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EXPERIMENTAL STUDY OF HUMAN SKULL LOADED BY ULTRASHORT IMPACT

EXPERIMENTÁLNÍ VÝZKUM LIDSKÉ LEBKY ZATÍŽENÉ ULTRAKRÁTKÝM PULSEM

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The paper consists of two parts. The first one illustrates the use of double pulse holointerferometry to enhance the study of stress wave propagation in human skulls, the second one shows how laser interferometry contributes to ultrasonic diagnostics of biocomposite shell structures.

The first part of the paper deals with the stress waves generated by an element, which includes an exploding wire, acting normally to the skull surface at the glabella. A holo-camera, with a double pulse ruby laser light source, is used to record the state of the wave propagation in a human skull. Simultaneously a normal component of surface point velocity associated with the wave propagation in the skull is measured by means of a laser vibrometer. It is shown that stress wave generation by an exploding wire and application of double-pulse holo-interferometry and laser interferometry are promising in the investigation of a human skull undergoing impact. Experimental results of empty skull and gelatine filled one are compared. The proposed method could be used for studying of impact loading on the human head in order to contribute to the knowledge base concerning the mechanisms resulting in a head injury.

In the second part of the paper, ultrasonic waves were generated by focusing a ruby laser beam at the skull surface point called the glabella. The laser interferometer has been used to measure a normal component of displacement history associated with stress wave propagation in a human skull. The history was measured at different points on the skull surface. It has been proved that stress wave generation by focused pulsed laser beam as well as the use of laser interferometry is promising in ultrasound diagnostics of bone tissue.

Keywords

human skull, laser generated impulse, laser interferometry, double-pulse holo-interferometry, stress wave propagation, exploding wires, impact phenomena

Introduction

Lasers have found application in many areas of science and technology. While the greatest initial impact of lasers was undoubtedly on optical techniques, they have more recently begun to make a significant contribution in fields such as engineering analysis. Inspection optical methods

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of experimental stress analysis are routinely used for the non-destructive examination of engineering materials and structures. A combination of these techniques is also promising in the investigation of behaviour of biocomposite materials.

It is known that head injuries caused by blunt impact are the major cause of the death. Impact loads on the head may cause that tissues are deformed beyond recoverable limits resulting in injuries. Knowledge of the mechanisms by which all impact loads result in injury is still incomplete.

Mathematical models provide a powerful tool in the analysis of the mechanics of head impact. Mathematical analysis, however, still requires improved accuracy in its input parameters and it requires improved experimental research. At the same time it is beneficial to compare numerical data with experiments.

Head impact response has been studied since the 1970s. The main attention was paid to the interaction of the brain with the inner surface of a skull during the impact [1], [2] and not to the wave phenomena occurring in the head during impact.

Impact loading on all structures initiates a transient state associated with the stress waves propagation. One of the most important things in the experimental research of transient phenomena is the generation of a known and defined impact. For the experiment described, the direction of the acting impact force and its point of application, as well as time history are typically known and very important, not only for the experiment realization, but also for comparison of the experimental results with the numerical or analytical results respectively [3].

Types of impact are typically generated through mechanical or electromechanical loading. The mechanical impact can be realized by using different types of impactors, e.g. by the ballistic pendulum, drop hammer or by shooting different projectiles. In the case of a holo-interferometric study of stress wave propagation in solids, the impact force generation has to cope with two problems. The first problem requires exact synchronization of the beginning of the impact with the flashing of the first pulse of the ruby laser in a holo-camera. The second problem is to control jittering. Jittering occurs if the time of impact is longer than the time of stress wave propagation in the object under investigation. In some special cases, it is possible to generate the stress waves by either focusing a pulse laser beam [4], [5], [6] or by an electromagnetic impulse generator (EIG), [7] [8]. If pulsed holo-interferometry is used to study wave propagation, loading by focused pulsed laser beam or by an EIG is effective only for metallic structures of thickness up to approximately 2-3 mm. This assumes that the energy in a laser pulse is 1J or approximately 20J in an EIG. The sensitivity of holo-interferometry is usually only l/4 where l is the wavelength of light of the laser used to holographically record the image and the smaller deformations are typically not visible.

When the coherent light from a short laser pulse is focused on a solid sample, a part of the energy is absorbed by various mechanisms, depending upon the nature of the sample surface and the wavelength of the radiation, while the remainder is reflected or scattered from surface. The material may be melted in the case of metal, plastically deformed, and damaged. It is possible to generate all types of waves by focusing of the pulse laser beam on the surface of the investigated object [9].

The laser beam interactions with different types of metal were deeply investigated e.g. [10], [11], [12], as well as attention was concentrated on the interaction of the focused pulsed laser beam with hard tissue [13], [14].

There are frequently used infrared lasers, Q-switched CO2 or Er:YAG lasers in the medical applications for different types of the tissue ablation. Hard tissue ablation with a mechanically Q-switched CO2 laser has several potential advantages in comparison with a classical bone incision with mechanical saws: no mechanical vibration, homeostatic and aseptic effects; intricate cut geometry; possibility to cut soft tissue covering the bone with the same laser “tool”. The statement regarding the vibration is right only from medical point of view. It will be shown in second part of our paper that impact loading by focused pulsed laser beam generates a stress wave and consequently the transient vibration of soft or hard tissue during ablation. A point-wise approach to investigate the wave propagation in skull was at first published in [4]. Respecting the aforementioned, we chose at first the impact generation by means of an exploding wire. The exploding wire enables us simple synchronization with launching of the first ruby laser pulse, and it also secures that the time of impact is short enough and the generated force is sufficient compared with other known ways of impact generation. The holinterferograms are recorded by the double-pulse holocamera. The second part of the paper is focused on a point-wise approach to investigate the wave propagation in a human skull.

Experimental Set Up and Procedures

Double Pulse Holointerferometry and Laservibrometry Study

The experiment was provided *in vitro* on a dry human skull of a forty-year old man, about fifty years after his death. The investigated skull lay on its cranial base on soft foam plastics and was dynamically loaded by the exploding wire acting on the glabella point “G” as shown in Fig. 1. The skull was without the mandible and the suture squamous was slightly damaged.

The optical setup used for holo-interferometric recording is shown in Fig. 2. The laser-beam is split using a beam splitter (BS1) into two beams. The main beam, the object beam, becomes divergent after reflection off of the mirror (Z1) and after passing the negative lens (O1). Part of the light is reflected on the first surface of the beam splitter (BS1). The reference beam reaches the hologram plate location after reflection off of mirror (Z2) and after passing the negative lens (O2). A very small part of the main beam, reflected onto the first surface of the splitter (BS2), is used for synchronization of impact generation with the launching of the first pulse of the ruby laser.

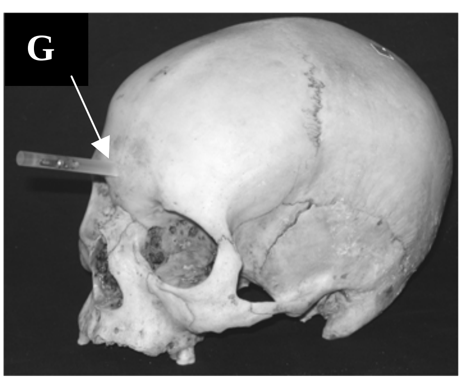

Fig. 1 - Investigated skull with glued loading element

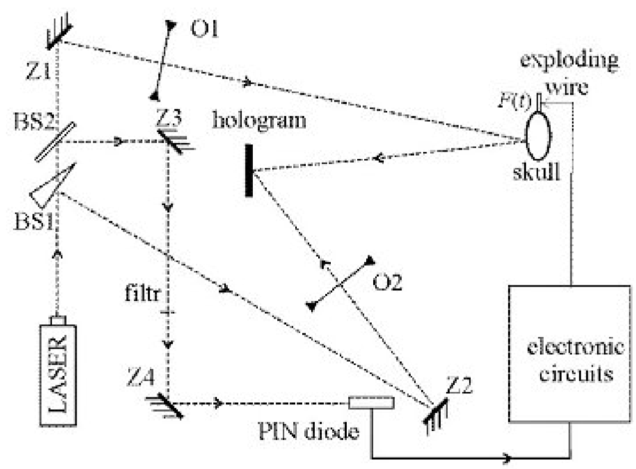

Fig. 2 - Schematic diagram of the optical set up

The first ruby laser pulse simultaneously triggers the pulse in the electronic circuits with the exploding wire and the holography record of the underformed state of the skull. Triggering is realized by means of a small portion of the ruby laser beam detected by PIN diode. A PIN photodiode exhibits an increase in its electrical conductivity as a function of the intensity, wavelength, and modulation rate of the incident radiation.

The second pulse is launched at a preset time (ranging between 1-800μs). A sequence of such holo-interferograms was recorded on holographic plates AGFA 8E75 Holo-test and reconstructed with a helium-neon (He-Ne) laser light.

The holo-interferograms of the empty skull showing "frozen" stress waves at 60μs and at 75μs after the triggering laser pulse are shown in Fig. 3. The Fig. 4 represents the holo-interferograms of the skull filled with gelatinate. Mechanical properties of gelatine are similar to the properties of a brain and to other tissues existing in a human head [15] [16].

The wide fringes on the holointerferograms represent "hills" or "valleys". The sign of displacement is ambiguous. It must be determined from the experiment where the direction of the loading force is known [17].

The main problem is in the interpretation of the interference fringes in the case of curved surfaces. Holo-interferograms seem to be, at first indication, an ideal way to illustrate the deformations they are measuring [18]. Their conversion into numerical data, however, is not a trivial problem. Therefore we compare the interferograms of the empty and the filled skull only qualitatively. It is obvious that the empty skull exhibits more fringes than empty one. The gelatine in the skull causes evidently the damping of the amplitude of stress wave propagating in the skull.

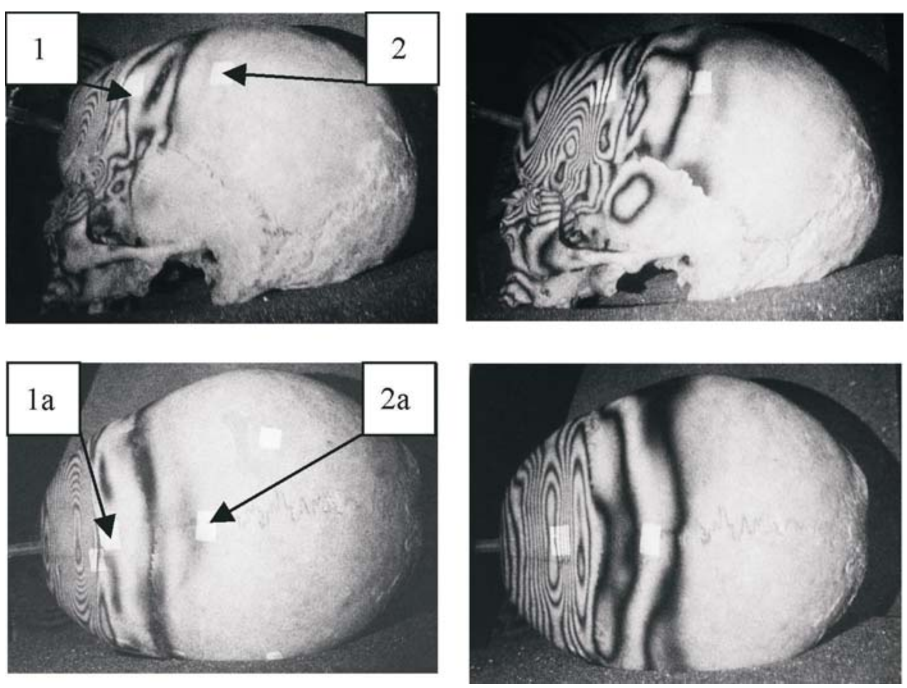

Fig. 3 - Stress waves in the empty skull at 60us and 75us after impact

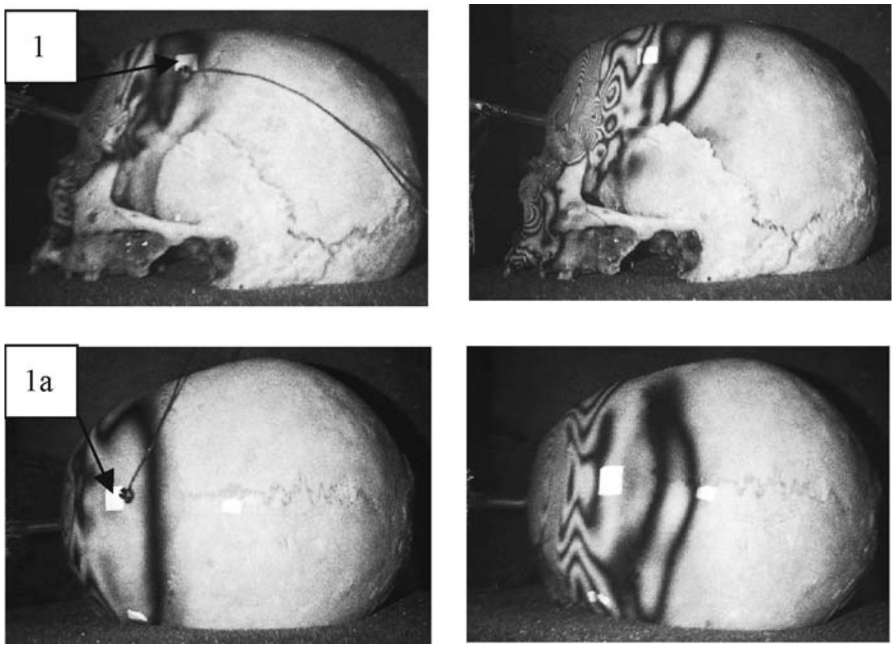

Fig. 4 - Stress waves in the filled skull at 60us and 75us after impact

We combined the full-field holography information with point-wise measurements by means of the laser vibrometer in the pursuit to get not only qualitative data but also to gain more reliable and representative quantitative data from the one experiment. Therefore we were able to collect and compare qualitative information with quantitative data from the one experiment simultaneously. We used a Laser Doppler Vibrometer (Polytec Series 3000, OFV-302) made by Polytec PI, Inc., which enables users to perform non-contact and point-wise measurement of motion from a remote position using interferometric techniques. The device includes a velocity and the displacement decoder.

Diagnostic optical methods based on interference allow measurements of displacements much smaller than the wavelength of the light source. When the surface of on object under investigation moves in such a way that it modulates the path lengths travelled by the laser beam, the interferometer can be used to detect the vibrational signals with subnanometer amplitudes.

The Polytec vibrometer used in our experiments is based on the well-known Mach-Zehnder interferometer modified for measurement of a moving object. The acousto-optical modulator is applied to distinguish between movement towards and/or away from the vibrometer [19].

Measurements are carried out at the point where the laser beam strikes the investigated structure. It is recommended to apply retro reflective tape on the measured points to increase better surface reflectivity and to achieve an almost noiseless output signal from the vibrometer.

In our case the laser beam from the vibrometer strikes normally to the surface of the skull at the place where the history of the components of the vector velocity, normally to the skull surface, is measured.

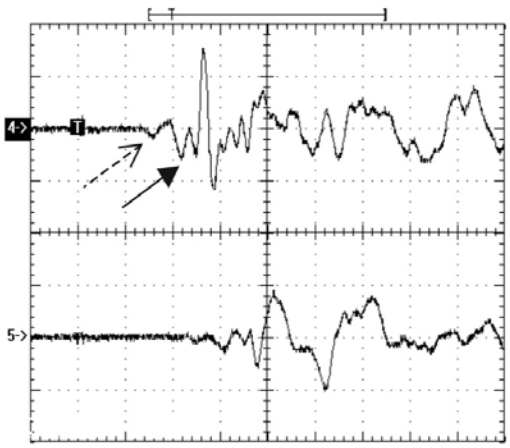

Fig. 5 - Time history of velocity measured at the points 1, 2.

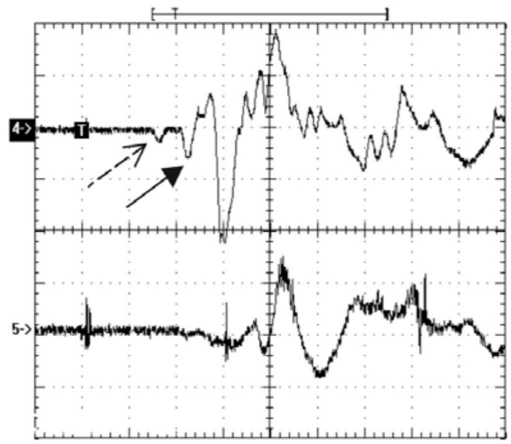

Fig. 6 - Time history of velocity measured at the points 1a, 2a.

The holo-interferometry experiments were carried out simultaneously including a record of the history of velocity at the points 1,2 and 1a, 2a respectively by the laser vibrometer.

The recorded oscillograms are shown in Fig. 5 and in Fig. 6. The upper traces represent the histories of velocities at points 1, 1a respectively and the lower traces represent the histories of velocities measured at points 2 and 2a, which are more distant from the loading point.

The anisotropy of a kalva, reveals itself by the changes indicated in the measured signals. This is obvious by comparing the shapes of the signals marked no.4 in Fig. 5, and Fig. 6 where the influence of a suture coronalis is not yet included. By comparing signal no.4 with no.5 in Fig. 6, we can observe the influence of damping and filtration of the bone (the bone deforms a transferring mechanical signal), the influence of suture coronalis, and the influence due to the distance of the loading point on the measured signal. The analysis of the traces recorded in Fig. 5 is more complicated. We are also able to observe the simultaneous influence of suture coronalis and suture sagittalis and their coupling on propagating waves.

All signals begin with a small peak caused by the arrival of the surface wave. The small surface wave peak, indicated by the dashed arrow shown in Fig. 5 and Fig. 6, appears more evident on the upper traces, which represents the signals recorded from a point closer to the acting force. This small peak begins approximately 35μs after the first triggering pulse of the ruby laser. The higher signal, marked by a solid arrow, begins approximately 18μs later and represents the front of the *bending* stress wave.

The velocity of the surface wave, evaluated from the distance between points 1 and 2 respectively from the glabella including its corresponding time, is approximately 3,750m/s while the velocity of the bending wave is 2,100m/s. The stress wave velocity, evaluated from the holo-interferograms, is approximately 2,400m/s. It is known that the approximate velocities of sound propagating in a human bone are in the range of 2,500 – 4,700 m/s [20].

In the case of the skull filled by the gelatine we combined the full-field holography information also with *point-wise* measurement by means of the miniature accelerometer (Brüel & Kjær type 4374). The applied accelerometer has the diameter 5mm and the high 6,7mm.

The weight of accelerometer is 0,65 gram. It is placed as close as possible to the point where is applied laservibrometer measurement. The holo-interferometry experiments were carried out simultaneously including a record of the history of velocity at the point 1, and 1a respectively by the laser vibrometer and by a miniature accelerometer B&K.

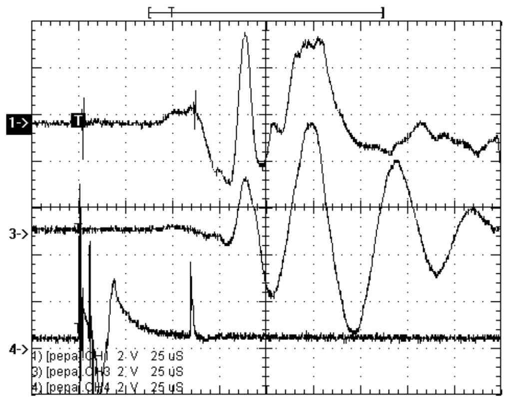

Fig. 7 – In the filled skull: history of velocity (trace 1), history of acceleration (trace 3), double laser flashing (trace 4)

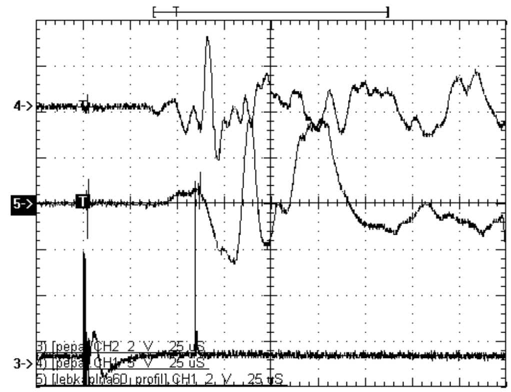

Fig. 8 – History of velocity in the empty skull (trace 4) and filled skull (trace 5)

The typical oscilogram recorded during the measurement is shown in Fig. 7 where the trace no.1 represents history of velocity at point marked **1** (see Fig. 3), the trace no.3 is history of acceleration (almost in the same point), and trace no.4 is the signal showing a double-flashing of ruby laser used for recording of a double pulse holointerferogram.

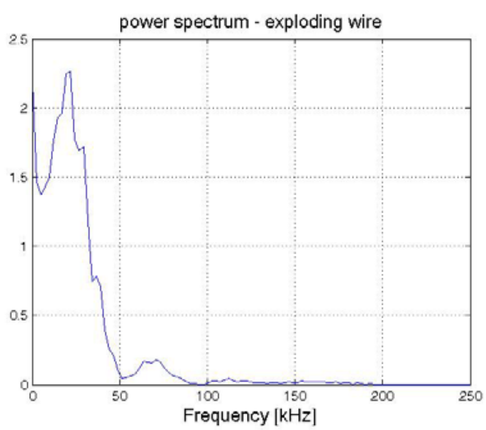

Fig. 9 - The power spectrum of the force generated by the exploding wire

To analyse signals of surface point velocity quantitatively, we focused on the power spectrum of the force pulse generated by the exploding wire. The power spectrum of the force pulse is shown in the Fig. 9. It is seen that the force pulse contains frequency up to cca 150 kHz.

The power spectrums of history velocity (the point 1) in the empty skull (the Fig. 8 trace 4) and in the filled one (in the Fig. 8 trace 5) are depicted in the Fig. 10 and in the Fig. 11. By comparing of the two spectrums is obvious that gelatinate markedly influences the measured signals. In the filled skull, the frequencies higher than 100 kHz are damped and amplitudes decrease up to a half in comparison with an empty one.

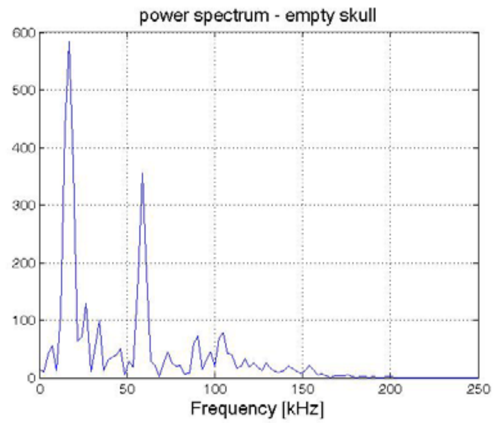

Fig. 10 - Power spectrum of velocity signal in the empty signal

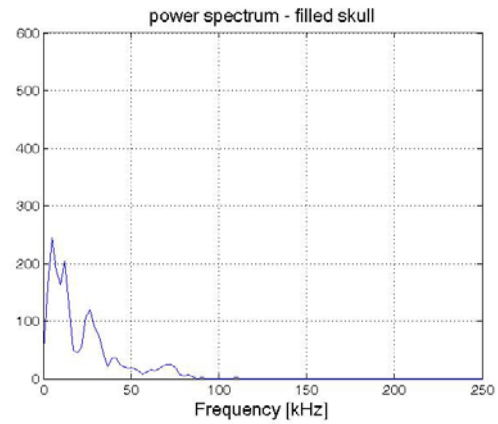

Fig. 11 - Power spectrum of velocity signal in the filled signal

Laservibrometry Study of Human Skull Impacted by Focused Ruby Laser Beam at Glabella

The experiments were provided on the same skull like the experiments mentioned above. The investigated skull was set on its cranial base on the soft foam plastics and was dynamically loaded by the focused ruby laser beam acting on the glabella point "G".The simple optical set up used in the experiments is shown in Fig. 12.

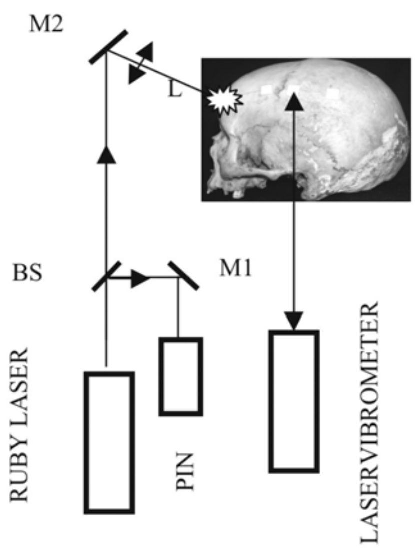

Fig. 12 - Optical set up with laservibrometer

In this setup, the coherent and monochromatic light from a pulsed ruby laser is divided into two parts by means of a beam splitter BS. One of these parts, going directly through the beam splitter, is directed by a mirror M2 and focused by a lens L on the surface of the skull to be studied. This part of the laser output generates the impact force acting in the glabella. The other part of the laser beam, reflected from a front surface of the beam splitter, is directed by mirror M1 towards the PIN diode. A signal from the PIN diode was used for oscilloscope triggering. The He-Ne laser beam from the vibrometer is focused on an investigated point and simultaneously its direction is perpendicular to the surface of the skull. This alignment made it possible to achieve maximum sensitivity of measurement with respect to the dominant component of the vector displacement.

The mechanical responses of the skull i.e. the history of the components of the vector displacement perpendicular to the skull surface were measured by laservibrometer Polytec. The displacements were measured at different points 4, 5, 6 (see Fig. 13) located on the kalva surface line beginning in the glabella. The recorded signals are shown in Fig. 14. The channel 3 is triggering signal.

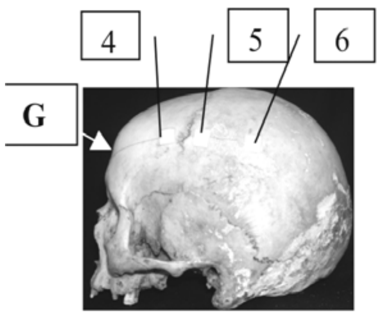

Fig. 13 - The skull and depicted points 4, 5, 6

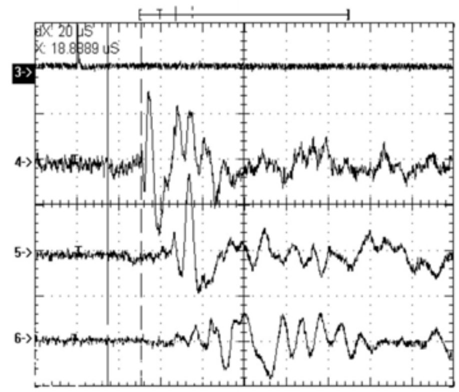

Fig. 14 - The displacement measured at points 4, 5, 6

An influence of the suture coronalis on the wave propagation (on damping, filtration and reflection of the measured signal) is evident by comparing signal 4 with 5.

The changes of the shape of the measured signal caused only by the propagation through a bone are apparent by comparing signal 5 with 6. Comparing the signals from Fig. 14 we can evaluate the local anisotropy of the kalva where no influence of a suture exists

Prominently decreasing of the amplitudes of the measured signals is evident from comparing the signals 4,6 in Fig. 14 where one can observe the influence of both suture coronalis and distance from the loading point –glabella- on the shape of measured signals.

Conclusion

This article described the generation and propagation of stress waves in human skull *in vitro*. The waves were generated by two ways. Et first by means of an element with exploding wire acting on the glabella, perpendicular to the skull surface. The wave propagation was recorded by double-pulse holo-interferometry. The time history of velocity was detected by a laser vibrometer on four points located on the upper part of the skull surface. Applying the second way, the waves were generated by focusing a ruby laser beam on the skull surface. The wave propagation was detected only pointwise by a laser vibrometer, which read time history of displacements at several points on the skull surface.

It is almost impossible to distinguish the types of propagated waves exactly because the skull structure is very complicated. When complicated structures are loaded by an impact force, the dominant components acting perpendicularly to the surface generate a bending oscillation and the corresponding waves are called bending waves. We can say that with respect to the kind of loading and detection device being used, that the dominant component of a propagating wave in the investigated skull is the bending wave.

A detailed study of the kalva structure may reveal additional wave dispersion effects. The influence of the curvature and the sutures of the skull on the direction of wave propagation, namely on the wave velocity. The influence of a filled skull on the damping of propagating stress waves, was also a subject area presented experimental analysis. As far as loadig by focused ruby laser beam is concerned we have found that not only did the focused laser beam not damage the skull but also it left no visible mark on the surface. If the same energy level is used as the pulse for the stress waves generation in a metal material, its surface is ablated and damaged and miniature craters occur. The experiments showed that the influence of the medium (gelatin) applied at the point of the focused beam, on increase level of excitation is negligible, while application of the gelatin for stress waves generation in metal bodies is necessary for efficient increase of excitation force.

Additional wave dispersion effect is expected in the case of the kalva structure. The influence of the curvature on the direction of wave propagation, namely on the surface wave velocity, will be a subject of our future experimental analysis.

Combining whole-field holo-interferometry and point-wise laser vibrometry we achieve a method which is powerful and promising in bone investigation, not only from an pathological point of view, but also from the viewpoint of the experimental biomechanics.

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Trnka, J., Veselý, E., Dvořáková, P.: A Study of Wave Propagation in a Human Skull Using Laser Interferometry. Experimental Techniques No.1, Vol. 28, 2004, pp. 27-30.

Trnka, J., Dvořáková, P., Veselý, E.: Optical Interferometry Methods Used to Study Stress Waves Propagation in a Human Skull. Experimental Techniques Vol.28, No2, pp. 29-34

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