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Abstract

We present an optical detection technique, called the beam deflection probe, to accurately measure contact times of normal-incidence impacts of steel and sapphire spheres with a transparent glass block. It exploits the deformation of the area that is in a mechanical touch during the rebound. The deformation of the surface acts as a dynamic contact mirror. When illuminated by a laser beam, total internal reflection takes place at the contact mirror, the beam is deflected from it, and its angular deflection history is monitored by a quadrant photodiode. A simple threshold-level data processing of the photodiode signals is used to determine the impact duration. It is shown that the shape of the signal is highly dependent on the location of the impact relative to the center of the laser-beam illuminated area while the determination of the contact time does not depend on the impact position. Using an automated ball release mechanism, the contact time of low-velocity impacts was measured for various ball diameters and approach velocities conforming to the Hertz contact theory. The proposed optical detection of contact times supplements the existing measurement techniques and represents the only alternative to the piezoelectric detection when contact times are to be measured on the microsecond scale.

Keywords

- Contact time
- Hertz contact theory
- Beam deflection probe
- Elastic impact
- Contact mirror

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Introduction

A general physical picture of a low-velocity, normal-incidence impact between two solid bodies consists of four successive phases [1]. It begins with the short-lasting super-seismic regime, followed by the development of the elastic phase which, in practice, often enters the plastic regime, and finishes with the recoil stage. The time during which the four phases take place is called the *contact time*, the *impact duration* or the *collision duration*. This time is confined between the starting and the ending point of a mechanical contact when the impactors firstly touch and then separate from each other. For a purely elastic collision, the impact can be simply described by time-symmetric approach and recoil phase.

Accurate measurements of the contact time are not only important in the basic studies of contact mechanisms in order to assess the validity of the proposed theory [2],[3], they are also important in a wide range of different applications related to, for example, contact mechanics, tribology, shot peening, wear, erosion, rock falls, military ballistics, measurements of hardness at high strain rates and granular matter research.

Due to its linear dependence on the radius, the contact time of spherical particles impacting thick plates is, for instance, a good criterion for their size [4],[5],[6],[7],[8] whereas particle sizing is an important requirement in many areas of industrial processing and manufacture [8]. If the velocity of the particle is known with some uncertainty, the size of the particle can be determined via its impact with another solid more accurately by measuring the contact time than the maximum force [5],[6],[8], because the contact time has a more gentle dependence on the approach velocity as opposed to the maximum force.

A sphere drop on a stationary plate or a block is also often used as a standard acoustic source of ultrasonic waves. These mechanical disturbances are then used as a known input signal for the calibration of piezoelectric (PZ) displacement sensors [9],[10].

Until now, measurements of short contact times of μs order of magnitude could only be accomplished by PZ detection of elastic waves generated during the impact [7],[8],[9],[10]. The accuracy of such measurements was primarily undermined by the need to remove the distortion effects of the sensor through a numerical deconvolution. However, this technique demands initial high-frequency calibration of such a sensor preferably with non-ball impact stimulus either with a short laser pulse [11] or a thin capillary fracture [12]. On the other hand, electrical circuit switch approach to measure contact times mandates physical attachment of wires to the impacting solids. This interferes too much with the dynamics of the impact and it is practically impossible to connect wires with negligible effects to balls with diameters smaller than 1 mm.

As opposed to the existing measuring techniques, the presented optical detection of the contact time exploits the deformation of the area that mechanically touches during the impact [13],[14]. The deformation of the surface acts as a dynamic mirror, which we hereafter refer to as the *contact mirror*. When the contact mirror is illuminated by a laser beam, the beam is deflected by this deformable surface and the angular deflection history can be monitored by a position sensitive detector, such as a quadrant photodiode.

In our experiments, steel balls with diameters from 1 mm to 5 mm and sapphire balls with 0.3-mm diameter were dropped on a stationary, large glass block from 2.5-mm to 50-mm height. The release mechanism enabled repetitive impact events in the low velocity (0.2 m/s – 1 m/s) regime. If the contact mirror was probed from above, the impacting ball would have screened the laser beam just before the collision, making this method useless. But when one of the solids is transparent for the probing light, such as the glass, full reflection from the contact mirror can be attained within the transparent object under the conditions of the total internal reflection. To extract the value of the contact time from the measured signal, a non-demanding data analysis suffices.

After a comprehensive review of the current contact time measuring techniques, exposing their pros and cons, the Hertz theory is briefly summarized, since we compare our optical measurements of contact times against its predictions. Then, the experimental setup consisting of the beam deflection probe and the conventional PZ detection is introduced. Contact times were optically determined for steel balls with various diameters dropped from the same height, and as a function of different heights for a 3-mm-diameter ball. To test the sensitivity limit of the measuring apparatus, sapphire balls with 0.3-mm diameter were released from an elevation of 25 mm.

Contact time measuring techniques

There is a substantial amount of methods for measuring collisional properties, particularly the contact time [13]. When two conducting materials are used, it is a reasonable way to measure the contact time by considering the contact as a switch, when colliding objects are connected in an electric circuit [2],[15],[16],[17],[18],[19].

An early realization of this method consisted of a swing made of two 50-mm-diameter ballistically suspended identical spheres [15]. The corresponding contact time for low velocity impact, where air drag had negligible influence, was 180 μs . A similar low-velocity, pendulum-based ball suspension experiments were later made with slightly smaller identical balls [2],[16]. Using steel balls with diameter of 25.4 mm in the impact velocity range 0.4 m/s – 1.5 m/s, the measured contact time was between 70 μs and 90 μs [2] and for the same velocity range, using steel balls with diameters of 27.0 mm and 38.1 mm, the contact times were in the interval 75 μs – 100 μs and 100 μs – 140 μs , respectively [16]. Minamoto and Kawamura also exploited the electrical circuit switch technique to measure contact times between 60 μs and 110 μs at low impact velocities from 0.3 m/s to 3 m/s with identical 25.4-mm-diameter steel balls [17]. This technique was also used to measure contact times of 27.0-mm-diameter steel balls impacting long rods normally on one of the flat ends with a velocity of 0.3 m/s and contact time of about 130 μs [18]. The impact velocity in pendulum-type setups is mainly limited by the arm length to about 3 m/s, so for larger velocity experiments, pendulums are replaced by air gun setups [20]. Using the same balls as in [17], Minamoto and Kawamura again exploited a modified electrical circuit switch technique to measure contact times of about 50 μs in the moderately high impact velocity range of 10 m/s – 20 m/s with 25.4-mm-diameter identical steel balls [20]. Other experimental results for the impact of a sphere against another sphere, a plate or a rod are summarized in Goldsmith [13].

Non-pendulum, free fall conditions took place in a recent experiment, where contact duration was studied for different lubrication conditions by application of complex impedance measurement [21]. Disadvantage of this method is in the inaccuracy caused by the wire that has to be connected with a 30-mm-diameter colliding steel ball. Electrical circuit method becomes unreliable for small ball diameters when the dynamics of the ball is affected too much by the connecting wires.

The evolution of the contact force and consequently the determination of the contact time can be also measured with a PZ film sandwiched between the colliding bodies [22],[23],[24]. Disadvantage of this method is its intrusion, because different materials in contact may change the contact properties significantly. Bacon et al. experimented with different ball materials with contact times of a few ms [22]. When the ball was dropped on the PZ wafer, the shape of the experimental force-time curve was asymmetric with the maximum force occurring closer to the starting point of the contact. Due to the dynamic response of the PZ crystal, at the end of the contact, some ringing of the signal was present. This made the ending point of the contact less accurately determinable.

The contact time can also be measured by observing ultrasonic waves that are launched from the contact area and then propagate, reflect, mode-convert, disperse and attenuate within both colliding solids. It was theoretically predicted that 3% [25] to 4% [26] of the initial kinetic energy is transformed into elastic waves at the elastic impact of a steel sphere with a steel or glass block if the contact is not interrupted by the reflected waves, and even more at impacts with rods [27]. Approximately 2/3 of the energy pertaining to ultrasound is carried by the surface-propagating Rayleigh waves, 5% – 10% by bulk compression waves and the rest by bulk shear waves [28]. Detection of elastic waves may be carried out using surface-deployed sensors that operate through transduction mechanisms based on piezoelectric, electrostatic, electromagnetic or optical (mainly light interferometric) principles [29]. Of these, PZ sensors are the most sensitive [30], making them particularly useful to detect low momentum-transfer impacts.

Ball-rod [18],[27] and ball-plate [7],[8],[9],[10],[19],[31],[32],[33] experiments involving the detection of ball-impact-induced elastic waves were realized. Long-enough rods allow the elimination of the disturbance caused by the wave reflections. The wave properties are measured at the unstruck end of the rod. In the first realization, the impact force history was determined optically from the velocity of the free end, measured with a laser-Doppler vibrometer [27]. The measured contact times ranged between 150 μs – 200 μs . In the second realization, the contact times of about 130 μs were measured with a displacement-measuring, fringe-counting Michelson-type interferometer [18]. However, in rods dispersion widens the length of the guided wave. This is in turn interpreted as a longer time of contact if dispersion effects are not deconvolved from the measurements [18],[34].

All the methods described above were used for ball diameters larger than about 10 mm, which are capable of producing impacts with contact times in the 100 μs range. For impacts involving balls with diameters as small as 35 μm [8], PZ detection of elastic waves seems to be the only alternative due to unmatched sensitivity of this detection technique. McLaskey and Glaser experimented with glass, ruby and hardened steel balls 0.4 mm to 2.5 mm in diameter. They were dropped normally onto steel, glass, aluminium, and polymethylmethacrylate plates at low approach velocities, yielding impacts with contact times down to 1 μs [31]. Temporal distribution of the force during the contact was obtained by performing a deconvolution of the output signal of the displacement-measuring PZ sensor located either on the impacted side of the plate or on the other. A similar technique was used by Buttle and Scruby in their particle sizing research involving PZ detection of acoustic

emission [7],[8]. Schnabel et al. also performed similar experiments by dropping steel balls with diameters ranging from 1.5 mm to 10 mm onto aluminium and steel plates of various thicknesses and studied the effects of the elastic waves returning to the contact site in the frequency domain [10]. They combined PZ detection with absolute readouts from laser Doppler vibrometer.

When the determination of the contact time is in question, the signal-distortion effects of the PZ sensor need to be eliminated through a numerical deconvolution which is per se a mathematically ill-posed problem [32],[33]. At an expense of a computationally demanding alternative, the described backward modeling approach can be circumvented by a forward modeling, where the sensor transfer function is convolved with the calculated sensor input and the result is iteratively fitted to the recorded signal until the desired similarity is obtained [35]. In any case, the effect of PZ sensor distortion cannot be fully removed. The value of the so-determined contact time is therefore questionable, especially when it is to be measured in the 100 ns extreme [8], because the frequency response of common PZ sensors drops significantly after a few MHz, due to sensor aperture effect [11], and intrinsic dynamics of the active element and backing material [36].

Experiments with high-speed cameras have negligible effect on collision properties but they are more suitable for measuring velocities before and after collision by comparing a sequence of images than determining the start and the end point of the collision [37],[38].

The Hertz theory

Hertz's dynamic linear elastic theory [13],[14],[39] for central collisions of non-adhesive, perfectly elastic solid spheres is surprisingly accurate in predicting the contact time t_c , because of its very weak dependence on the impact velocity v [3]. It is valid when adhesion energy is negligible compared to the kinetic energy, gives a symmetric temporal dependence of the force [23],[26],[40], assumes no energy loss, no plastic deformations, no generation of elastic waves and neglects the super-seismic regime [1]. If the radius of one of the spheres is infinitely large, the problem describes the collision of a sphere with a half-space. It has been shown many times that in the low-velocity regime its predictions agree with the experimental collision times [18],[31] even when non-unity coefficient of normal restitution accounting for impact dissipation is included in the analysis [1],[41].

According to the quasistatic Hertz's theory, the sphere (ball, $i = 1$) and the half-space (large block, $i = 2$) are considered homogeneous and isotropic with Young's modulus Y_i and Poisson's ratio μ_i . The sphere with a radius R_1 and a mass density ρ_1 is assumed to collide normally with a half-space with an approach velocity v without any rotation relative to the half-space. This theory predicts a perfectly elastic reflection with unity coefficient of restitution, the contact time

$$t_c = 8.041 R_1 \rho_1^{2/5} v^{-1/5} (\kappa_1 + \kappa_2)^{2/5}, \quad (1)$$

the maximum contact radius

$$R_{\max} = 1.653 R_1 \rho_1^{1/5} v^{2/5} (\kappa_1 + \kappa_2)^{1/5}, \quad (2)$$

and the indentation depth $d = R_{\max}^2 / R_1$, where $\kappa_i = (1 - \mu_i^2) / (\pi Y_i)$. Reed [26],[31] obtained a symmetric loading of the form $F(t) = F_{\max} \sin(\pi t / t_c)^{3/2}$ for $0 \leq t \leq t_c$ with the maximum force

$$F_{\max} = 1.917 R_1^2 \rho_1^{3/5} v^{6/5} (\kappa_1 + \kappa_2)^{-2/5}. \quad (3)$$

The first half of the purely elastic loading pertains to the approach phase and the last half to the recoil stage. The contact time is linearly dependent on the radius of the sphere, while the impact velocity of the ball has, because of the $-1/5$ power, just a slight influence. On the contrary, the maximum force has a strong dependence on the impact velocity and quadratic on the sphere radius.

Each contact time dependence x in Eq. (1) has an absolute uncertainty δx . If $\delta x \ll x$ then the relative uncertainty of the contact time can be expressed with the relative uncertainties $\delta x / x$ as

$$\frac{\delta t_c}{t_c} \approx \frac{\delta R_1}{R_1} + \frac{2}{5} \frac{\delta \rho_1}{\rho_1} + \frac{1}{5} \frac{\delta v}{v} + \frac{2}{5} \sum_{i=1,2} \kappa_i \left[2 \frac{\mu_i^2}{1 - \mu_i^2} \frac{\delta \mu_i}{\mu_i} + \frac{\delta Y_i}{Y_i} \right] / (\kappa_1 + \kappa_2), \quad (4)$$

Given that the sphere is dropped from the height h , the approach velocity is $v = \sqrt{2gh}$ and the contribution of its uncertainty to $\delta t_c / t_c$ can be further expanded $1/5(\delta v / v) = 1/10(\delta g / g) + 1/10(\delta h / h)$, where g is the local gravitational acceleration. We have calculated the influence of air drag on the impact velocity and found

that the relative error in computing the impact velocity simply as $v = \sqrt{2gh}$ is never larger than 0.4 % for all experimental events and never larger than 0.1 % when estimating the contact time.

Experimental setup

The side-view schematic drawing of the experimental setup is shown in Fig. 1. The glass cube (6) with $a = 100$ mm edge-length is made of a commercial K9 crystal, primarily intended for 3D decorative laser etching/engraving. It has a refractive index of $n_1 = 1.515$ at 633 nm. Its mechanical properties are given in Table 1 along with the properties of the steel and the sapphire balls. The larger sized balls are made of AISI 52100 magnetic steel and comply with the DIN 5401 International standard, grade G80. Their diameters range from 1 mm to 5 mm with a 0.5 mm increment, except that the 4.762 mm diameter balls substitute the missing 4.5 mm balls. The glass balls of 0.3-mm diameter are made of ruby doped sapphire (Al_2O_3) and are commercially available as ball lenses (Edmund Optics, product number #46-223). Even though these balls have a pale red appearance owing to the traces of chromium oxide, they are barely visible to the naked eye and are difficult to handle due to electrostatic attractive forces. The balls were released from the height h , ranging from 2.5 mm to 47.5 mm, impacting the center of the top face of the glass cube.

Fig. 1 Side-view schematic drawing of the experimental setup. The setup consists of the laser source (1), two convergent lenses (2), electromagnet (3), piezo (PZ) sensor (4), deployed at a distance d from the center of impact, and quadrant photodiode (5). α is the incidence angle on the side-face of the glass cube (6) with refractive index n_1 and β is the refraction angle. In the air with refractive index n_0 , the ball was dropped on the cube from the height h

Table 1
Material properties

Material	Mass density [kg/m ³]	Young's modulus [GPa]	Poisson's ratio
BK7 / K9 glass cube	2532 ± 8	78 ± 5	0.21 ± 0.01
AISI 52100 100Cr6 Chrome steel balls $R_1 = 0.5 \text{ mm} \pm 1 \text{ } \mu\text{m}$ to $2.5 \text{ mm} \pm 1 \text{ } \mu\text{m}$	7810 ± 10	200 ± 10	0.29 ± 0.01
Ruby doped sapphire (Al_2O_3) balls $R_1 = 0.15 \text{ mm} \pm 2.5 \text{ } \mu\text{m}$	3980 ± 10	440 ± 10	0.30 ± 0.01

Using the mechanical properties given in Table 1, the following velocities of the different types of the released elastic waves are calculated: the bulk compressional P-wave velocity is $c_p = 5890$ m/s, the bulk shear S-wave velocity is $c_s = 3570$ m/s and the surface-propagating Rayleigh R-wave velocity is $c_r = 3260$ m/s. For a normal force excitation of a half-space, the surface-propagating P- and S-waves cause negligible normal displacement of the surface [42], so the first significant elastic wave to return to the contact area is the once-

reflected Rayleigh wave that has travelled a distance equal to the edge-length of the cube. This occurs at the time $t_R^{\text{top}} = a/c_R = 31 \mu\text{s}$. The second, important disturbance returning to the origin is the P-wave, reflected from the bottom face of the cube, traversing a distance $2a$. Its arrival is expected at the time $t_P^{\text{bottom}} = 2a/c_P = 34 \mu\text{s}$. We conclude that for times smaller than $31 \mu\text{s}$, the contact area is not disturbed by the reflected elastic waves propagating in the glass cube, so in this case, the glass cube is equivalent to a semi-infinite space. This is true for all contact times measured in our experiments.

A Glaser-type conical PZ sensor (4) (sensor: KRNBB-PC, KRN Services, USA; external amplifier: KRNeWB-PC) was brought in contact at the distance $d = 21 \text{ mm}$ from the center of the impact. It measures the out-of-plane displacement history of the top surface under the tip of the sensor. It has a nearly flat sensitivity from 50 kHz to 2.5 MHz and a noise floor close to 1 pm. Its repeatable signal was used as a trigger for the impact event. The same signal is often used to determine the contact time [7],[8],[9],[10],[31],[33]. It has to be noted that it is more convenient to estimate the impact contact time when a PZ sensor is deployed directly beneath the location of impact, because this way the undesired aperture effect is minimized [9]. Moreover, in this experimental arrangement, the shape of the signal closely resembles the force-time function, from which the contact time can be read directly if a sensor with a flat frequency response is used [43].

The Gaussian output of the He-Ne laser (1) with the wavelength of 633 nm and power of 1 mW was used as a probe beam. The incident angle on the side face was $\alpha = 24.0^\circ$. After refraction, the beam illuminated the center of the top face at an angle of $\beta = 15.6^\circ$ with respect to the top surface, which is well below the critical angle $\beta_c = 48.7^\circ$. The difference between the above-mentioned angles, 33.1° , is the maximum angle of the contact mirror at which total reflection still occurs. In general, the total reflection on the top surface of the glass cube requires the entry angle α on the side face to be smaller than the critical angle α_c . If the reflection index of glass n_1 is larger than $\sqrt{2}$, this condition is always fulfilled, else the following expression gives the maximum allowed entry angle $\alpha_c = \arcsin \sqrt{n_1^2 - 1}$.

Two convergent lenses (2) were used in the setup. The first one is used to vary the size of the probing area, while the second to change the spot size on the photodetector. By reducing the illumination size at the contact mirror, the sensitivity of the probe is increased, but it is at the same time more difficult to make certain that the impact area coincides sufficiently with the illuminated area. We had ensured that after reflection from the probing site, the beam has not passed the focus neither of the first nor of the second lens so that left-right and up-down inversion of the optical transformation has not occurred.

The steel balls of all sizes were dropped from the height h using the same magnetic release mechanism (3) but using a proportionate strength, while a tiny, vacuumed injection needle was used to hold the sapphire 0.3-mm-diameter ones. The height is measured vertically from the top surface of the glass cube to the lowermost point of the ball.

The magnetic release mechanism allowed us to rapidly generate repeatable impacts [10]. The electrical circuit was fed with two different electrical currents: the high and the low current. Turning off the electromagnet resulted in the release of the steel ball. After it rebounded from the top face of the glass cube and just before it reached to highest point, the electromagnet was switched on using a pulse of a high current which was set to a value just above the threshold to overcome the energy lost by impact. Once the ball was caught, the current was set to a lower value, just large enough to prevent the release. By minimizing the needed magnetic field to still hold the ball, we provided better free fall conditions and reduced the magnetic force that acted on the ball just after the turnoff of the magnet. Moreover, by minimizing the field, the ball descends to the lowermost point on the tip of the electromagnet. With this, the location and drop height of the impact was more repeatable.

The injection needle with a flat tip and the inner diameter smaller than that of the ball was connected with a syringe by a rubber tube. While sucking the air in the syringe, the sapphire ball was brought close to the tip until it stuck to the tip due to the pressure difference. The ball detached for the tip of the needle when the air pressure in the syringe slowly approached the ambient pressure by letting the ambient air flow in the syringe through a small hole. If the sapphire ball would not detach due to static electricity, the electrical static charges were neutralized by illumination with ultraviolet light [44]. All sapphire balls were dropped from the height of 25 mm. The purpose of choosing tiny sapphire balls was to estimate the smallest momentum transfer that can still be detected by the method described in this paper.

Deflection of the laser beam from the contact mirror, shown in Figs. 2 and 3, was measured by a position sensitive detector (5). We used a quadrant position detector, called the *quadrant photodiode*, consisting of four identical, square-shaped Si photodiodes placed as to resemble the quadrants divided by the axes in a two-dimensional Cartesian coordinate system. The diodes are separated by a small gap and together form a large

square-shaped detection area capable of monitoring the position of the illuminated area on the sensor. Each quadrant (labeled: UL, UR, DL and DR, where U stands for up, D for down, L for left and R for right) produces a photocurrent proportional to the light power impinging on it. The following combinations of the photocurrents, the up-down signal $UD = (UL + UR) - (DL + DR)$ and the left-right signal $LR = (UL + DL) - (UR + DR)$ were extracted from the sensor, converted to voltage and amplified using a homemade amplifier with a flat frequency response from DC to 100 MHz. If an axially symmetrical beam is centered on the sensor, the separate photocurrents from all four quadrants will be equal, resulting in null signals UD and LR. If the beam is moved in the horizontal direction, the UD will remain unchanged while the LR will become positive when the beam moves to the left and negative when it moves to the right. Similarly, if the beam is moved in the vertical direction, the LR stays zero while the UD will become positive when the beam moves up and negative when it moves down. Note that the outputs UD and LR are not normalized by the sum of all four quadrants as is usually done in the beam deflection readouts used in atomic force microscopy to make to signals independent of the laser power fluctuations [45].

Impact mechanisms influencing the UD and the LR signal

Because the UD and the LR signal is not normalized by the total incident power impinging on the quadrant photodiode, beam deflection causing a spatial redistribution of the beam profile on the imaging plane is not the only phenomenon that produces non-zero signals. Variations of the reflected laser beam power also affect the signal.

We have identified three distinct mechanisms related to the impact that could affect the UD and the LR signal. The most relevant one is beam deflection caused by the transient dynamic reshaping of the contact mirror. Signals could also depend on the change of the Fresnel reflection conditions under the contact area and on the possible beam deflection caused by the bulk waves propagating within the material, through which the probing laser beam passes.

Later in this paper, we shall give an experimental proof that the *beam deflection* caused by the change of the surface geometry under the impact has the only detectable effect on the signal.

Beam deflection from the contact mirror

For simplicity, we make the following assumptions whose validity will be discussed later in the paper. The surface of the contact mirror has a simple shape—a smoothly varying, circularly symmetrical depression with the maximum depth under the center of the impact (see Fig. 2) [46]. The temporal evolution of the contact mirror is symmetric in time, meaning that after half of the contact time $t_c/2$, the surface of the contact mirror changes as if the time was rolled back. The glass cube deforms elastically so that after restitution the contact mirror returns to its original, plane mirror shape.

Fig. 2 Ray deflection on the dynamic contact mirror. The Gaussian laser beam is composed of a pencil of weighted rays (only 3 are drawn). For simplicity, we assume that the contact mirror has a shape of a transiently changing depression. Four time instants are labeled: (1) the beginning of the contact; (2) and (3) two time instants during the approach period;

- (4) time of maximum approach (half of contact time). The inset graph shows the vertical position $y(t)$ on the quadrant photodiode as a function of time

We also assume a collimated laser beam impinging at an angle β measured from the top face of the cube. This beam can be thought of as composed of a parallel pencil of rays weighted according to Gaussian spatial distribution. When the laser beam is much smaller than the size of the contact mirror, one should only follow the deflection of a single ray, representing the total laser beam, to understand how UD and LR signals change with time. But when the beam has a comparable size or is much larger than the contact mirror, the time-varying superposition of the deflected, weighted rays on the quadrant photodiode is what describes the shape of the UD and LR signals.

To further describe how the shape of the contact mirror influences both signals extracted from the quadrant photodiode we shall follow three rays propagating in a plane of incidence that symmetrically cuts the contact mirror in half. Due to this symmetry, these three rays only change the vertical, up-down position y on the quadrant photodiode and have no influence on the horizontal left-right displacement.

The ray that reflects just under the center of the impact prior to collision (the black solid line in Fig. 2), arrives just on the edge between the upper and lower quadrants. The rays (not shown in Fig. 2) that strike the initial plane mirror left from the center, hit the lower quadrants while those that strike the plane mirror before the impact right from the center (two are shown in Fig. 2: the red dashed line and the blue dotted line), illuminate the upper quadrants.

Deflection of these three rays is given at four time instants which are labeled (1)-(4) in Fig. 2. The label (1) represents the beginning of the contact; labels (2) and (3) stand for two time instants during the approach period; and (4) denotes the time of maximum approach occurring at half of the contact time. These four time instants are also shown as grey vertical dashed lines in the inset graph in Fig. 2 which gives the temporal evolution of the vertical displacement $y(t)$ of a separate ray. Each $y(t)$ dependence in the inset graph was obtained qualitatively by following the position and deflection angle of a chosen ray from the time-changing contact mirror. It is seen in Fig. 2 that during the impact, the central ray (the black solid line in Fig. 2) only illuminates the lower quadrants. The ray represented by the red dashed line initially moves up into the upper quadrants and then makes a downward deflection into the lower quadrants. After the maximum indentation in the middle of the impact duration, the motion is rewound. The ray represented by the blue dotted line has a similar deflection characteristics as the previously described red one, except that the amplitudes of the deflection and the times when the deflection direction is changed differ.

We would like to stress that we have only described a simplified qualitative physical picture of how the contact mirror transforms the spatial distribution of the probe beam intensity on the quadrant photodiode if all the light is reflected at the surface due to total internal reflection. A more rigorous, qualitative transfer function can be obtained if the distortion effects of the contact mirror on the impinging wavefront are calculated using the Fresnel diffraction theory. This approach was employed in a similar technique, called the time-resolved thermal mirror method, used for quantitative measurements of thermal and mechanical properties of materials with the sole exception that the thermal mirror arises from light-induced heat generation in a sample followed by the expansion or contraction of the sample surface [47].

Additionally, we would also like to point out that at higher impact momenta plastic deformation may also be present. In this case, the shape of the contact mirror may develop a pile-up around the impact, further complicating the effect the contact mirror has on the probe beam [48].

Local intensity decrement

The second mechanism that could affect the quadrant photodiode signals is the *local laser beam intensity decrement*, schematically depicted in Fig. 3. Before the impact, the refraction index of air above the glass cube is smaller than that of the cube, what leads to a total reflection of the probe beam. But when the ball comes in contact with the surface, the conditions for the total reflection may no longer be satisfied. For instance, some light could transmit to the dielectric ball at the area of contact or could be absorbed when the ball is metallic. Because of it, the power of the laser beam is locally reduced. This phenomenon is illustrated in Fig. 3, where for the clarity of presentation, the diameter of the probe beam is larger than the ball diameter. It is shown that the ball strikes the left part of the illuminated area. In this case, the laser beam intensity is reduced on the lower half of the quadrant photodiode resulting in a positive UD signal.

Fig. 3 Schematic illustration of a local change in intensity distribution when the ball is in contact with the surface

The intensity of the reflected light may begin to decrease even before the ball touches the surface due to the tunneling effect of the evanescent field called the frustrated total internal reflection. This effect becomes significant when the distance between the ball and the glass surface is in the order of the magnitude of the laser light wavelength. For this reason, the UD and LR signals may begin to deviate from the zero value slightly before the impact occurs and may persist a little longer than the actual time of the physical contact. To estimate the time scale of this effect, we take the laser wavelength of 633 nm and the impact velocity around 1 m/s, corresponding to the release height of 50 mm. Using these experimental values, the contact time could appear as longer for values up to $2 \times 0.6 \mu\text{s}$. This effect is therefore relevant when shorter ball impact times are to be measured accurately. In our experimental signals, there is no evidence of the tunneling effect, so we can safely ignore it.

Beam deflection from the bulk elastic waves

The third source of the nonzero photodiode signals are the *elastic waves generated by the impact*. The compressions and rarefaction of the propagating ultrasonic waves locally change the refractive index of the transparent material. Spatial variations of the refractive index deflect the laser beam as in the acousto-optic modulator.

With a separate experiment, where the laser beam was targeted directly through the transparent material (without total reflection), it was found that the change of refraction index caused by the elastic waves is too small to produce a detectable deviation of the laser beam. It should be noted that a similar beam deflection by the sound waves propagating in the air or liquid is a well-developed diagnostic tool for the detection of fluid-coupled ultrasound [49].

In summary, in our experimental layout, the beam deflection, caused by the change of the surface geometry at the contact area has the strongest effect on the quadrant photodiode signals, therefore the beginning and the end of the ball impact can be deduced directly by the determination of the time, when the quadrant photodiode signals move from their zero-position. When the ball first comes in a physical contact with the glass cube, the signal from the quadrant photodiode begins to change. The only condition that has to be satisfied is that the first touch of the ball with the surface occurs within the illuminated area. Moreover, the relative size between the ball diameter and the beam size at the reflection surface does not affect the measured contact time. Using a larger beam size, the sensitivity is reduced, but it is easier to locate the impact on the area, where the laser beam reflects.

Experimental results

Determination of the contact time from the deflection probe signals

The up-down (UD) and left-right (LR) signals from the quadrant photodiode (the blue lines in Fig. 4(a)) and the PZ sensor signal (the red line in Fig. 4(a)) were captured and digitalized by an 8-bit DSO (WaveRunner 6050A, LeCroy, USA) with a sampling frequency of 0.5 GHz. Typical signals for a single ball impact are shown in Fig. 4(a).

The data processing begins with the removal of a linear trend from the UD and LR signals. This operation brings the mean value of the noise before and after the collision to zero [50]. For presentation purpose only, an offset of 0.05 V was respectively added or subtracted from the UD and LR signals. Waveforms were then smoothed (the black lines in Fig. 4(a)) by a 2nd-ord, low-pass digital Butterworth filter with a cutoff frequency of 2.5 MHz.

The beginning of the contact was defined as the intersection point of two lines (12.7 μ s in Fig. 4(b)): the zero line (the black dotted line in Fig. 4(b)) and the linear fit to the rising filtered signal (the black dashed line in Fig. 4(b)). The time interval used for the linear fit is specified as follows. The beginning of the fitting interval was specified as a time when the absolute value of the filtered signal first overcame the value chosen as 1.5 times that of the noise maximum, while the end of the interval was chosen as the time when the absolute value of the filtered signal reached one third of the absolute value of the filtered signal extremum. The end of the contact was specified in the same manner. The contact time was then calculated as the time between the end and beginning of the contact.

Fig. 4 (a) Typical measured signals from the quadrant photodiode in the up-down (UD) and left-right (LR) direction and from the piezo (PTZ) sensor, deployed on the top surface of the glass cube. This experiment was made with the ball having a 1.5-mm radius, dropped from the height of 28.5 mm. The enlarged area of (a) is shown in detail in (b). The beginning of the contact was defined as the intersection point of the two lines

To determine the contact time t_C , both the UD and the LR signals were used. The only criterion on which signals are to be evaluated was a sufficient signal-to-noise ratio (SNR), defined as the ratio of the maximum value of the signal to the maximum value of the noise. Only the waveforms with sufficient SNR were accepted. In our experiments, the SNR is strongly dependent on the location of the impact and on the approach momentum of the ball. Therefore, for small ball diameters and small release heights, we set the SNR threshold lower than for the large ball diameters and higher drop heights. By increasing the SNR threshold, the standard deviation of the measured contact times decreases, but the larger the SNR threshold, the fewer measurements satisfy the chosen criterion. To keep these issues balanced, we set the SNR threshold to 35 when 0.5-mm-radius balls were used. When larger, 2.5-mm-radius balls were used for impacts, the SNR threshold was set to 80. The higher the SNR, the more abrupt is the transition between the noise floor and the non-zero part of the signal during the collision.

Determination of the contact time from the piezoelectric (PZ) signal

The elastic waves released during the impact were detected by the piezoelectric (PZ) sensor. The most dominant feature in the detected waveform (the red line in Fig. 4(a)) is the surface propagating Rayleigh wave, seen as the large depression. Except for the negligible contributions of the surface skimming pressure and shear waves, the Rayleigh wave is also the first wave to arrive at the PZ sensor. It was used to trigger the DSO. The time delay between the beginning of the photodiode signals and the beginning of the PZ signal corresponds the time-of-flight of the Rayleigh wave across the distance between the impact location and the PZ sensor. The calculated delay $t_R = d/c_R = 6.4 \mu$ s matches the experimental value that can be extracted from Fig. 4(a).

Using the PZ waveform, the temporal distribution of the force during the impact and consequently the contact time can be obtained through numerical deconvolution with the sensor transfer function

[7],[8],[11],[31],[32],[33]. The duration of the depression can be used as an approximate measure of the contact time only when the frequency response of the PZ sensor is sufficiently flat in the frequency region given by the dominant Fourier components of the force distribution. For the Glaser-type conical PZ sensor we have used, this condition is satisfied for contact time larger than a few μs . Note that if the PZ sensor was deployed in the epicentral position—beneath the impact site—the waveform would even more closely resemble the loading history since in this arrangement the initial P-wave induces an out-of-plane surface displacement with nearly the same time-dependence as the loading force, assuming the near-field ramp between the P- and S-wave arrivals can be neglected [9].

Even if the ball misses the area illuminated by the probe beam, the propagating Rayleigh wave still passes it causing ripples on the surface. In our experiments, the amplitudes of these ripples are too small to appreciably deflect the probing beam. Therefore, no change in the UD and LR signals is detected due to the perturbances of the surface-propagating elastic waves. We intentionally dropped balls near the illuminated area but not directly onto it. In this case, the UD and LR signals remained flat (noise only), while the PZ signal remained the same if the impact location was changed by a distance smaller than the initial source-detector separation.

Moreover, the UD and LR signals are highly symmetric, so there is no evidence of asymmetry in the measurements that would be expected if surface-propagation elastic waves also contributed to the deflections under the sensing area.

Impact mechanisms: beam deflection vs. power reduction

With an intention to determine what impact mechanisms influence the quadrant photodiode signals, we performed the following experiment where only the UD signal was monitored. This only gave us the information on the redistribution of the probe beam intensity in the vertical direction.

Fig. 5 The UD signal in three different initial positions. Position 1: the center of the photodiode. Position 2: the middle of the bottom quadrants. Position 3: only the top half of the beam falls on the sensitive part of the bottom quadrants. The beam size shown on the scheme is larger than its actual size

The quadrant photodiode was placed in three different positions relative to the center of the probe beam as is shown in the inset in Fig. 5. In position 1, the beam illuminates the center, in position 2, it impinges near the middle of the lower quadrants and in position 3, only about half of the beam irradiates the lower quadrants while the other half falls on the light insensitive part.

When the beam illuminates the center, the upper and lower quadrants consume the same amount of light. The unperturbed UD signal is therefore zero. During the impact in this specific experimental arrangement, the contact mirror deflects the beam towards the upper quadrants, giving a positive UD signal (signal 1 in Fig. 5). Position 1 was used in all experiments described later on in the paper except in the following two cases.

In position 2, the probe beam illuminates the area where the quadrant photodiode is not sensitive to the deflection of the laser beam in the vertical direction as long as deflections are not too large. However, in this position, the UD signal is sensitive to the change of the laser beam power. The measurements reveal that the signal is undisturbed during the impact (signal 2 in Fig. 5), from which we can conclude that the power decrement, caused by the ball-glass cube contact, is negligible. This proves that beam deflection from the contact mirror

represents the dominant influence on the shape of the signal. Since laser power reduction is not detectable, the error that could have occurred because of the tunneling effect does not affect the accuracy of the contact time measurements.

Interestingly, in position 3, the UD signal responds to the impact in the opposite direction (signal 3 in Fig. 5) relative to the signal obtained in position 1. In this case, the same upward deflection in the imaging plane brings more light to the lower quadrants whose output is subtracted from the upper quadrants in the UD signal. The amplitude of signal 3 is smaller than that of signal 1 since the effect of beam deflection in the vertical direction has a double contribution to the UD signal when in position 1. The measurement principle in position 3 is similar to the knife edge method [51].

Impact-site-dependent signal shape

The shape of the UD and the LR signal strongly depends on the relative position of the center of the impact with respect to the center of the area illuminated by the probe beam. We shall qualitatively describe the underlying reasons why the shape of the photodiode differential signal changes so dramatically. Regardless of the signal shape, the contact time remains independent of the impact site.

All the experiments shown in Fig. 6 were realized with a 2.5-mm-radius steel ball, dropped from the height of 29 mm. Using Eqs. (1)-(3), the following impact parameters are calculated: the contact time $t_c = 23.8 \mu s$, the maximum indentation depth $d = 6.0 \mu m$, the maximum force $F_{max} = 60 N$ and the maximum contact radius $R_{max} = 0.12 mm$. The radius of the laser beam at the probed area was measured to be 0.5 mm, about 4 times larger than the maximum contact radius.

The magnetic ball release mechanism was mounted on a linear translation stage. The direction of translation was perpendicular to the plane of incidence of the probe beam. The photodiode UD and LR signals were captured at 16 different impact sites. The values in the bottom-left part of each subfigure in Fig. 6 correspond to the displacement of the release mechanism from the initial point. The illuminated area was symmetrically scanned from its leftmost part across the center to the rightmost edge. The displacement steps were finer (0.1 mm) near the center of the illuminated area and coarser at the edges (0.2 mm). 5 impact events were captured at each location. The corresponding UD and LR signals are shown for each event.

Fig. 6 Variation of the UD and the LR signal shapes obtained when scanning with the impact site along the line perpendicular to the plane of incidence of the probe beam. The steel ball with 2.5-mm radius was dropped from the height of 29 mm. The label in the bottom-left part of each subfigure indicates the displacement along the line of scanning from the initial position. Both, the UD and the LR signals were captured 5 times at each release position

The first observation of the result given in Fig. 6 leads us to conclude that all the signals are time-symmetric with respect to the approach and restitution.

Away from the center of the illuminated area (the first and the last row in Fig. 6), the signals of all 5 measurements are much more repeatable compared to the signal obtained near the center (the middle two rows in Fig. 6). The same spread of impact sites for a given release position gives more variation in the shape of the observed signals the closer the impact is to the center of the illuminated area.

The amplitudes of the signals are smaller if the impact occurs near the edges of the probed area (the first and the last row in Fig. 6) as when it happens near the center (the middle two rows in Fig. 6). This is due to the Gaussian distribution of the laser beam intensity. When approaching the center of the laser beam, the amplitude of the UD and LR signals increases, due to the increasing intensity of the laser beam in the central part.

When the ball impacts on the left side of the probed area (the first row in Fig. 6), the half of the contact mirror that is closer to the beam center deflects more light to the right quadrants than the other half of the contact mirror deflects to the left quadrants. This is observed as a negative LR signal. Similar explanation is valid when the ball impacts the right edge of the probed area (the last row in Fig. 6). Here, the LR signal is positive. The LR signal is thus asymmetric with respect to the center of the illuminated area.

On the contrary, but as expected, the UD signal is symmetric with respect to the center of the probed area. Using the same reasoning as for the LR signal, a positive UD signal for the impacts at the edges (the first and the last row in Fig. 6) indicates that the line of the impact scan passes the illuminated area near the center, slightly towards the incident side of the laser beam (this configuration is also shown in Fig. 3). The half of the contact mirror that is closer to the beam center deflects more light to the top quadrants than the other half of the contact mirror deflects to the bottom ones. If the impact takes place near the edge of the illuminated area

(the first and the last row in Fig. 6) the shape of both, the UD and LR signals is a simple, monopolar, time-symmetric curve.

In the close vicinity of the center of the probed area (measurements at 1.1 mm and 1.2 mm), the shape of the signals is more complicated and very sensitive to small deviations of the impact position. An explanation of such multiple-peaked shapes is more involved. We shall restrict our description to the fact that a Gaussian laser beam can be thought of as being composed of a pencil of weighted rays, as is described in Fig. 2. Following the deflection of each weighted ray from the contact mirror and summing them up in each quadrant that they later illuminate explains the multiple oscillations seen in the measurements. It is not excluded that surface propagating Rayleigh waves could also have a detectable contribution when the center of impact coincides with the center of the probed area.

From the calculated maximum contact radius (0.12 mm) and the measured radius of the probe area (0.5 mm) we can estimate that significant overlying of the contact mirror (whose effect has a larger extent than the maximum contact radius) and the probed area is present in the measurements at displacement from 0.8 mm to 1.5 mm.

Due to the symmetric nature of the problem, we can conclude that the ball impacts in the center of the probed area somewhere around 1.1 mm and 1.2 mm from the starting point of the impact scan. For the present application of contact time measurements, the SNR is the largest the closer together are the centers of the impact and the probed area, but they should not coincide as the signal amplitudes are reduced in the arrangement of the coincidence.

Even though the shape of the signal and its polarity is strongly dependent on the ball impact location, the duration of the non-zero part of the signal remains the same, what allowed us to repeatedly determine the contact time.

Contact time as a function of ball radius

The contact time was measured for steel balls with radii ranging from 0.5 mm to 2.5 mm (Fig. 7). They were dropped from the height of 31.5 mm using the repetitive magnetic ball release mechanism. To optimize the SNR of the signals, the impact location relative to the center of the probed area was chosen in such a way that both signals were monopolar (see, for example, the UD signals at the distance 0.7 mm, 0.8 mm, 1.4 mm and 1.5 mm in Fig. 6). Due to different impact momenta at different ball radii, the SNR threshold was set to 80 for 2.5-mm balls and 35 for 0.5-mm ones. Linear interpolation was used for the other radii.

20 impacts were registered for each event. Both, the acquired UD and LR signals were used. The measured contact times are shown as black dots in Fig. 7.

The theoretical line was calculated using Eq. (1) with the input parameters given in Table 1. Its uncertainty, shown as the shaded band, was evaluated with Eq. (4). The measurement and the theoretical prediction show a perfect match. The ball-plate restitution coefficient is larger than for the ball-ball one when both balls are identical. It is therefore expected that in our case, the Hertz theory will be more compliant with measurements than if ball-ball geometry was used.

Fig. 7 Measured contact times (dots) as a function of ball radius. Release height of the free fall was 31.5 mm. The measurements are compared with the result of Hertz theory (Eq. (1), the blue line)

Contact time as a function of release height

Fig. 8 Measured contact times (dots) as a function of release height. The ball radius was 1.5 mm. The measurements are compared with the result of Hertz theory (Eq. (1), the blue line) and agree for heights larger than 22.5 mm

The contact time for a single size, 1.5-mm-radius ball was measured for different drop heights in range from 2.5 mm to 27.5 mm with a 2.5 mm increment and from 27.5 mm to 47.5 mm with a 5 mm increment (Fig. 8). The measured results were again compared to the theory of Hertz (Eq. (1)). Disagreement between the measured contact times and the theory at release heights smaller than 22.5 mm is a consequence of various phenomena that take place at low-velocity impacts. First, the magnetic ball release mechanism has an important influence on the free fall conditions. Because of the coil inductivity, the magnetic field is not nullified immediately when the current is switched off. The magnetic force generated meanwhile decreases the ball acceleration at the beginning of the free fall, what leads to smaller approach velocities at the collision. Smaller velocities lead to larger contact times. As was reported by McLaskey and Glaser [31], inelastic deformation of surface roughness of the contacting solids and the influence of dust stuck to these surfaces or grease due to handling may sap a non-negligible portion of ball's kinetic energy. This in turn increases the measured contact time and amplifies the scatter —both effects are seen in Fig. 8. The contact times for the release heights larger than 22.5 mm are less influenced by this effect and the theory conforms well to the measurements.

Sub-microsecond contact time

The purpose of performing impact experiments with tiny sapphire balls was to estimate the smallest momentum transfer and the corresponding contact time that can still be detected by the presented beam deflection probe. A sapphire ball, barely visible with the naked eye, with a 0.15-mm radius was released from the tip of the injection needle from the height of 25 mm. The impact parameters estimated with Eqs. (1)–(3) are: $t_c = 1.0 \mu\text{s}$, $d = 0.25 \mu\text{m}$, $F_{\max} = 0.14 \text{ N}$ and $R_{\max} = 6.1 \mu\text{m}$.

Fig. 9 The measured photodiode signal (blue line) obtained during the impact of the 0.15-mm-radius sapphire ball dropped from the height of 25 mm and the corresponding low-pass filtered signals (black line). The dashed black lines represent an approximate determination of the start and the end of the contact

Typical UD and LR signals are shown in Fig. 9. The measured contact time was $0.9 \mu\text{s}$, what is slightly smaller than the contact time of $1.0 \mu\text{s}$ predicted by the Hertz theory. Deviation from the theoretical value is considered to be a consequence of the injection needle release mechanism. If the negative air pressure in the syringe that held the ball stuck to the needle tip increased too fast or if it had to surpass the electrostatic forces between the ball and the needle tip, the air stream from the needle gave the ball an initial velocity that led to the measured contact times that were smaller than the theoretical ones.

We would like to note that the approach momentum of the sapphire ball was 40 nNs which is equal to the momentum of a light pulse with an energy of 12 J. This fact inspires hope that in the near future, light reflection (optical analogy of the mechanical impact) from a lossless mirror could also be optically detected by a similar beam deflection scheme. Even if optical detection is less sensitive than the piezoelectric one, it can probe directly the impact area where surface displacements are the largest.

Conclusions

We have introduced a non-perturbing, fully stand-off optical method to repeatedly measure the duration of the contact time of balls as small as 0.15 mm in radius with a transparent glass solid cube. The novelty of the method is that it exploits an internal laser beam reflection from the area of contact during the impact. The temporal dependence of the beam deflection, detected by a quadrant photodetector, is directly correlated with the contact time.

We have described different impact mechanisms that could influence the course of the signals extracted from the quadrant photodiode. Supported by experimental evidence, we found that the most relevant one is beam deflection caused by the transient dynamic reshaping of the contact mirror.

Contact times were measured for steel balls with radii ranging from 0.5 mm to 2.5 mm and released from the height of 31.5 mm. Using 1.5-mm steel ball we also measured the dependence of the contact time on the release height varying from 2.5 mm to 27.5 mm. The measured contact time dependence on the ball size matches perfectly with the theoretical prediction of the quasi-static solution of Hertz. Similar comparison between the measured and modeled curves for various drop heights revealed good agreement for the heights larger than 22.5 mm, while for smaller release elevations the measured contact times are larger than the theoretical results due to the influence of the automated magnetic release mechanism.

Using the sapphire ball, we have shown that the presented method is sensitive enough to determine the contact time of impacts of a 0.3-mm-diameter ball with an approach momentum as low as 40 nNs.

The only complementary method which enables measurements of contact times as small as $1 \mu\text{s}$ is based on piezoelectric (PZ) detection of propagating elastic waves launched during the impact. Even though the PZ method cannot probe the area directly under the contact, it is still the preferable method to estimate the force history of an impact and to measure contact times on optically opaque materials.

In contrast to the other contact time detection techniques, we estimate that an extension of the presented approach using photodetectors with nanosecond response times could also enable measurements of high velocity and extremely short contact times (~ 10 ns) that have not yet been experimentally accessible. The current setup can be additionally simplified by replacing the quadrant photodiode with a simple optical fiber where one end serves as the deflection sensitive entrance for the probing beam and the other one is connected to a GHz photodiode. This way, the information of the direction of beam deflection is lost, but the measured signal would still deviate from the zero value only during the time of impact thus enabling simple trigger-level determination of contact times. Since the sensitivity of the beam deflection technique is proportional to the square root of the laser power, it can be enhanced by employing laser sources with larger output power. However, the unprecedented sensitivity of the PZ transducers cannot be reached by optical techniques based on photodiode detection [30]. We anticipate that further quantitative analysis of the shape of the detected signals could open an interesting new way to probe the evolution of the contact mirror deformation which would in turn reveal the detailed dynamics of the contact area, including the propagation of elastic waves under the mechanical touch.

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