New Measuring Stand for Estimating a Material’s Ability to Damp the Energy of Impact Strokes

Abstract
In this work, we present a new measuring stand designed for estimating and analysing the ability to damp the energy of impact strokes of a free falling impactor of materials destined for anti-stroke protectors inserted in clothing and protective equipment used in ‘traumatic’ sport activities, such as hockey, horse riding, football, combat sports and martial arts, as well as clothing for motorcyclists. A qualitative and quantitative analysis of the phenomenon of kinetic energy absorption allows us to record the sample deformation and the impactor’s acceleration before, during, and after the stroke on the sample, the maximum force value, the energy absorbed by the sample, and the maximum sample deflection. The record of the impactor’s acceleration changes as a function of the sample deflection is made by using a laser gauge intended to measure the sample deflection over time. The correctness of the measurement results is verified by three diverse methods.

Key words: protective clothing, anti-stroke protectors, impact strokes, damping ability, dynamic characteristic, measuring stand.

On the basis of research carried out in 1999 by the Sports Traumatology Section of the Polish Orthopaedic and Traumatology Society, it has been estimated that the total number of injuries created by ‘traumatic’ sports in Poland exceeds 10,000; the number of people crippled for life reaches nearly 600 per year. Especially alarming is the fact that young people constitute the majority among those injured.

It is symptomatic that the majority of the injured are people who practise sport in their leisure time. This may result from their lack of physical fitness, as well as from the fact that people interested in sports as a recreational activity significantly outnumber professional sportsmen. The most ‘traumatic’ sports are motorcycling, cycling, horse riding, skiing, and contact sports such as hockey, basketball, football, handball, and wrestling [2-6]. The necessity of using effective protective clothing has been confirmed on many occasions by reports and medical research [7,8]. Protection against injuries caused by impact strokes, blows and falls should also be secured by the use of protective clothing by the police and paramilitary forces taking part in riot control, jail staff, and by security guards and escorts [9].

The dynamic tests which determine the material’s damping ability of stroke energy are generally impact tests according to the majority of standards. No adequate standard or equipment has been accepted by international authorities. The British Standardisation Committee has also carried out projects (PH3/12) aimed at developing the first international standard concerning protective clothing and equipment for paramilitary forces entitled ‘Protective clothing and equipment for use in violent situations.’

The above-mentioned circumstances justified our decision to design and construct an impact-measuring stand in accordance with standards connected with the above-mentioned sports.

The brief pre-design for the stand construction was elaborated on the basis of a literature review of Polish, European and US standards concerned with the dynamic characteristic of impact strokes and standards concerning the requirements and the testing methods for sports wear and equipment used in the above-mentioned sports.

The above-mentioned circumstances justified our decision to design and construct an impact-measuring stand in accordance with standards connected with impact investigation carried out in the countries which lead in these kinds of research tests. The aim of this intention was to achieve results comparable with those obtained not only in European countries but also world-wide, and which could be accepted by international authorities.

Introduction
The problem of injuries among people devoted to sports both professionally and as a recreational activity has become more and more important over recent years, due to the increasing scope of this phenomenon. Each year, 75 million people world-wide suffer from different sporting injuries, while over 10% of whom die or become crippled for life [1].
investigation of protectors used in clothing for motorcyclists, in protective equipment of a military character, and in contact sports such as hockey, rugby, horse riding, and martial arts (combat sports).

**Brief Pre-design of the Measuring Stand Destined for Impact Investigation**

The brief pre-design for building the stand was elaborated on the basis of research methods described in the following European and US standards:

- EN 13277-1:2000, Protective equipment for martial arts - Part 1: General requirements and test methods.
- EN 13158:2000, Protective clothing - Protective jackets, body, shoulder protectors for horse riders - Requirements and test methods.

The method described in standard ASTM F355-95 seems to be the most universal of all the methods listed above. The record of the impactor’s acceleration as a function of time before, during, and after the stroke on the sample allows us to perform not only a qualitative analysis (such a limitation is characteristic of all European standards), but also a quantitative analysis of the phenomenon of kinetic energy absorption. Independently, the measuring stand was equipped with a laser displacement gauge which allows us to record in real time the transverse dimension changes of the sample during the stroke.

**Description of the Stand and the Measuring Channels**

A general view of the stand is presented in Figure 1. The requirement of measuring the dynamic damping ability of the sample in accordance with the above-mentioned standards is met by an arrangement where the anvil with the sample is attached to a base with a mass of about 600 kg. The base is placed on a frame platform with a plane of about 3 m². The free fall of the impactor on the sample is realised by fixing a vertical frame to the massive stand base. This frame is equipped with two rods (ground and polished), which serve as slide guides for the impactor’s beam with a snap fastener, which in its turn enables the adjustment of the beam’s position height in relation to the anvil. The position of the beam with the snap fastener is adjusted by a hand-wheel with brake, which enables the beam to be locked at the desired height. The base of the anvil is specially designed in order to arrange anvils of two different profiles.

The impactor construction is also differentiated. Version A of the impactor, which is its basic form with a mass of 5 kg, is equipped with a piezoelectric accelerometer and a system generating a light spot for the displacement gauge. The impactor is composed of two parts, the basic part and the cover plate. The plate can be removed, then the remaining part constitutes the version B impactor with a mass of 2.5 kg. The dimensions of the impactor and of the anvil which we made enable the impact tests to be carried out in accordance with the standards concerned with protective clothing for motorcyclists and horse riders [3].

The laser transducer, which measures the sample displacements, is mounted on the back of the base by means which enables...
The mounting height to be adjusted. This adjustment is necessary when the impactor is changed and when samples with large thickness differentiation are tested.

The stand was equipped with the two following kinds of measuring channel, which enables the impactor acceleration and the sample deflection to be measured:

- the impactor acceleration measurement channel, composed of the accelerometer mounted on the impactor’s top, and a measuring amplifier, and
- the impactor displacement measurement channel, composed of the laser gauge measuring the sample deflection.

The outputs of the measuring channels are connected to a fast measuring card coupled with a parallel port.

The signal courses obtained from the gauges are recorded in real time by the computer’s memory, and are then analysed. A block diagram of the measuring channels is shown in Figure 2.

**Factors Determined by Means of the Designed Measuring Stand**

The records of the impactor acceleration enables us to determine the changes in the force compressing the sample as a function of the sample deflection over the time of stroke, in accordance with the equation

\[ F = ma \]

where:

- \( m \) - the impactor mass, and
- \( a \) - the deceleration (negative acceleration) of the impactor.

If the maximum impactor acceleration value is substituted in equation (1), we obtain the maximum direct measured value of the force \( F_{\text{max}} \) which is the sample’s rebound to the stroke.

This force, in accordance with Newton’s third law of action and reaction, is equal to the reaction force of the sample which is recognised as the hypothetical protector of the body to be protected.

The records of the changes to the impactor position made by the laser gauge enable the impactor’s stroke and rebound velocity to be measured. This measurement is performed in relation to the so-called basis line. The moment at which the impactor comes into contact with the sample is characterised as the moment at which the pressure of the impactor on the sample (during the stroke) equals the impactor weight; this point determines the basis line.

The velocity of the stroke has been determined as the average value of the impactor velocity over a path of 4 mm, immediately before the contact of the impactor with the sample, i.e. before attaining the basis line. The rebound velocity has been determined as the average value of the impactor velocity on the path of 1 mm after rebound, i.e. after the moment when the interaction of the impactor with the sample decreases below the statistical impactor pressure.

The segment of the path along which the stroke and rebound velocity is measured has been experimentally determined. This determination is aimed at minimising the measurement error while at the same time not decreasing the value of the maximum velocity, as the result of accepting too long a measurement segment. The differences of the measurement paths result from the predicted ratio of the stroke and rebound velocities (generally, the rebound velocity is four times lower than the velocity of the stroke).

The time of the impactor contact with the sample has been determined as the time interval beginning with the impactor crossing the basis line (when the pressure of the impactor during the stroke on the sample equals the impactor weight) up to the moment when the interaction of the impactor on the sample decreases below the statistical impactor pressure.

The determination of the impactor stroke and rebound velocity enables the calculation of the impactor’s kinetic energy value.
before the stroke, and after the rebound, as well as the energy absorbed by the sample, which is the difference between the stroke and the rebound energies.

An alternative measurement of the energy transmitted to, yielded by and absorbed by the sample can be performed by recording the deflection and force time-dependencies. On the basis of these measurements, a graph of force in dependence on deflection has been constructed, and the areas below the individual hysteresis loops have been calculated. The integrals are the measures of the energy transmitted to and yielded by the sample, whereas the area included by the integral is the measure of the energy absorbed by the sample.

The comparison of the energy calculated by means of both the above-mentioned methods is the first quantitative verification of the correctness of the device’s indications.

The measuring stand is also equipped with a build-in synthesising conformity test of the v-a data based on the following equation:

\[ |v_i| + |v_r| = \int \frac{dv}{dt} dt \]

where:
- \( v_i \) - the impactor velocity at the moment of stroke,
- \( v_r \) - the impactor velocity at the moment of rebound, and
- \( t \) - the contact time of the impactor with the sample.

The equation comes from the acceleration definition \( a = \frac{dv}{dt} \); therefore \( dv = adt \), and further:

\[ |v_i| + |v_r| = \int dv \]

Equation (2) allows us to compare the velocity measuring channel (the left side of the equation) with the acceleration measuring channel (the right side of the equation).

A graphic comparison of velocity courses versus time, obtained by differentiating the deflections and integrating the accelerations, allow us to follow up the resultant correctness of channels ‘v’ and ‘a’ over the whole stroking process (see Figure 3). This is the second verification of the measurement results.

The theoretical fall height is the next factor which has been determined during the investigation. This quantity is the height calculated by determining the potential and kinetic energy of the impactor. Its value is determined using equations (3) and (4):

\[ H_t = \frac{1}{2} mgv_i^2 \]

\[ H_t = \frac{1}{2} g \left( \frac{v_r^2}{v_i^2} - 1 \right) \]

where:
- \( H_t \) - the theoretical fall height of the impactor, in mm,
- \( v_i \) - the impactor velocity, in mm/s, and
- \( g \) - the gravitational acceleration \( (g=9806 \text{ mm/s}^2) \), in mm/s^2.

The difference between the real and the theoretical impactor height increases with the increase in the fall height. The increasing time of action of the impactor beam friction against the guiding rods influences the above-mentioned difference. This test is aimed at determining the possible energy losses caused by the friction of the elements guiding the impactor beam.

**Figure 3.** Graphs of force, deflection and impact velocity as a function of time by different values of impact energy: A - 13.93 J, B - 18.57 J, C - 22.41 J; 1 - deflection \( d_p \) in \( \mu \text{m} \) - the deflection value obtained by means of the laser deflection gauge; 2 - deflection \( d_c \) in \( \mu \text{m} \) - the deflection value calculated by doubled integration of the acceleration; 3 - stroke force \( F \) in N - impactor stroke force calculated from the equation \( F=ma \), where \( a \) is the impactor’s deceleration; 4 - impactor velocity \( v_p \) in mm/s - velocity calculated by deflection differentiation; 5 - impactor velocity \( v_c \) in mm/s - velocity calculated by integration of the deceleration.
## Example of Results

In order to illustrate the ability of the new measuring stand to estimate the damping properties of materials, a full test was completed using the elastomeric sample provided by the Davies Odell company. The elastomeric material which they produced in the form of a foam represents a class of the new material specially designed for anti-stroke protectors. The test was completed in three runs, using different drop height values of the impactor. The results of the tests are presented in Table 1 and illustrated in Figure 3.

The analysis of the graphs presented in Figure 3 indicates the great coincidence of the curves illustrating the changes of deflection and velocity in time, as determined according to the direct measurement and by the integration of impactor deceleration. There is only a limited difference between the values of deflection determined using the direct and indirect methods in the rebound region.

### Conclusions

- The measuring stand we designed and constructed enables the time dependencies of the sample deflection changes and the rebound force of the sample during the process of stroke to be recorded.
- The graphs obtained provide the basis for determining the kinetic energy absorbed by the sample during stroke.
- The measurement correctness of the sample deflection values during stroke has been verified by doubled integration of the acceleration.
- The conformity of the time dependence of the impactor velocity changes as recorded directly by the use of the laser gauge and determined from integration of the acceleration recorded by the accelerometer has been demonstrated.

### Table 1. The results of the test for estimating the damping ability of foam produced by Davies Odell.

<table>
<thead>
<tr>
<th>Type of parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>First test</th>
<th>Second test</th>
<th>Third test</th>
<th>Type of calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop height - real</td>
<td>H</td>
<td>mm</td>
<td>300</td>
<td>400</td>
<td>500</td>
<td>Direct</td>
</tr>
<tr>
<td>Drop height - theoretical</td>
<td>Hₜ</td>
<td>mm</td>
<td>284.2</td>
<td>378.7</td>
<td>457.1</td>
<td>Direct</td>
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<tr>
<td>Maximum force</td>
<td>Fₘₐₓ</td>
<td>N</td>
<td>6399</td>
<td>13 683</td>
<td>22 252</td>
<td>Direct</td>
</tr>
<tr>
<td>Maximum sample deflection</td>
<td>Dₘₐₓ</td>
<td>mm</td>
<td>7.13</td>
<td>7.66</td>
<td>7.83</td>
<td>Direct</td>
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<tr>
<td>Contact time between impactor and sample</td>
<td>t₀</td>
<td>ms</td>
<td>8.29</td>
<td>7.18</td>
<td>6.41</td>
<td>Direct</td>
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<tr>
<td>Impact velocity</td>
<td>vᵢ</td>
<td>m/s</td>
<td>2.361</td>
<td>2.725</td>
<td>2.994</td>
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<tr>
<td>Rebound velocity</td>
<td>vᵣ</td>
<td>m/s</td>
<td>0.5728</td>
<td>0.7322</td>
<td>0.7917</td>
<td>Direct</td>
</tr>
<tr>
<td>Impact energy</td>
<td>Eᵢ</td>
<td>J</td>
<td>13.93</td>
<td>16.57</td>
<td>22.41</td>
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<tr>
<td>Rebound energy of impactor</td>
<td>Eᵣ</td>
<td>J</td>
<td>0.82</td>
<td>1.34</td>
<td>1.57</td>
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<td>Energy absorbed</td>
<td>Eₛ</td>
<td>J</td>
<td>13.11</td>
<td>17.23</td>
<td>20.84</td>
<td>Eₛ = Eᵢ - Eᵣ</td>
</tr>
<tr>
<td>Time to maximum of deflection</td>
<td>tₒₘₐₓ</td>
<td>ms</td>
<td>4.443</td>
<td>3.759</td>
<td>3.161</td>
<td>Direct</td>
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<tr>
<td>Time to maximum of deceleration</td>
<td>tₒₘₐₓ</td>
<td>ms</td>
<td>3.845</td>
<td>3.503</td>
<td>2.991</td>
<td>Direct</td>
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<tr>
<td>Maximum deceleration (gravity acceleration)</td>
<td>aₘₐₓ</td>
<td>m/s²</td>
<td>130.5</td>
<td>279.0</td>
<td>453.8</td>
<td>Direct</td>
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<td>Test of conformity</td>
<td>vᵢ</td>
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<td>2.934</td>
<td>3.457</td>
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<tr>
<td></td>
<td>vᵣ</td>
<td>m/s</td>
<td>3.150</td>
<td>3.648</td>
<td>4.064</td>
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### References


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