must be greater than the threshold value at which excitation of the photosensitive layer occurs (the generation of a current greater than the dark current).

The fragment of the woven fabric under observation, indicated by a circular marker of about 0.2-0.5 mm diameter of a fluorescent emulsion, is illuminated by the light source (5). The light reflected by the fluorescent marker is focused on the photosensitive surface of the PSD transducer (4) with the use of an optical system (6).

After releasing the tension wave, its propagation begins, and after a certain time the front of the wave appears before the head of the induction detector (3), which activates the signal recording system by means of the analogue-digital transducer (8). The arrival of the pulse at the point under observation is accompanied by surface changes of the point position and the fluorescent marker position. The changes in the position of the marker, thanks to the optical system, are related to the spot changes on the photosensitive surface of the PSD detector. These changes are transformed into two pairs of currents which finally determine the momentary position of the point under observation in the x-y co-ordinates. Next, all the currents are transformed by

Figure 7. Character and parameters of the pulse input function (the displacement of point B).



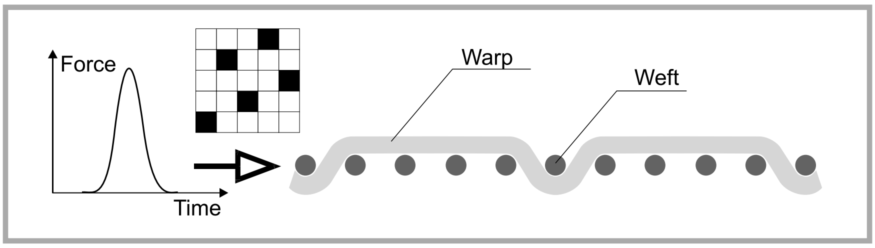


Figure 8. *Weave notation and model of the tension wave advance on the interlacement of warp and weft threads in a woven fabric with twill weave.*

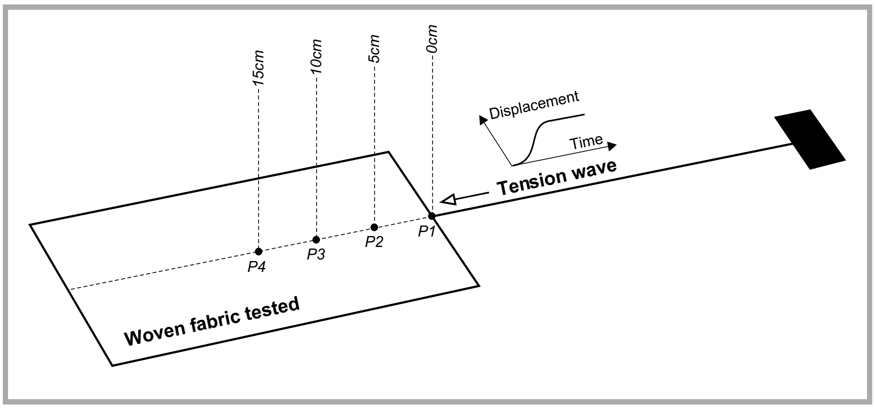


Figure 9. *Scheme of the test for assessing the transport delay of the tension wave in a woven fabric.*

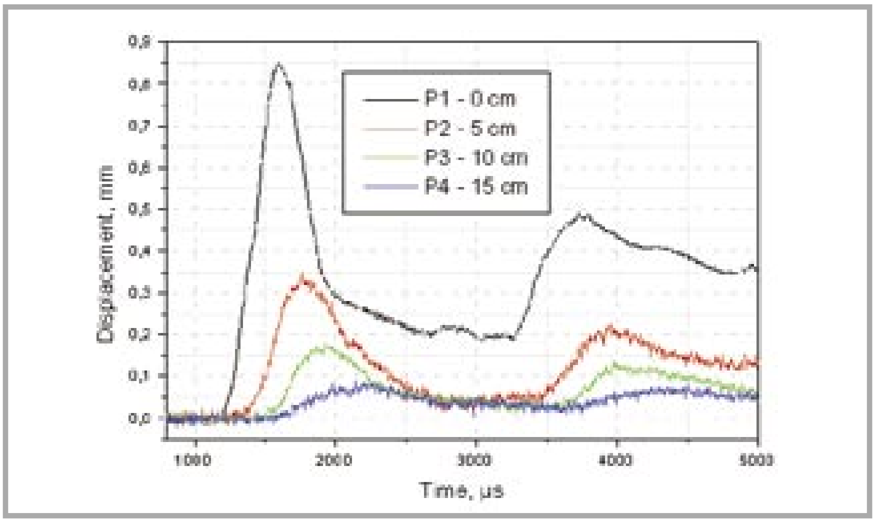


Figure 10. *Examples of measurement results of displacement changes of selected points during the tension wave transition in a woven fabric with twill weave.*

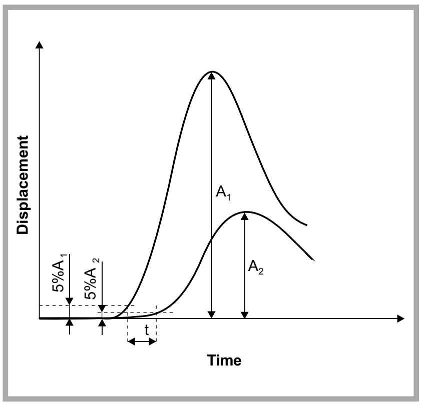


Figure 11. Determination of the transport delay Δ*t.*

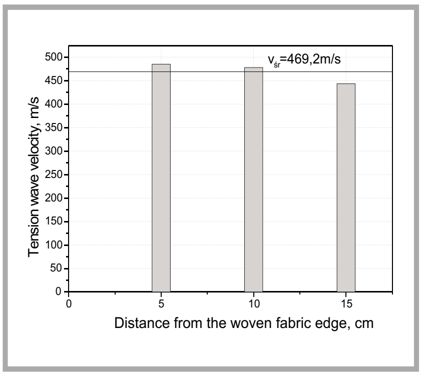


Figure 12. Tension wave propagation velocities in a woven fabric with twill weave.

a three-stage electronic system composed of an amplifier (7), an A/C transducer (8), and a computer (9). The computer system enables data to be recorded, stored, and analysed.

Research Results

The method developed was tested experimentally by determining the tension wave propagation velocity by means of assessing the transport delay. The tests were carried out for a woven fabric with twill weave (Figure 8). The measurements were performed for the selected direction along the warp, according to the scheme shown in Figure 9. Cotton yarn with a linear density of 30 tex x 2 was used as raw material for warp and weft.

The displacements of the points P1, P2, P3 and P4, which lie on the line of the tension wave action, were observed and recorded. The distances of the points under observation were respectively 0, 5, 10, and 15 cm. Examples of displacement change with time of the points P1, P2, P3 and P4 are presented in Figure 10.

The test results allow us to analyse the displacements of selected material points of the woven fabric which are positioned in the tension wave propagation direction, and of the wave dumping which is accompanied by this phenomenon. The dumping caused by the product medium results in an almost total fading of the wave action after its displacement of 15-20 cm in the woven fabric. An analysis of the displacements recorded indicates a time delay in the reaction of the material points P1, P2, P3 and P4 on the action of the tension wave front. A secondary tension wave can also be observed. This wave results from the reflection of the primary wave at the boundary of regions with different wave impedance, i.e. the woven fabric and the monofilament which is used for the transportation of the tension wave after its generation process. The partially reflected wave returns in the direction of the generator, is then reflected from the non-transient barrier, and next returns once more as the secondary tension wave in the direction of the woven fabric.

Calculation of the Tension Wave Velocity

The tension wave propagation velocity was determined on the basis of the knowledge of the response time delay in the form of displacements of the particular points under observation of the tested woven fabric with twill weave, and of the distance traversed by the tension wave. The boundary of the time delay at the particular points under observation was determined by accepting as the time delay the time after which the displacement amplitude achieved 5% of the maximum. This is the so-called 'five-percentage activation threshold', which is clearly visible in Figure 11.

The average values of the tension wave propagation velocity at the particular observation points from some tests, and the total average value representative as a medium feature, are shown in Figure 12. The total average value was estimated on the basis of v_{av}=469.2 m/s. It should be mentioned that at this stage of investigation the wave propagation velocity value was accepted as constant, although in Figure 12 it is evidently visible that the velocity decreases with the increase in the distance from the fabric's edge. Acceptance of such a hypothesis requires further investigations connected, among other things, with the development of the measuring method used.

Summary

The research method developed allows us to determine the tension wave transport delay, and indirectly the tension wave propagation velocity in the 2D-plane of a flat textile product in any selected direction, by means of the conversion of an optoelectronic signal.

The tests carried out revealed a great disproportion between the tension wave propagation velocity in the woven fabric and the pulse propagation velocity in the threads used for warp and weft. Velocity values of 2000-3000 m/s are acceptable for cotton yarns, depending on their linear density and the preliminary thread tension. As was shown above, the pulse propagation velocity was five times lower in a flat woven structure manufactured from the same raw material type.

Taking into account the great importance of the action efficiency of anti-stroke barriers in practical applications, the ability to determine the tension wave propagation in determined selected directions of a flat textile product can assist the optimisation of the product's structure from the point of view of the absorbed amount of the penetrator's kinetic energy.

The investigations presented in this article are preliminary research which will be continued with the aim of developing the measuring method, as well as to investigate the phenomena connected with the propagation of a tension wave in flat textile products.

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