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**Study of detonation phenomena and related processes by optical methods**

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## ABSTRACT

This work focuses on the use of optical methods to study detonation and related phenomena. New visualization methods were introduced in the exterior and on a laboratory scale. Emphasis is placed on the determination of the blast wave parameters using a photogrammetric method and optimize it for small-scale experiments. This method can be used to monitor blast wave front over time. The work also presents new applications of optical methods, such as measuring the deflection of a steel plate by laser interferometry. To achieve the goals, 3D printing and graphics programs for image processing were newly used.

## Keywords

Detonation, blast wave, optical methods, high-speed imaging, PDV, Optimex.

## ABSTRAKT

Práce je věnována využití optických metod ke studiu detonace a jevů s ní spojených. Cílem práce bylo zavést a optimalizovat fotogrammetrickou metodu stanovení rychlosti vzdušné rázové vlny s následným přepočtem na přetlak. V souvislosti s tím byly zavedeny nové vizualizační metody v exteriéru i v laboratorním měřítku. V práci jsou dále představeny nové aplikace optických metod, jako měření průhybu ocelové desky laserovou interferometrií. K dosažení cílů byl nově využíván 3D tisk a grafických programů ke zpracování obrazu.

## Klíčová slova

Detonace, rázové vlny, optické metody, vysokorychlostní záznam, PDV, Optimex.

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## AIMS

The aim of the work is to expand the awareness of the study of detonation and related phenomena by modern optical methods. Study of explosives by these methods is directly conditioned by rapid development in other industries such as telecommunications or computing, therefore their use was not economically possible in the past. The emphasis is placed to study air blast waves produced by detonation of explosives, especially to determine their parameters. Moreover, the work focuses on the study of interaction of blast wave to its surrounding material. The main goal of the work can be summarized by the following points:

- Introduction an optical method for blast wave parameters calculation.
- Verification of optical method by an independent technique.
- Introduction of a modern method for quantification of material blast loading.

The main goal of the work is followed by several sub goals, which expand the main one or serves as an intermediate step to its fulfilment. Their achievement also represents significant progress in the use of the optical methods at the Institute of Energy Materials. Sub goal can be summarized by following points:

- Introduction of blast wave visualization methods in the laboratory scale.
- Design of image processing method for blast wave visualization.
- Finding new applications for optical methods established in the past.

## INTRODUCTION

The study of explosives covers a wide area across a number of disciplines. It may seem like pure chemistry, as the substances that make up explosives need to be synthesized first. Even the subsequent analysis of the prepared chemical substances could still give the impression that the study of explosives is exclusively a matter of chemistry. However, since explosives are used in the form of mixtures, with a few exceptions, it is appropriate to look at them more from the point of view of materials engineering. Sensitivity tests for mechanical, electrical, optical or thermal influences form a smooth transition from chemistry to physics, with which the functional properties of explosives are linked. On the side of pyrotechnics or propellants, combustion and associated ballistics are studied. On the side of detonating explosives, the physics of shock waves is studied. Hydrodynamics, thermodynamics and other subfields of shock wave physics together with chemistry connect the process of detonation with the process of formation and propagation of shock waves.

From the above, it is clear that the study of explosives is very broad and has a multidisciplinary dimension. This work is focused on the part including the effect of detonation of explosives, especially with regard to the study of the propagation of blast waves. The parameters of the blast wave are used to evaluate the effects of the explosion on the environment, so it is necessary to determine them correctly. For this purpose, pressure sensors were used, especially for calibration and comparison measurements, but mainly a newly method based on image processing, so-called photogrammetry was introduced. Optical measurement has a number of advantages over pressure sensors. For example, there is no restriction for experiments where there is a risk of the sensors being hit by a flying fragment or affected by a flame from detonation. Without the need to use a large number of sensors, cables and related measurement techniques, this method provides a large number of experimental points using only high-speed recording.

The characterization of blast wave is followed by the study of its interaction with surrounding. Thus, new method for determining the deformation of materials due to the blast loading were designed and tested. The formation of blast wave is linked to the parameters of the charge, and therefore attention was also paid to this issue as well as the issue of accelerating the material in contact with the charge.

Optical methods have evolved in recent years due to industries such as computers or telecommunications. Therefore, some methods described in this work were not possible a few years ago. Modern optical techniques such as high-speed imaging or methods based on fiber optics such as PDV laser interferometry and the Optimex passive system are used to perform the experiments. The mentioned techniques are not new at IEnM, but their use is extended by new applications. For the preparation of experiments, the

use of 3D printing is newly introduced, which was used to prototype assemblies to individual experiments.

Chronologically, the measurements of blast parameters and detonation parameters overlapped. However, because the work deals with a wide range of processes, it is arranged so that the processes associated with detonation and measurement of detonation wave parameters are first described. Subsequently, the description proceeds from the charge to the surroundings. The events connected with the effect of detonation on the material in contact with the explosive are discussed. The following is a description of the phenomenon in the near surroundings in the form of the resulting flame from the detonation and finally the blast wave as an effect to distant surroundings is described. The theoretical part is summarized in the form of a review. The description of individual experiments to fulfil the objectives of the work is presented in the experimental part together with methods of experimental data processing. The results of the experiments are summarized in the results and discussion section.

## RESULTS AND DISCUSSION

### 1. Study of detonation wave

In the first chapter of the work, focus is first placed to determining the detonation velocity of explosives. This is followed by a section on the influence of initiation and propagation of detonation, including the possibility of influencing it using a plane wave generator. To achieve these results, optical methods such as high-speed imaging and the passive optical system were used.

#### 1.1 Velocity of detonation

The measurement of the detonation velocity served to characterize the explosives used or also as a starting value for consecutive experiments. A summary of the performed measurements is presented in this chapter.

The detonation rate of nitromethane (NM) was measured optically using the six channels of the Optimex-64 instrument. The explosive was diluted with methanol in connection with the subsequent development of plane wave generators. The dependence of the detonation velocity on the addition of methanol was studied. The experiments were performed in a pipe with an inner diameter of 47 mm and a length of about 28 cm. 120 mm was left to stabilize the detonation.

The results were simultaneously compared with the values published in the literature and the computer software *Explo5* [1]. While Koldunov [2], [3] performed experimental measurements of parameters with a diameter of 50 mm, Dattelbaum [4] used the computer software *Cheetah 6.0* and then recalculated the values into an infinite charge. The results after the correction are lower (thus closer to the results measured in the submitted work), therefore the table shows the values after recalculation.

*Table 1- Summary of detonation velocities*

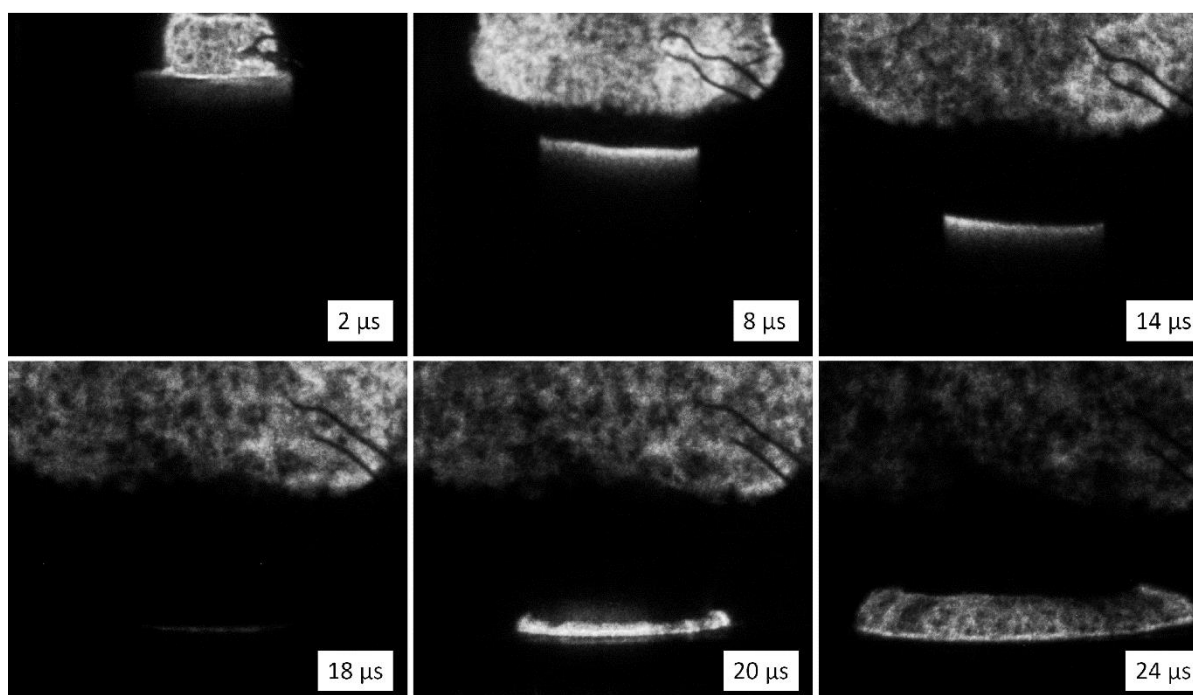
Ratio NM/MeOH	Density [g/cm <sup>3</sup> ]	VOD <sub>experiment</sub> [m/s]	VOD <sub>Koldunov</sub> [m/s]	VOD <sub>Dattelbaum</sub> [m/s]	VOD <sub>Explo5</sub> [m/s]
100/0	1.13	6230	6270	6260	6323
90/10	1.088	5900	5910	5990	6047
80/20	1.044	5521	5580	5740	5786
70/30	1.005	5179	5250	5490	5542

The table shows a very good agreement with the results reported by Koldunov [2], [3]. On the contrary, the results calculated by Dattelbaum do not agree very much with the measured values. The calculation using the *Explo5* program for undiluted explosive overestimated the detonation rate. With the degree of dilution, the detonation rate

decreased faster than the experiment showed. The dilution limit at which the explosive will no longer detonate has not been evaluated.

### 1.2 Booster size influence

As part of a series of experiments in the study of detonation, experiments to determine the minimum booster size were performed. In addition to high-speed imaging, pressure sensors were also used to validate the findings, the results of which are presented in full version of the work. The images taken for the booster sublimit size are shown in Figure 1, where a charge of 154 grams of cast TNT was initiated by 5 grams of Semtex 1A. In the first image at time  $2 \mu\text{s}$ , only the detonation products can be observed.



**Figure 1:** Cast cylindrical charge 154 g of TNT initiated by 5 grams of Semtex 1A. Sequence taken at 500k FPS and an exposure time of 200 ns.

From the second image, a fading bright circle can be observed propagating downwards. It is evident from the above images that 5 grams of plastic explosive was not enough to initiate TNT. However, the shock wave caused by its detonation propagates through the TNT charge until it reaches the solid ground. Here, at  $20 \mu\text{s}$ , the shock wave is reflected, which increases the pressure by reflection due to different impedances of the charge and ground. The reflected shock wave already has a sufficiently high pressure, so the TNT charge is initiated from below, as confirmed by the image taken at  $24 \mu\text{s}$  after the trigger. The described findings were also published in the conference paper [5].

## 2. Study of detonation effects

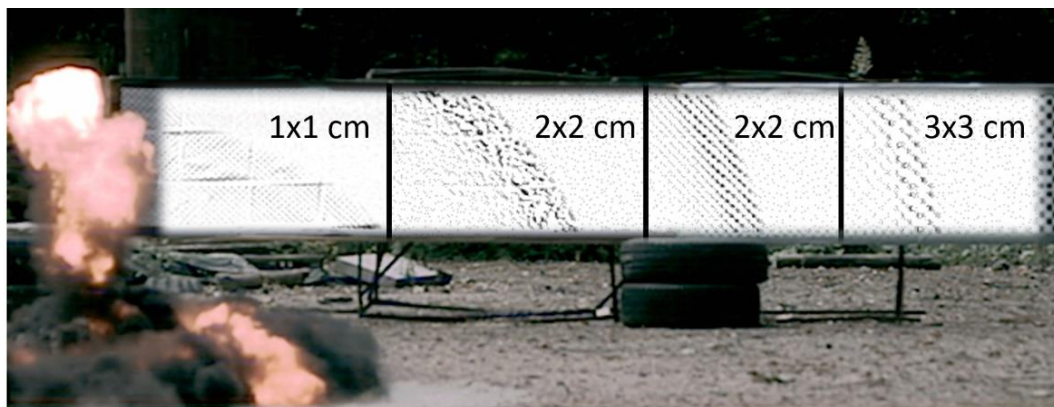
The results of experiments aimed to study the detonation are summarized in this chapter. The main point is an optical measurement of a fireball size caused by the explosion. Also, the results of determining the parameters of the blast shock waves, are presented.

### 2.1 Blast wave visualization

Visualization of the blast wave is the first step in determining its velocity. This chapter therefore describes the selection of the background for successful visualization. Attention is also paid to visualization in the laboratory, where experiments can be performed with small samples of explosives.

#### 2.1.1 Visualisation in exterior

To visualize the blast wave, it was first necessary to optimize the background pattern, which was placed behind the charge from the camera's point of view. In the literature [6], [7] a striped background can be found, so it was chosen for the first experiments. During the optimization, the stripes with inclination of the  $45^\circ$  was tested. It was shown that tilting to the left, where the BW proceeds perpendicular to the stripes, is inappropriate. During the subtraction, the position was distorted and sometimes the BW position was completely lost. Thus, some other patterns were tested, as shown in Figure 2.



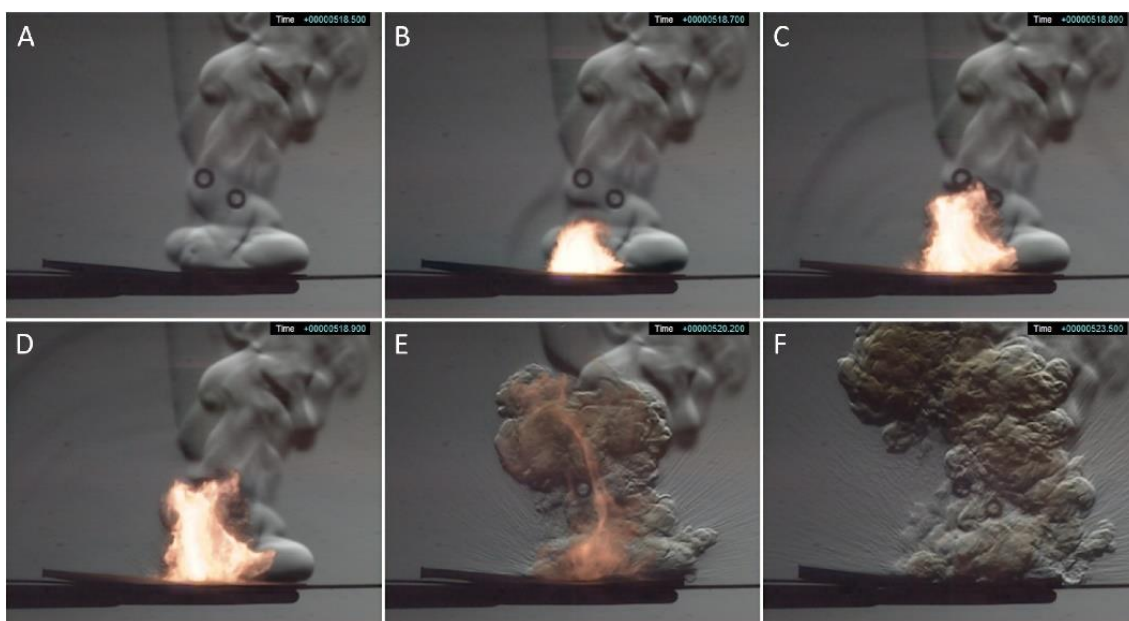
**Figure 2:** Comparison of four different backgrounds. A charge of 98 grams of Semtex 1A.

The figure shows how important is the size of the background pattern. Here, the first quarter of the board was covered with a chessboard with squares of the size 1x1 cm. This was followed by randomly generated 2x2 cm squares, the third part was covered with a 2x2 cm chessboard pattern and last section was again a chessboard, but with a square size of 3x3 cm. From the picture it is clear that the size 1x1 cm is not suitable, because the position of BW is almost invisible. Both the 2x2 cm squares and the 3x3 cm checkerboard patterns provided a clearly visible BW front. The checkerboard pattern was chosen as the standard.

### 2.1.2 Lab-scale visualization

Blast waves can also be observed on a very small scale. Within the IRS2020 project, a visualization technique for laboratory scale was designed, assembled and tested. The Schlieren method was tested in two variants. Specifically, it was an arrangement with one mirror and a z-arrangement with two mirrors.

Experiments with ignition of explosives were performed. TATP and silver acetylide were tested. The sequence of acetylide deflagration is shown in Figure 3. Image A shows a column of hot air rising from a burning stick. Images B, C and D show the deflagration together with the blast wave. Images E and F show burning products and also fine dust particles flying to surroundings can be seen.



**Figure 3:** Sequence of the initiation of silver acetylide at 10,000 FPS.

The Schlieren method was successfully introduced and tested in order to visualize the blast wave. However, the results showed insufficient frame rate of the GX3 camera to evaluate BW parameters. At higher speeds, it would be possible to capture BW on multiple images and use a calibration in the record to determine the BW velocity photogrammetrically.

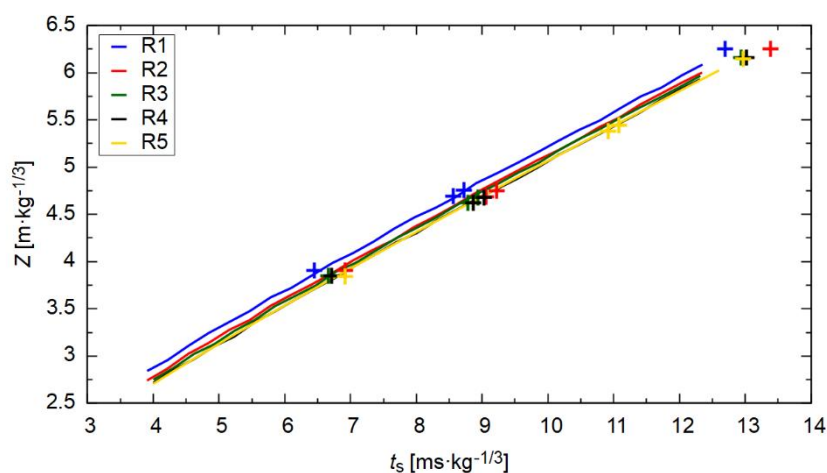
### 2.2 Measurement of blast wave parameters

As part of the determination of the parameters of blast waves, the velocity of propagation of BW was measured both by pressure sensors and by the photogrammetry. The velocity can be then used for overpressure calculations. The results of these experiments are summarized in this chapter.

### 2.2.1 Optical measurement

Two methods described in more detail in the full version were used to evaluate the incident overpressure by the photogrammetry [8]–[10]. The names of the authors are used to name the methods for easier orientation. The results of both methods were compared with each other, with pressure sensors and also with literature data. In the initial step, it was studied whether the arrival times of the blast wave determined from the camera recording coincide with the arrival times measured by pressure sensors. It served as an independent control method for the validation of photogrammetry.

The aim was to test whether the described method can achieve accurate results on a small scale. For precise delineation of distances and angles, the shooting range was geodetically focused. Spherical cast TNT charges with central initiation were used. The charges were hanged in free air to exclude the ground influence and reflection before the primary BW measurement was finished. The summary of the BW front positions in time is shown in Figure 4.

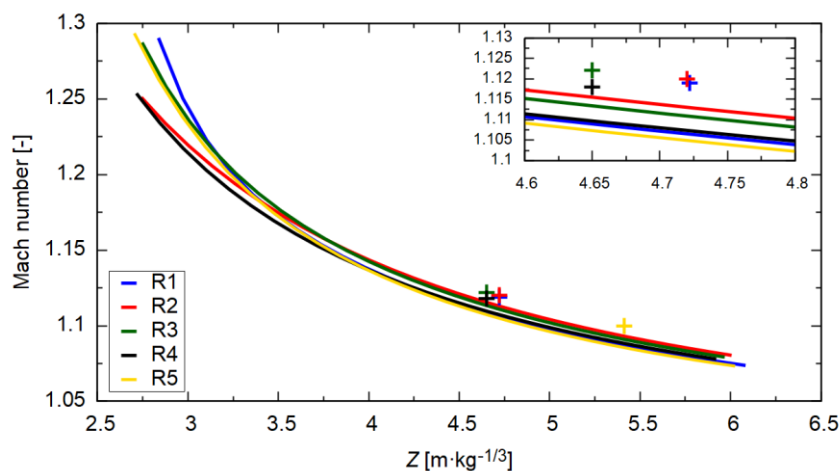


**Figure 4:** Optically determined times of arrival compared to pressure gauges.

The graph shows the scatter in the horizontal direction. This scatter can be explained by the inaccuracy of a high-speed camera which triggered with an error of about one frame. The relatively low resolution of the recording also had a negative effect. Because the slope represents the blast front velocity, this scatter should not have any negative effect to the results. In addition, the times of arrival data from pressure gauges are in the agreement with the times recorded by the camera.

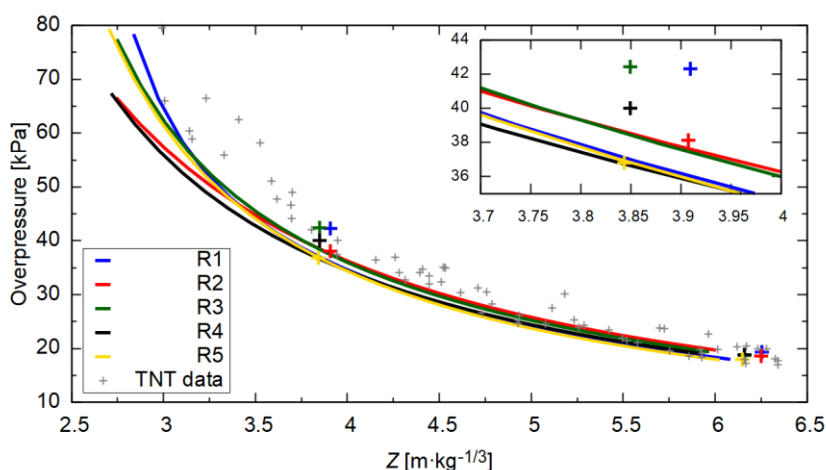
The individual curves were converted by the Sadek's method to Mach number, as shown in Figure 5. When compared to the velocities measured by the custom BW speed sensor, agreement was obtained with the minimum deviation of the Mach number, as shown in the full version of the work. The scatter in obtained experimental results can be observed

only in the area of the lowest scaled distances, where the position of the BW was taken from the edge of the fireball.



**Figure 5:** Mach number determined by the Sadek's method for TNT free air experiment.

The determined velocities were recalculated to incident overpressure. The obtained results are summarized in the Figure 6. The graph shows a good agreement of the optical method with the pressure sensors. The maximum overpressure deviation was 6 kPa, which can be considered as normal experimental scattering. Overpressures are also compared to the TNT dataset. Because the blast front velocities and overpressures are highly reproducible and agree with the independent measurement by pressure sensors, the optimization of the method on a small scale can be considered successful.



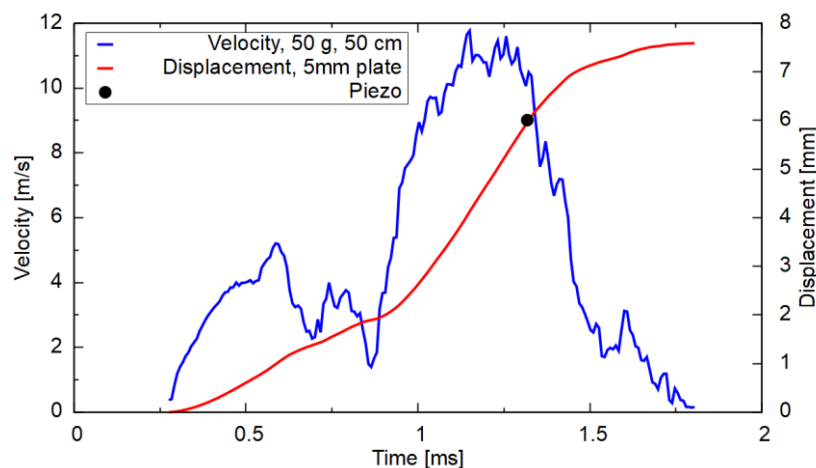
**Figure 6:** Impact overpressure determined by the Sadek's method for TNT free air experiment.

### 2.3 Blast loading of steel plate

By detonating an explosive charge hanged in the air, the blast wave was generated, which loaded a steel plate placed in a massive metal structure. This caused the plate to deflect, which was recorded by PDV laser interferometry. The measuring probe was

located under the steel plate exactly in its center. To initially verify the reliability of the results, the experiments were supplemented by a piezoelectric sensor at a precisely known distance under the steel plate. At the moment of the corresponding displacement, the sensor was hit, and signal was recorded. A result of such a record is shown in Figure 7, where the blue curve corresponds to the PDV velocity profile in the center of the plate. The integral curve is then shown in red, which shows the dependence of the current displacement in time. The moment of contact with the piezoelectric sensor is shown by a black point. Comparing the time at which the contact occurred and the integral curve, it is clear that both measurement techniques are in very good agreement. Furthermore, the graph can demonstrate the significant advantage of laser interferometry over piezoelectric sensors. The PDV method provides the entire velocity profile, while older techniques only give the number of points corresponding to the number of sensors used.

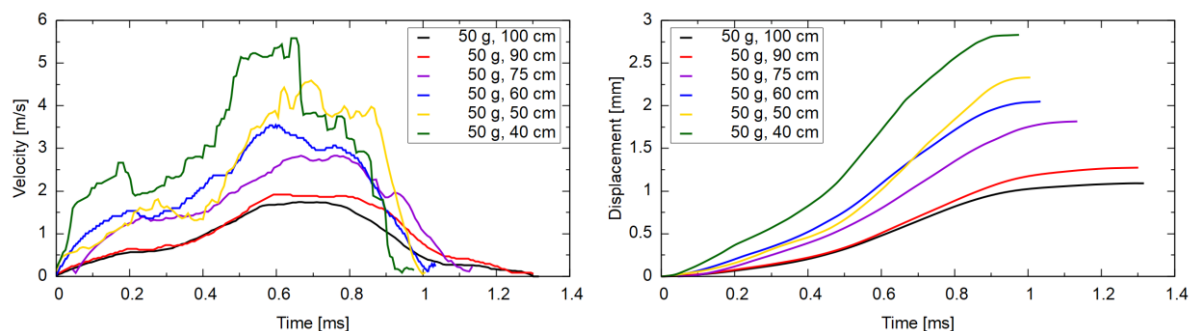
The following graphs show a clearly repeatable trend of all measured signals. After the initial acceleration, there is a deceleration, but not a complete stop. Acceleration follows again until the maximum speed is reached. Then it decelerates to zero speed, which means the moment when the steel plate is bent to its maximum deflection. The signals were evaluated only up to this point. This was followed by a phase where there was an acceleration again. This time in the opposite direction, which meant moving the plate back away from the probe to its original position.



**Figure 7:** Comparison of the result of a piezoelectric sensor with laser interferometry.

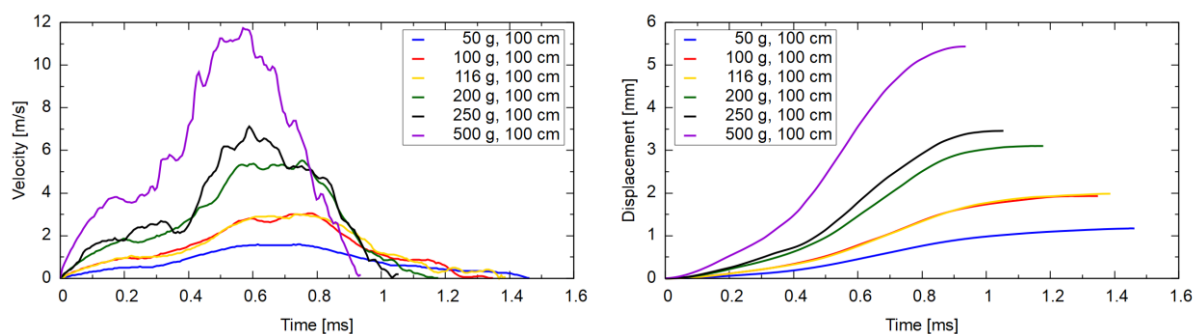
A series of experiments were performed on the initial verification of the methodology, during which the influence of the charge size, the influence of the distance, and as well the influence of the thickness of the steel plate was studied. Due to the high maximum deflections of the plate, it was decided to perform most of the experiments only with a thicker 10 mm plate. The results are shown in Figure 8 on the right. For a charge distance of 50 cm the plate reached a velocity of 4.6 m/s and at a distance of 100 cm only

1.75 m/s. The graph to the right shows the dependence of the maximum displacement on the distance of the charge.



**Figure 8:** Influence of 50g charge distance on steel plate deflection. 5 mm thick board on the left, 10 mm on the right.

The effect of the charge mass on the displacement was also studied. All charges were detonated at a distance of 100 cm above the plate. A comparison of the measured records is given in the Figure 9. The expected effect can be observed on the graphs, when the largest (500 g) charge was able to accelerate the steel plate up to 12 m/s, which led to a maximum deflection of 5.43 mm.



**Figure 9:** Influence of charge weight on speed and deflection of 10mm steel plate.

The experiments were designed so that the steel plate did not have to be changed, so no larger charges or shorter distances were used. The static deflections of the plate were zero and the plate could be used repeatedly. Based on the performed experiments, the PDV method can be considered suitable for measuring slow processes with velocities of only few meters per second. Thus, the method is generally applicable for measuring the dynamic loading of materials.

## CONCLUSION

The presented work brings a literature review including detonation and related phenomena, such as the acceleration of matter by explosion, the formation of a fireball or the propagation of a blast wave to the surroundings. Optical methods including high-speed imaging, laser interferometry (PDV) or the passive optical system Optimex were used for the experimental study of the mentioned processes, which were described in the experimental part.

The main goal of the work was to introduce a method enabling optical measurement of blast wave parameters. To achieve the goal, a method called photogrammetry was successfully introduced. The method makes possible to determine the blast wave velocity followed by the calculation of the incident overpressure. Because pressure sensors were used at the Institute of Energetic Materials to measure blast wave parameters, another aim of the work was to verify the results of optical method by this independent technique. Based on the comparison of the results of the optical determination with the values available in the literature as well as the data from the pressure sensors, the photogrammetric determination of the blast parameters can be considered successful. In addition, the blast velocity sensor was built for additional verification. This also verified the concept of measuring the overpressure directly from the blast front velocity what can be used to build a commercially available sensor.

Due to the complexity of the method, it was necessary to overcome a number of complications during optimization, which gained a lot of valuable knowledge from the need to choose the right background, its pattern, setting up a high-speed camera to the necessary video processing, which was a partial goal. Therefore, a new image processing method is described.

Another goal of the work was to introduce a method to quantify the material deflection under blast loading. Thus, photonic Doppler velocimetry (PDV) was used. The velocity of deflection of a steel plate was measured for the first time at IEnM. The presented measurements are promising for the characterization of materials. This application achieves the course of velocity of deflection in time, which was not possible with older methods in the form of contact or shorting sensors. The mentioned methodology was newly introduced and has not been published yet. Laser interferometry was also used to measure the velocity of metal disks accelerated by detonation.

Photogrammetry was also optimized to measure the size of the fireball created by detonation. This is the first time that this parameter can be measured at IEnM. The effect of the bear-field loading is different from the blast loading, thus this parameter should not be neglected.

The visualization of the blast wave introduced mainly for outdoor experiments was also described on a laboratory scale. The proposed and tested Schlieren method in a two-mirror arrangement was newly introduced. Although the method made it possible to successfully visualize the blast wave, due to the insufficient frame rate of the camera used, the method was not optimized to determine the parameters of weak blast waves in the laboratory. Because the development of technologies can be expected, the method opens up space for further optimization or use in teaching.

The partial goals of the work were to put into practice new applications of existing optical methods available at IEnM. The detonation velocity of explosives was measured in experiments aimed at studying detonation. Powder explosives, emulsion explosives, and the dependence of the detonation velocity of nitromethane on dilution with methanol were successfully characterized using the passive optical system Optimex. This was used for the subsequent development of a cheap plane wave generator. The Optimex optical system thus also served to measure the curvature of the detonation wave.

During the work, 3D modeling and 3D printing were newly used to create prototypes of specialized assemblies to specific experiments or Octave, Gnuplot and Vegas Pro software for more efficient processing of experimental data and video recordings. The written scripts are listed in the appendix to facilitate future work in data processing in similar experiments.

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