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Chapter 8

TERAHERTZ KINETICS SPECTROSCOPY FOR LAMINATED HELMET MATERIALS CHARACTERIZATION

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ABSTRACT

Kinetics spectroscopy is defined by a time-dependent spectrum acquired at a high speed for analyzing fast events such as a ballistic impact on an object. The reflected terahertz energy, for example, constitutes a kinetics spectrum that is an effective tool for layered materials' deformation characterization under ballistic impact. In this chapter, we describe utilizing the kinetics spectrum for quantifying a deformation event due to impact in layered materials used for Soldiers' helmets. The same technique may be utilized for real-time assessment of trauma or concussion by measuring the helmet wore by an athlete. The deformation of laminated materials is dependent on the nature of impact and the projectile; thus, can uniquely characterize the impact condition

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leading to a diagnostic procedure based on the energy imparted on an athlete's head during an impact. We outline the calibration process for a given material under ballistic impact and then utilize the calibration for extracting physical parameters from the measured kinetics spectrum. Measured kinetics spectra are also used to outline the method and rationale for extending the concept as a diagnostic tool. In particular, captured kinetics spectra from multilayered plates subjected to ballistic hit under experimental conditions by high speed digital acquisition system were analyzed to ellucidate the technique. An algorithm was devised to extract the deformation depth and deformation velocity profile from which the energy imparted on the skull was computed via laws of non-relativistic motion. This energy is assumed to be related to actual injury conditions, thus forming a basis for determining whether the hit would cause concussion, trauma, or stigma. Such quantification may be used for diagnosing a Soldier's trauma condition in the field or that of an athlete's.

Keywords: Terahertz kinetics spectroscopy, laminated material, deformation kinetics, diagnosis of trauma conditions

INTRODUCTION

Unlike other form of energy that can be used for probing materials and physiological events, such as, X-ray, UV, Visible, Infrared and ultrasonic, terahertz radiation (T-ray) provides unique advantages in that the T-ray can penetrate through many materials and biological tissue, allowing sub-surface interrogation in a non-destructive and non-invasive fashion. T-ray is non-ionizing, therefore, does not involve radiation damage. Consequently, T-ray based reflection beam's kinetics spectrum can produce a clearer picture of the internal layers of composite laminates and their delamination than simple surface measurements. Additionally, a transmitted beam's kinetics spectrum may also be used to probe any mass loss of the material due to evaporation at impact or mass gain due to sticking of projectile fragments. The real-time kinetic spectrum can be used for computation of force and energy of impact that in turn may be exploited for the evaluation of trauma conditions from the Sturdivan criterion [L. Sturdivan et al., 2005]. Currently available technologies offer limited sensitivity to certain important parameters, such as dynamic mass loss that are crucial to fully quantify a ballistic event. Existing methods such as digital image correlation (DIC) [P. L. Rieu, 2008] suffers from critical limitations because visible light cannot penetrate helmet material, therefore, not able to quantify changes of the internal layers. While X-ray can penetrate, one can only view a snapshot after the event has already taken place (ex-situ); no dynamic, real-time information is available. While DIC offers time-evolution of the deforming surface, is not capable of providing any information regarding interior delamination or change in mass. Moreover, DIC lacks very fine resolution necessary for in-situ inspection of time-dependent changes in materials. Microwave could potentially be used for similar interrogation but lacks sensitivity necessary for probing ballistic events. On the other hand, terahertz kinetics spectroscopy is very effective technique that can address the aforementioned deficiencies by providing information for a more complete characterization of ballistic events. Recently we reported on capturing ballistic kinetics on the Army Research Laboratory's test-bed using a terahertz scanning reflectometer (see [A. Rahman et al., 2014] for details).

In this Chapter, we used non-relativistic equation of motion for interpreting the kinetics spectrum for ballistic event characterization of less-than-lethal impact, the so called blunt criterion [L. Sturdivan et al., 2005]. The experimental setup and the calibration procedure for quantifying deformation from the kinetics spectra are briefly described below. Live-fire shot on a multi-layered panel have been analyzed in details. We also describe calibration and calculation of mass loss due to ballistic impact. Details of terahertz generation have been reported elsewhere [A. Rahman, et al., 2012]. Briefly, we have used a dendrimer dipole excitation (DDE) based terahertz source, first proposed by A. Rahman, et al., [Rahman et al., 2008] where an electro-optic dendrimer with high second order susceptibility is pumped by a suitable laser system. This mechanism does not require a femto-second pulsed laser; it is capable of generating continuous wave (CW) T-Rays with relatively high power (>10 mW). DDE based terahertz system is attractive, because it eliminates the use of a femto-second pulsed laser needed by other techniques that makes it cost effective and tunable for both bandwidth and output power.

Quantitative Analysis of a Ballistic Event

In the case of a Soldier's helmet, an important quantity in the non-lethal case is the available energy for potential impact to the Soldier's head that may lead to trauma, concussion or other injury. The same principle will also apply for sport helmets with a lesser degree of impact force. Therefore, it is important to quantify the trauma generating energy, E_{tr}. At the point of impact, the kinetic energy, E_K, of the projectile is $E_K = \frac{1}{2} m_p V_p^2$, where, m_p is the mass of the projectile, and V_p is the impact velocity of the projectile. Sturdivan et al., (2005) indicated that the physical quantity properly expressing the capacity to do work on tissue and cause damage from blunt impact is the "energy." The authors expressed potential blunt criterions (BC) for the head as a measure to predict head injury from blunt, less-than-lethal projectiles, as

$$BC = ln\left\{\frac{E}{(T*D)}\right\}, \tag{1}$$

where, E is the impact kinetic energy (Joules) of the deformed volume, D is the diameter of the projectile in centimeters, and T is the thickness of the skull in millimeters. One need to recognize that, as a projectile (e.g., a bullet) impacts the outside of a helmet, the inside of the helmet is deformed inwards, thus imparting energy to the Soldier's head. It is this energy that causes trauma, concussion or other injury; which is less than the impact kinetic energy, E_K, of the projectile on the helmet's outer skin (see Figure 1). Eq. (1) therefore takes the form,

$$BC = ln\left\{\frac{E_{tr}}{(T*D)}\right\}, \tag{2}$$

where, E_{tr} is the trauma generating energy.

The kinetics spectrum is used to compute the velocity profile from which the deformation propagation velocity for the helmet interior surface is obtained at the maximum deformation, V_{max}. However, since

$$E_{tr} = \frac{1}{2} m_{eff} V_{max}^2 \qquad (3)$$

where, m_{eff} is the effective mass of the trauma generating volume, excluding the mass of the bullet. Therefore, to quantify the energy of BC, m_{eff} must be known. But neither DIC nor X-ray can determine m_{eff}, because, while the density may be approximated from the known material properties and the effective area may be estimated from the post-firing device under test, the effective mass of the trauma-generating volume is still not determined. Since the helmets are made from a multi-layered material, one needs to know the delamination characteristics and the lost mass of material due to impact. Thus, m_{eff} must be determined experimentally. Here we exploit T-Ray's penetration properties through the helmet material to determine any mass loss/gain due to impact. In this case, calibration of material mass as a function of T-Ray transmission energy must be done á priori.

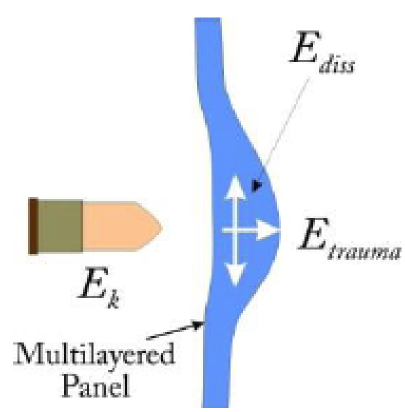


Figure 1. The incident energy is the sum of trauma-generating energy and dissipated energy: $E_K = E_{tr} + E_{diss}$.

In light of the foregoing, the total energy delivered by the projectile is then comprised of two components: $E_K = E_{tr} + E_{diss}$, where E_{diss} is the energy dissipated by the helmet material (see illustration, Figure 1). While it can be easily assumed that $E_{diss} = E_K - E_{tr}$, the nature of E_{diss} has some interesting connotations. One may argue that since the helmet is made of a multilayered material, E_{diss} is not likely to be just the dissipated heat energy. It is hypothesized that ballistic impact may generate shock waves [R. Stoughton, 1997] which may also contribute to trauma. In either case, the net effect of a ballistic impact, under BC, is the trauma generating energy E_{tr}, and thus, E_{tr} is still dependent on m_{eff} which must be measured.

EXPERIMENTAL

Figure 2 shows the experimental setup for real-time, in-situ ballistic kinetics spectra measurements (all instruments from Applied Research & Photonics, Harrisburg, PA). Projectiles (762 rounds and fragment-simulating projectiles) were shot at composite panel targets to demonstrate feasibility of the proposed measurement system. An electro-optic dendrimer (DDE) based terahertz source was used for the present measurements. The source and the detection units remain stationary and are oriented at angle $\theta = 35°$ but may be oriented at any suitable angle such that the projectile path is clear from entering the instruments (Figure 2). Under these conditions, as the target moves from its initial position along the x-axis, both θ and the deformation (S) become position dependent; $\theta \rightarrow \theta(x)$ and $S \rightarrow S(x)$. Thus the reflected power is a function of x that can be described by the Fresnel's law of refraction [R. C. J. Piesiewicz et al., 2007].

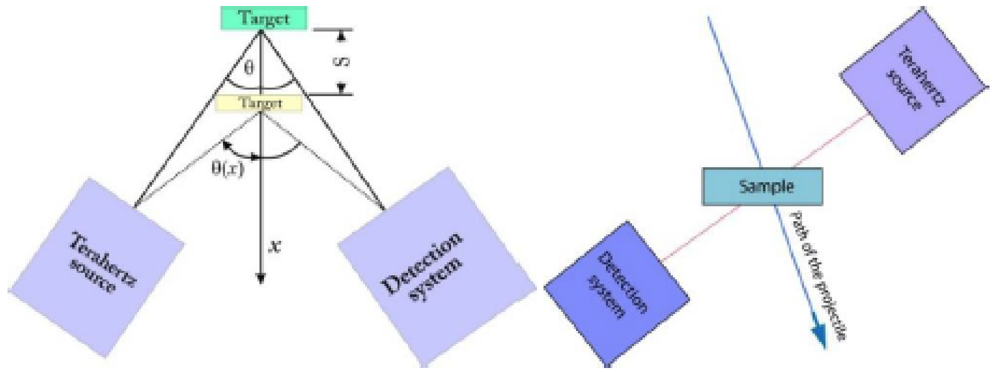


Figure 2. Experimental setup of TDR. (a) Reflection calibration: the terahertz source and the detection unit remain stationary while the target undergoes sudden deformation by absorbing ballistic impact. The beam from the source is incident at an angle (35°) on the target and reflected back into the detection system. (b) Experimental setup for mass vs. transmission calibration.

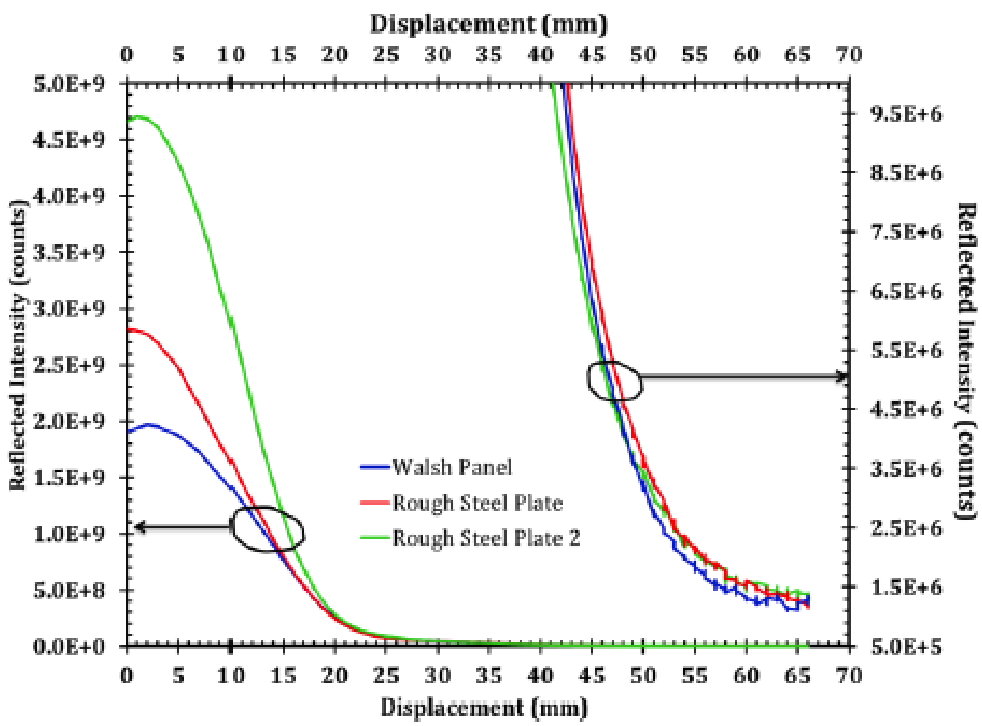


Figure 3. Calibration of reflected intensity as a function of deformation (displacement).

Deformation Calibration

Deformation calibration involves measuring the reflected energy as a function of known deformation at a given distance and at a known angle of incidence. Figure 3 shows the results for three different materials. Here panels of those materials were mounted on a linear stage that has sub-micron lateral resolution. Since helmet deformation is usually in a few millimeter range under ballistics impacts, calibration was conducted over at 1 mm intervals. However, calibration could have been done at a finer resolution for more sensitive experiments. This calibartion curve may be utilized for reading off the actual deformation under experimental conditions knowing the difference between the initial and final reflected intensities.

Mass Calibration

The effective mass m_{eff} may be read off from the mass vs. transmission calibration curve (see Figure 4). The governing principle here is the Beer-Lambert's law. Ordinarily, the Beer-Lambert's law is used to determine the concentration dependence, C, of a solute in a solvent from absorbance (A) data: $A = \varepsilon l C$, where l is the path length and ε is the extinction coefficient (or molar absorptivity). However, for a ballistic impact, all material parameters may be assumed fixed, with the path length l being replaced by mass, m, due to delamination. Thus, the transmittance (T) is proportional to the variation in path length, or equivalently, the mass change. Therefore, a priori measurement of $T(t)$ vs. known m can be utilized to compute the change of mass: $T(t) = \varepsilon m \rho$, where, ρ is the density and t is the observation time. The mass calibration setup was shown in Figure 2(b).

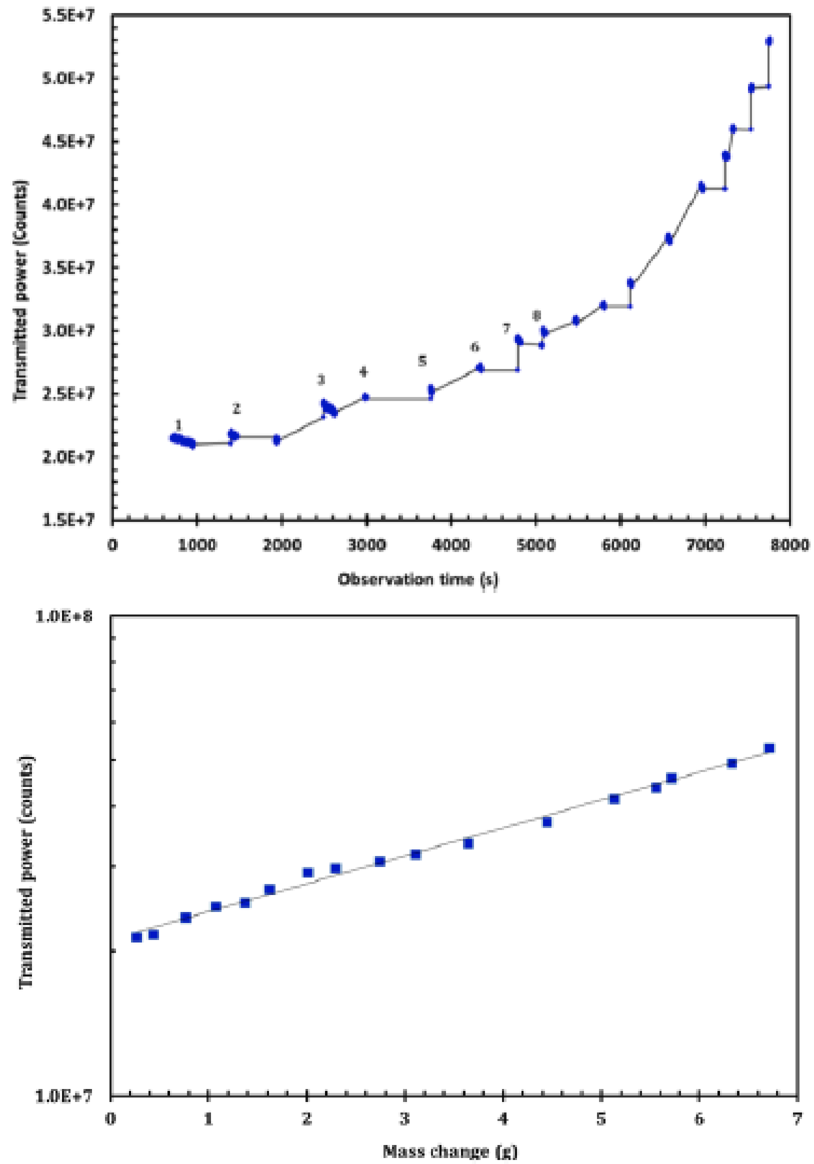


Figure 4. (a) Transmitted power increases as successive layers are removed from the panel under calibration. (b) The transmitted power is plotted as a function of cumulative mass removed from the panel. The change in mass for this particular panel may be read from this curve or may be calculated from Eq. (4).

Here the target, the terahertz source, and the detection system are organized such that the projectile path remains clear. With this orientation the source and the detection system was aligned such that the detector received the maximum power. A multilayered panel, mounted on a fixed platform, was then introduced in the beam path and the initial power was recorded. Then a cluster of a few layers of the panel was peeled off and transmission was measured again. This way transmitted power was recorded while other clusters from the panel were removed successively. For each cluster removed, a small disk was cut out (approximately equal to the beam spot) and its mass was measured on a micro balance. Figure 4(a) shows the successive layers' mass dependence of the transmitted power. Figure 4(b) shows the measured power vs. measured mass of the disks cut out of the peeled clusters. This will serve as the calibration for determining mass change during the ballistic impact. This calibration must be done á priori for a given geometry and for a given material.

As seen from Figure 4 (a), the transmitted power increases as successive layers are removed from the panel under calibration. In Figure 4 (b), the transmitted power is plotted as a function of cumulative mass removed from the panel. The change in mass for this particular panel may be read off from this curve or may be calculated from the fit:

$$Y = 2.11614423 \times 10^7 \exp(0.13377147) \cdot X, \qquad (4)$$

where, Y is the transmitted power and X is the mass in gram. Note that the coefficients of Eq. (4) have 8 digits after the decimal point; this is for better accuracy.

Results and Discussion

Results of Live Firing Test

The test results and findings are summarized in Table 1. This experiment yielded a bigger picture about the robustness of the technique and sets the stage for a terahertz test protocol for trauma diagnosis. Two different kinds of panels and a helmet (total 18 shots) were tested. Thus, the results demonstrate that the proposed terahertz technology is suitable for a non-bio-marker based diagnostic tool. Column 1 of Table 1 lists the number assigned to a particular live shot. Column 2 indicates the mode of measurement, i.e., either in reflection or in transmission, while Column 3 gives a brief description about the nature of the short and related observation. The actual kinetics spectra corresponding to respective shots are given in Table 2.

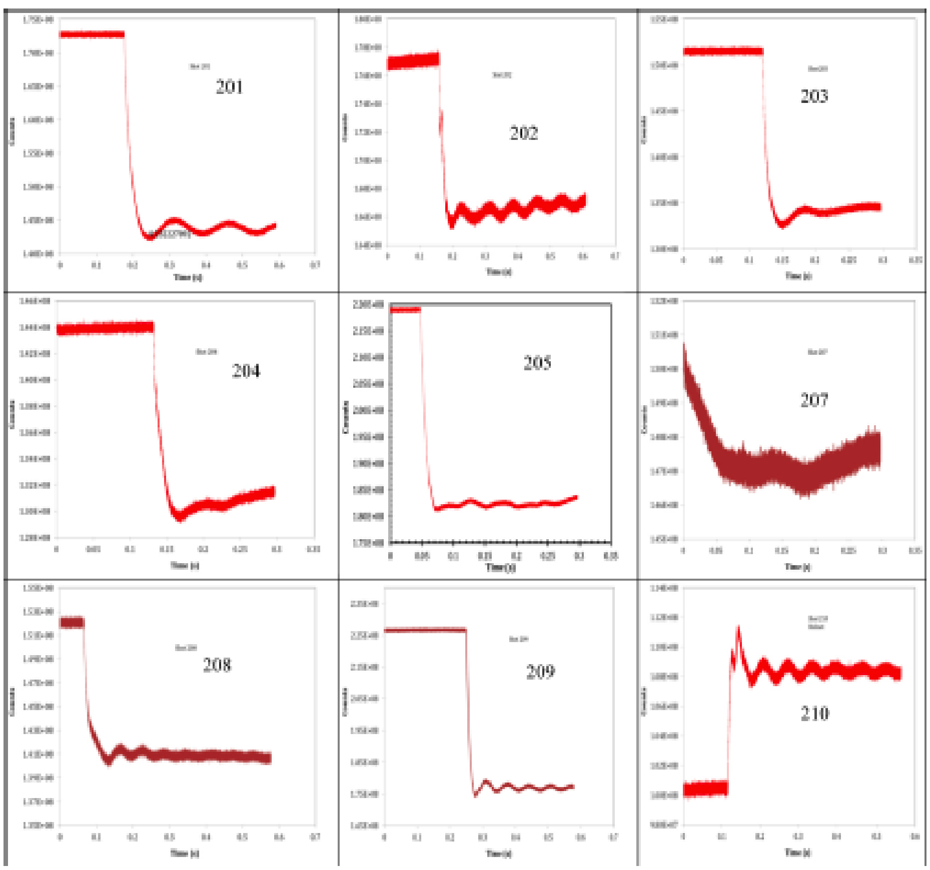
Table 1. Summary of observation of different shot experiment. Kinetics spectra are shown in Table 2. Each shot was taken on a different panel on an unaffected region of the panel. The kinetics data are shown in Table 2

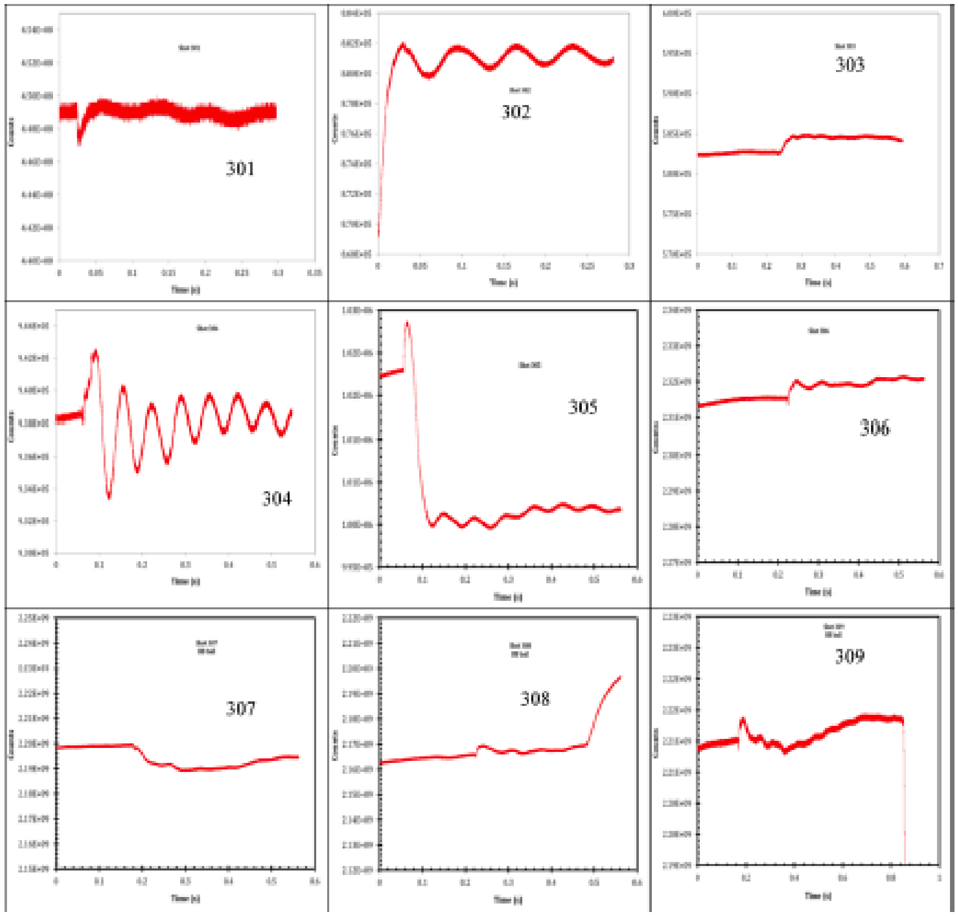
Shot#	Mode	Comment
201	Reflection	Typical reflection kinetics spectrum of a multi-layered panel. The spectrum is used for computing deformation and propagation profile, and other parameters. The vibrations in the tail end of the spectrum (at 0.2s onward) are indicative of vibration of the mounting platform.
202	Reflection	Typical kinetics but two distinctly different slopes with an upward shift in the fast decay region that indicates shaking of the mounting platform during the shot.
203	Reflection	Typical kinetics acquired over a shorter period (0.3 s)
204	Reflection	Two or more slopes in the fast decay region indicative of movement of composite layers in groups (clusters) leading to subsequent delamination of internal layers.
205	Reflection	Similar to shot 204 but a bigger variation in reflected intensity is indicative of a bigger deformation depth.
207	Reflection	Incomplete data due to data acquisition synchronization error
208	Reflection	More than one slope in the fast decay region is indicative of movement of a cluster of layers as opposed to the whole panel and subsequent delamination of internal layers.
209	Reflection	Typical kinetics similar to shot 204. Two or more slopes in the fast decay region indicative of movement of composite layers in groups (or clusters) leading to subsequent delamination of internal layers. See Figure 2 for analysis.
210	Reflection	This shot is on a helmet. The helmet was mounted with a clamp system that could not be made very sturdy. So this spectrum cannot be interpreted unless further helmet shot is taken
301	Transmission	Incomplete data due to acquisition start error
302	Transmission	Typical transmission kinetics except the initial portion was not captured due to synchronization error in data acquisition. Some loss of mass due to the bullet shot causes an increase of the transmitted intensity. A priori calibration of mass vs. transmission may be used to quantify the loss of mass due to the ballistic event.
303	Transmission	Typical transmission kinetics profile. Once calibrated with respect to transmission vs. mass change for a given panel, this curve will quantify the loss of mass during ballistic deformation.
304	Transmission	This kinetics shows the flaw in mounting apparatus. The oscillatory nature of the platform holding the panel is clearly visible
305	Transmission	While this curve shows initial increase of power, indicative of mass loss due to impact. However, the moving panel and its vibrations due to weak mounting are responsible for the decrease in transmission.

Table 1. (Continued)

Shot#	Mode	Comment
306	Transmission	Resembles a typical transmission kinetics spectrum. Once calibrated with respect to transmission vs. mass change, this curve will quantify the change in mass during ballistic deformation
307	Transmission	This shot was done with BB ball instead of a bullet as was in the previous cases. Kinetics was inconclusive due to vibration of the unstable mounting platform.
308	Transmission	Also a BB ball shot. Transmission increased immediately after shot. The oscillatory pattern is due to vibration of the mounting platform. However, the transmission takes off towards the end because this shot actually went through the panel creating a hole that caused the increased transmission.
309	Transmission	Also a BB ball shot. This shot is very similar to typical transmission kinetics. However, the BB ball got stuck in the panel that caused a sharp decrease in the transmission.

Table 2. The kinetic spectra below were measured in reflection. The X-axis is the time of duration and the Y-axis is the reflected intensity (counts). Shot number is arbitrary, mainly for identifying the shot corresponding to the comments in Table 1





Computation of Parameters

Once the maximum displacement is read off of the kinetics spectrum utilizing the calibration curve, the deformation propagation profile is calculated from the kinetics spectrum. From this profile the next most important parameter to calculate is the velocity profile of deformation. Here the following boundary conditions are utilized. Initially the target is at rest; therefore, the initial velocity, v_0, is zero. As the deformation propagates, the propagation accelerates and then at the maximum deformation the velocity is again zero. If the target recoils (in the opposite direction), the velocity again increases and then comes to zero when the target stops at the relaxed position. So one can utilize the fundamental physical principle, the Newton's law for uniformly accelerated motion:

$$S = v_0 t + \frac{1}{2} a t^2,$$

where, S is the deformation (see Figure 3), a is the acceleration and t is the time. Since $v_0 = 0 \rightarrow S = \frac{1}{2} a t^2 \rightarrow a = 2S/t^2$. Knowing the acceleration, a, one can then determine the velocity, v, from,

$$v^2 - v_0^2 = 2aS \tag{5}$$

Figure 5 displays the calculated deformation profile from the kinetics spectrum (shot 209, Table 1) and the velocity profile calculated from Eq. (1). Here the kinetics spectrum was de-noised with a curve-fitting routine and then a moving average was adapted for calculating velocity profile. Since the deformation calibration for this sample was not done ahead of time, the information available from a simultaneous digital image correlation (DIC) measurement [see Reu et al., 2008] was used to calculate the deformation profile. The velocity profile of Figure 5 reveals that the deceleration of the panel after the initial acceleration (between time 0.26s and ~0.28s) exhibit several small accelerations (indicated by the upward shots or "kinks" in the blue curve) followed by small decelerations. This is indicative of the clusters of layers are moving together as opposed to the whole panel; i.e., a few layers forming a cluster and being delaminated whose motion is captured by the kinks in the velocity profile. Altogether 4 clusters are visible following the initial deceleration of the panel. It is notable here that being able to apply the Newton's law of motion lends credibility to the approach that does not depend on any empirical formula.

Figure 6 shows another example of kinetics spectral analysis of shot 201 (see Table 2). Although from Figure 6 (a) it seems to be a single slope from the strike point to the first inflection point, actually there are distinct slopes before the deformation reaches the maximum, as evidenced from Figure 6 (b). This is indicative of delamination of layers in a cluster within the panel rather that every individual layers.

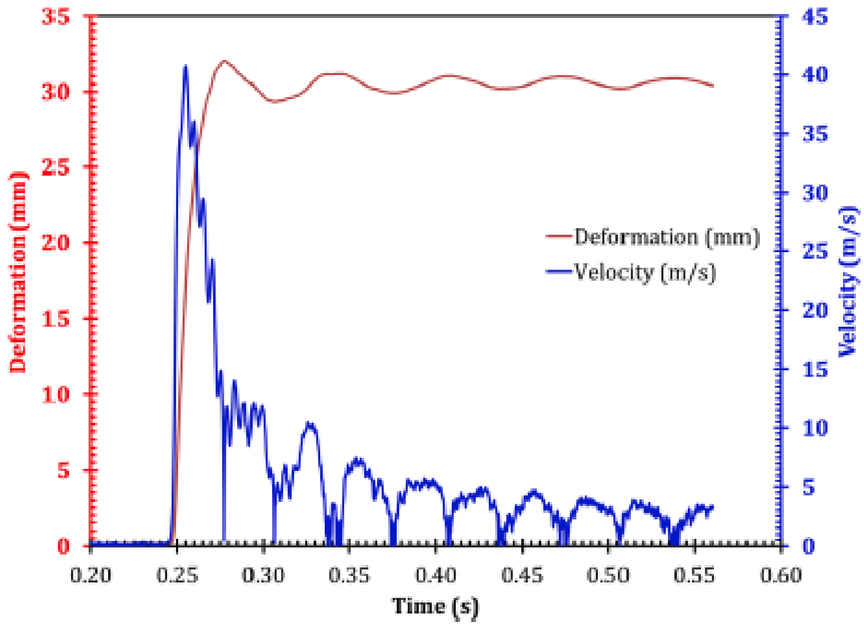


Figure 5. Analysis of shot 209 in Table 2. Deformation profile (left Y-axis) calculated from the kinetics spectrum with a depth of 34 mm (from DIC under identical conditions). Calculated velocity profile of deformation is shown in blue (right Y-axis).

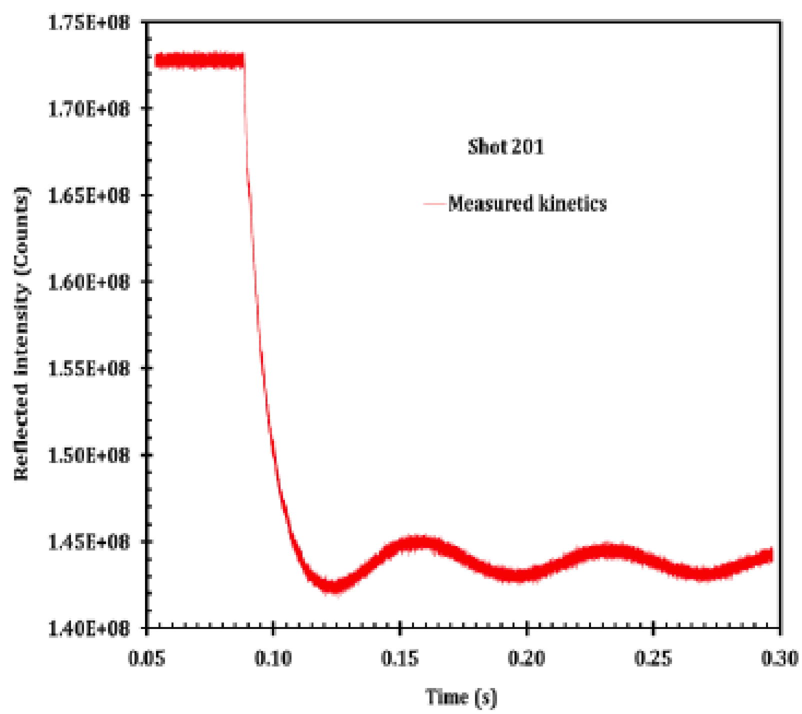


Figure 6. (Continued).

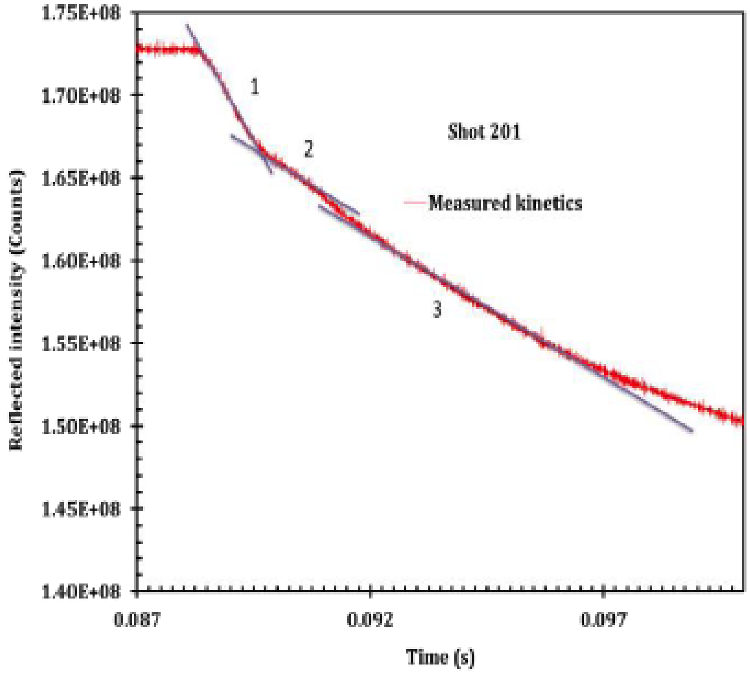


Figure 6. (a) Kinetics spectrum of a live shot indicating the target underwent permanent deformation. The wavy nature at the tail end most likely occurred from the vibrations of the mounting platform. (b) Close-up of the kinetics spectrum.

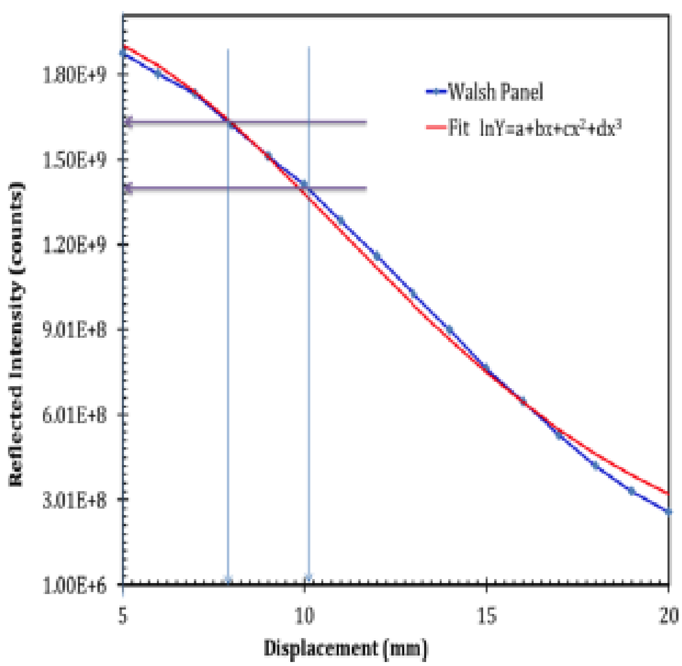


Figure 7. (Continued).

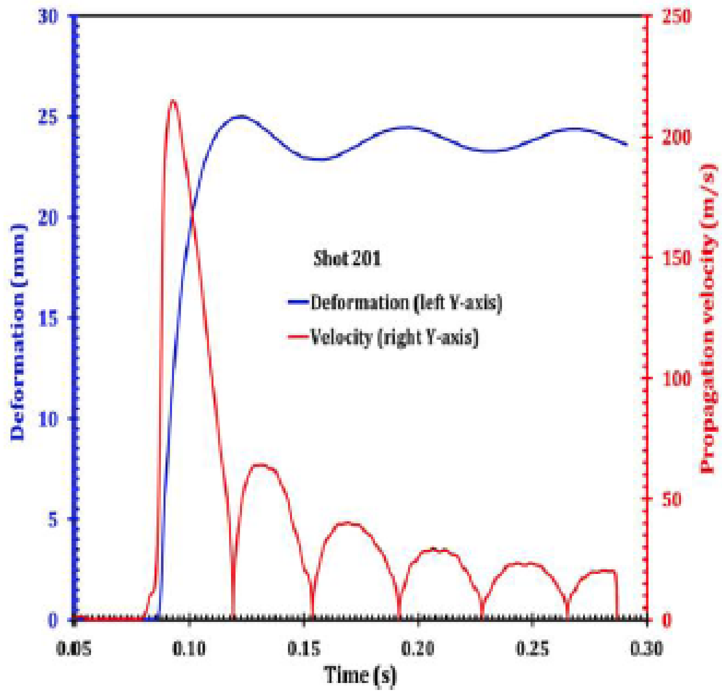


Figure 7. (a) Deformation extraction from the calibration curve. (b) Deformation profile (left Y-axis) calculated from the kinetics spectrum of Figure 5(a) with a depth of 10.4 mm (from DIC under identical conditions). Calculated velocity profile of deformation is shown in the right Y-axis.

Figure 7 (a) shows a zoomed-in part of the calibration curve from Figure 3 corresponding to displacement from 5 mm to 20 mm for the plate termed as "Walsh Panel." From this, the deformation is read of off the *X*-axis for corresponding dip in the reflected intensity.

Conclusion

Terahertz kinetics spectroscopy under high speed data collection has been used to capture real-time kinetics spectra of ballistic events. Testing was done with prototype instrument (from Applied Research & Photonics, Harrisburg, PA) to demonstrate applicability for ballistic event characterization. Critical parameters such as deformation profile, maximum deformation and deformation propagation velocity profile were computed from the measured kinetics spectrum utilizing the non-relativistic equation of motion. The analysis for panels that are used for manufacturing Soldiers' helmets has been carried out for less-than-lethal ballistic impact, i.e., the blunt criterion. Kinetics spectra from reflection measurements have been utilized for calculation of deformation profile and its propagation velocity profile. The kinetics spectra from transmission measurements were used for calculating the mass change due to delamination or material evaporation in a ballistic impact. Examples of mass calibration have been provided. This technique does not depend on the biomarkers; rather utilizes the impact energy measured in real time for trauma or concussion assessments. Thus, the technique may be used for diagnosing head injury conditions for less than lethal cases. The same principle may be used for analyzing helmets used by athletes for detection of trauma, concussion or stigma.

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9. Rahman and A.K. Rahman, "Effective testing for wafer reject minimization by terahertz analysis and sub-surface imaging." *Proceedings of ASMC* 2014, pp 151–155. Link: http://arphotonics.net/ASMC2014_5.8.pdf

10. Anis Rahman, Aunik Rahman, Ruby Dale, and Trevor Broadt, "Terahertz investigation of adjuvant and recombinant HPV vaccine candidate fusion protein," (paper no. ANYL 203), Wednesday, March 19, 2014 02:30 PM, *Advances in Analytical Spectroscopy* (01:00 PM - 03:55 PM), Location: Hyatt Regency Dallas, Room: Cumberland E
11. Anis Rahman, Aunik K Rahman "Fick's law characterization of diffusion properties of bio membranes by terahertz reflectometry, Division of Biochemical Technology Poster Session" (06:00 PM - 08:00 PM), Paper No. *BIOT* 280, Tuesday, March 18, 2014 - 06:00 PM, Omni Dallas Hotel, Dallas Blrm A-C, 247th ACS National Meeting and Exposition, March 16-20, 2014, Dallas, Texas.
12. Anis Rahman, Aunik K Rahman, "Emerging terahertz imaging for sub-surface biomedical tomography", Paper No. *BIOT* 282, Poster session at 247th ACS National Meeting and Exposition, March 16-20, 2014, Dallas, Texas.
13. Anis Rahman, "Art and science of a start-up company in light of the JOBS Act," paper No. *SCHB* 12, True Stories from Chemical Entrepreneurs (08:00 AM - 12:00 PM), 247th ACS National Meeting and Exposition, March 16-20, 2014, Dallas, Texas.
14. Mukund Chorghade, Stan Seelig, Sharon Vercellotti, David Deutsch, Patrick Kearney, Joseph Sabol, Anis Rahman, Jennifer Maclachlan, Keisha Hylton-Rodic, Carlyn Burton, George Ruger, "Division of Small Chemical Businesses SCHB is your connection to entrepreneurial resources," paper No. *SCHB* 1, 247th ACS National Meeting and Exposition, March 16-20, 2014, Dallas, Texas.