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HIGH-SPEED THEE-DIMENSIONAL TOMOGRAPHIC IMAGING OF FRAGMENTS AND PRECISE STATISTICS FROM AN AUTOMATED ANALYSIS

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For the investigation of fragments and debris, witness plates or sandbags are usually used to name a few. The distribution of masses is determined from longsome counting. Velocities of the fastest fragments only are calculated from time measurements with trigger devices. Fragment energies are estimated.

Our novel investigation method provides three-dimensional images of high-speed events as mentioned above. In this paper this method that is referred to as High-Speed Tomography is applied for the investigation of fragment characteristics after a detonation. Extensive statistics are derived automatically from the computed 3D reconstruction of fragments' shape, density and position with special analysis software. Masses and velocities are calculated for all fragments.

For our novel method we simultaneously image few, in this case three, flash x-ray projections. From that we iteratively reconstruct the 3D image. The spatial distribution of fragment masses and velocities is provided. The kinetic energy for every fragment is calculated. Therefore this new developed method overcomes inevitable inaccuracies with respect to the estimation of energies as hitherto since this is available for every particle.

Experiments that were performed concern a cylindrical explosive that is located in a cylindrical metal jacket. The explosive is brought to detonation and the jacket fails. Fragments are formed. These fragments travel at very high velocities in the km/sec-range. Measurement and reconstruction was performed in a volume of 0.5 m in diameter. Smallest fragments that were detected are below 2 mm.

INTRODUCTION

For the investigation of fragments and debris caused by a detonation, an impact event or something else the knowledge of the momentum and kinetic energy of every individual fragment would be desirable. Therefore the shape and mass of objects and the direction and magnitude of movement of objects in three dimensions are interesting aspects in high-speed physics. One technology to deduce the above information would be radiographic imaging. Nevertheless established radiographic methods as described below do not always provide sufficient information.

State of the Art

Radiographic imaging of high-speed dynamic processes is usually performed with flash X-ray technology [1]. As a consequence motion blur is insignificant due to the very short flash X-ray exposure of about 20 ns.

Common detectors are radiographic film in combination with fluorescent screens or storage phosphor image plates. One projection of a passing process at one specific point in time is possible.

For three-dimensional radiographic imaging, computed tomography is an established method. 500 projections are typically used for medical and non-destructive testing applications. Here, the projections are obtained one after the other. In high-speed physics, projected images around the process have to be taken simultaneously. Therefore and due to geometric reasons only few projections are possible [2]. Thus computed tomography as regards measurement setups as well as reconstruction algorithms cannot directly be applied.

Limitations

Computed tomography cannot directly be used in any case as described above. The other above radiographic methods lead towards two-dimensional radiographs. This is not always satisfyingly enlightening. Spatial information in the direction of the radiation cannot easily be deduced. Information on the position in space and the geometric shape of objects and therefore their mass are not outright present. This limits deductions that refer to the dynamics of the process.

Approach

To overcome these limitations we have developed a novel imaging method. We refer to this as “High-Speed Computed Tomography” (XCT). The output after measurement, reconstruction and visualization are three-dimensional pictures. Therefore reasonable information on kinematics and dynamics of high-speed processes are available.

This development has been realized in three steps. These are first the measurement setup and second a novel reconstruction algorithm. Third extensive statistics are derived automatically from the computed 3D reconstruction of fragments' shape, density and position with special analysis software.

MEASUREMENT SETUP

Multichannel Setup

The measurement for the three-dimensional reconstruction is performed in our tomography setup. All projected images around the process have to be taken simultaneously. Therefore every projection requires its own source-detector pair. Furthermore, due to geometric reasons, only few projections are possible. In the case of fragment characterisation three source-detector channels, i.e. projections have been used.

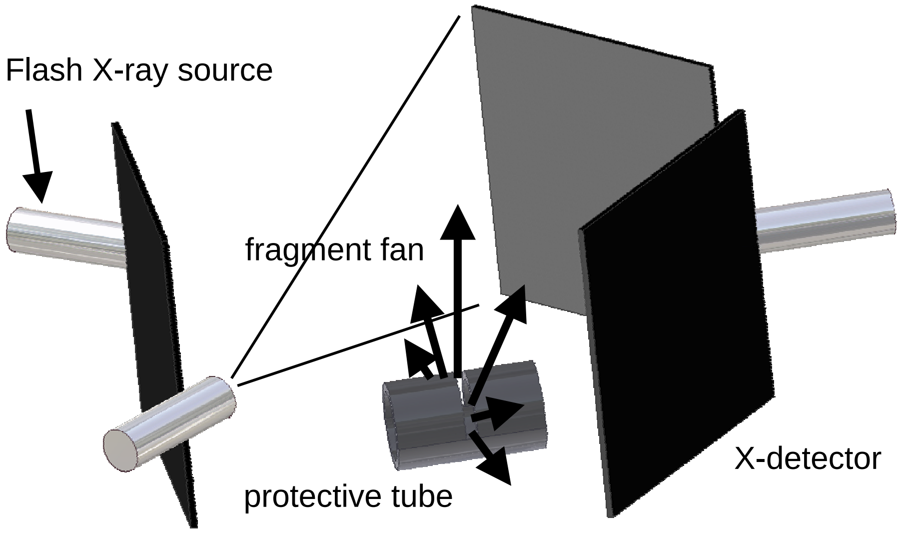

Figure 1. Flash X-Ray Computed Tomography measurement setup. Few, e. g. three in the figure above, radiographic projections of a high-speed event are taken at one point in time.

Challenges due to Several Channels

In such a setup it is essential to ensure that x-radiation from one flash x-ray tube only reaches the associated opposite detector-system. A collimation of x-radiation must be ensured. This is done by shielding the x-ray sources with lead.

Furthermore the flash x-ray images at acceleration voltages of up to 450 kV are considerably influenced by Compton scattering as attenuation mechanism. That is, real absorption as it is the case with photo effect does not occur. Image quality regarding the signal-to-noise ratio has to be considered.

The most challenging aspect relates to the geometry of the measurement setup. For a reasonable reconstruction the exact positions of sources and detectors have to be known. The quality of the result of a reconstruction with respect to the spatial resolution will only be as good as the measurement of the 3D coordinates of these positions. The figure below illustrates this. In common CT measurement setup this problem does not occur since only one pair of a source and detector or the specimen within this pair is rotating. Therefore there is only one degree of freedom unknown that is easily determined.

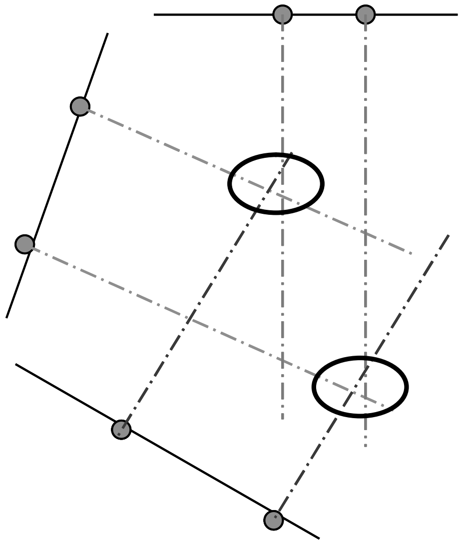

Figure 2. Precise knowledge of the positions of sources and detectors of the measurement setup is essential. Otherwise projected points will not intersect when reconstruction is performed as is shown in the figure above.

Since the measurement of the positions is a not too simple task with commercially available measurement devices, we have chosen an own procedure. We have developed an iterative algorithm that provides the exact positions of sources and detectors in a CT measurement setup with several but few projections. The input is an approximation of the coordinates of these positions from a rough measurement and measured projections of an item with known dimensions.

Not before the exact positions are calculated with the above algorithm that is implemented in an own software, a three-dimensional tomographic reconstruction can take place.

DIRECT THREE-DIMENSIONAL RECONSTRUCTION

Algorithm Input

For the direct three-dimensional reconstruction out of few measured projections a novel algorithm has been developed. Commonly used algorithms with a number of at least 500 projections could obviously not be applied.

Our algorithm needs the following input data. Information on the geometry of sources and detectors in three dimensions has to be provided as above. The second information is the correlation of grey level of a pixel in the images and the attenuation coefficient and the thickness of matter respectively of a ray path. This is done by calibrating each detector plane to a given standard material. Densities that are calculated refer to this material.

Adopted ART Algorithm

Our novel algorithm is based on ART methods [3] and implemented in a software package. The information on geometry and grey levels is directly used: With cone beam geometry, standardized densities for a three dimensional mesh are calculated directly. The result is reached in iterative loops of forward and back-projections with a simultaneous evaluation for all voxels comprising this volume for each step until a stop criterion is met.

The result of the reconstruction process is a density distribution of the voxel volume. Different materials in the reconstruction volume can be distinguished by their standardized reconstructed densities that refer to the density of the reference material. If knowledge of extinction of all materials in the measurement volume is provided the correlation of standardized densities and physical densities is possible.

FRAGMENT STATISTICS

The reconstructed density distribution of the voxel mesh is evaluated by software that identifies fragments, determines their volumes and masses and the locations of their centres of gravity. The algorithm is able to distinguish between separate fragments and connected parts. Combined with the knowledge of the detonation origin, charge form and detonation time the (average) velocity, momentum and kinetic energy for every individual fragment is calculated. The results are output in a spread sheet or graphically.

RESULTS

Measurement and Reconstruction of the Fragment-Distribution after a Detonation

The measurements have been performed in a three channel tomography setup as shown in Figure 1. The Experiment presented in this paper concerns a 40 g cylindrical explosive that is located in a cylindrical metal jacket. The explosive is brought to detonation and the jacket fails. Fragments are formed. To prevent the destruction of the experimental setup by fragments the charge is placed in a protective steel tube. Only a 15° wide fan shaped fragment cloud is let out by a slit. These fragments travel at very high velocities in the km/sec-range. 250 µs after detonation simultaneous all three radiographs have been recorded. Measurement and reconstruction were performed in a volume of 0.5 m in diameter

The radiographs and the information on the projection geometry are input for the 3D reconstruction as described above. The resolution of the reconstructed volume is 0.7 mm per voxel. For visualization the computed 3D data is edited in such a way that a commercial 3D viewer can be used. Different views of the reconstructed fragments are shown in figure 3. The location and the geometry of the charge and the protective tube are sketched on the lower half of the images. The reconstructed tetrahedron visible in the upper half of the images is the reference item to determine the exact geometry of the setup. The reconstructed fragments are clearly visible between protective tube and tetrahedron. The smallest visible fragments are below 2 mm in diameter.

Performance of the System

The spatial resolution of our multi-material tomography method is better than 2 mm. The theoretical limit due to the focal spot of the anodes that are used is 1 mm. The reason for this is that projections have a spatial blur of the size of the focal spot since objects are near the middle of the distance from source to detector. A further blur that could influence the reconstruction is due to jitter between the channels. That is the object position is not the same for all projections. This jitter is below 1 µs that is 0.1 µs for most cases and a corresponding difference in position depending on the velocity of the experiment.

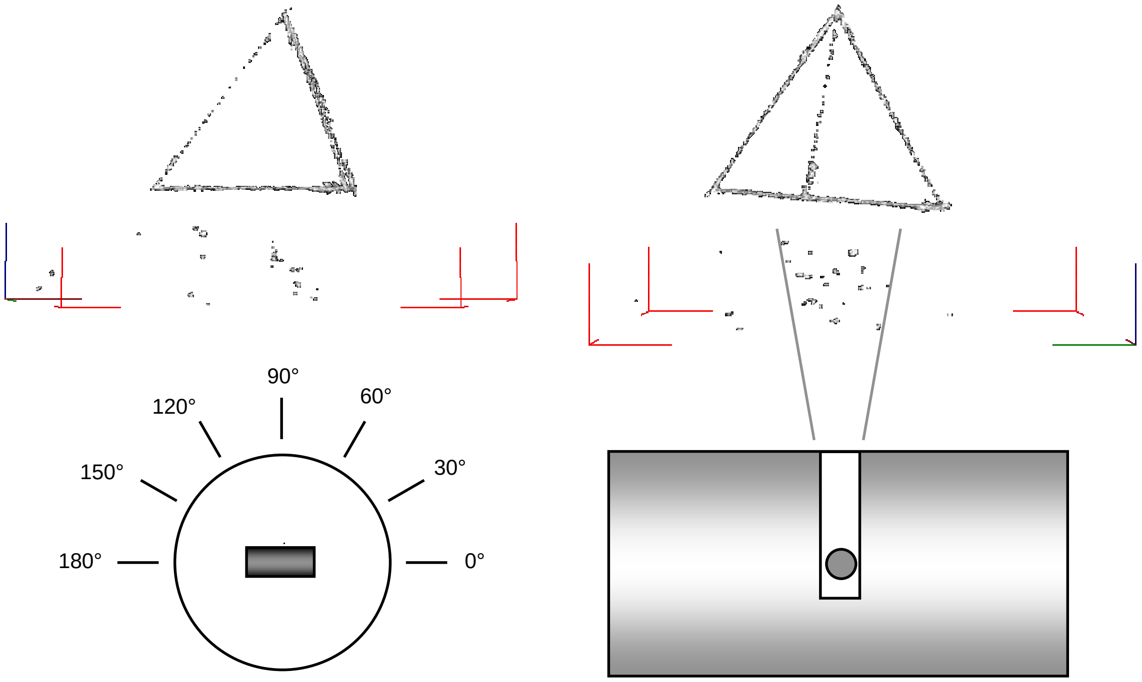

Figure 3. 3D Reconstruction of the fan shaped fragment cloud. The smallest detected fragments are below 2 mm. Below the 3D Reconstruction the position of the charge inside the protective tube is depicted.

Automated derivation of fragment statistics

The reconstructed density distribution is basis for the automated fragment evaluation described above. By means of calculated fragment masses and velocity vectors the polar diagrams depicted in figure 4 are calculated. The left part of the figure shows the fragment mass as a function of the ejection angle that is given in figure 3 (The longitudinal axis of the cylindrical charge is oriented parallel to the 0°-180°-line). In the right part of figure 4 the fragment velocity versus the ejection angle is shown. For the reason of clarity only the data of the biggest fragments are shown. One can clearly see a correlation between the fragment mass and its average ejection velocity (averaged over the first 250 μs).

SUMMARY

A novel three-dimensional flash x-ray measurement technology and ART based cone-beam reconstruction algorithm has been developed. The jitter of the data acquisition is less than 1 μs which results in a corresponding spatial blur within the physical spatial resolution. The results show that this new method is performing well regarding applicability and deducible results in the field of fragment analysis. These are in the first instance direct three-dimensional spatial data with a physical spatial resolution in the mm-range that can be evaluated automatically.

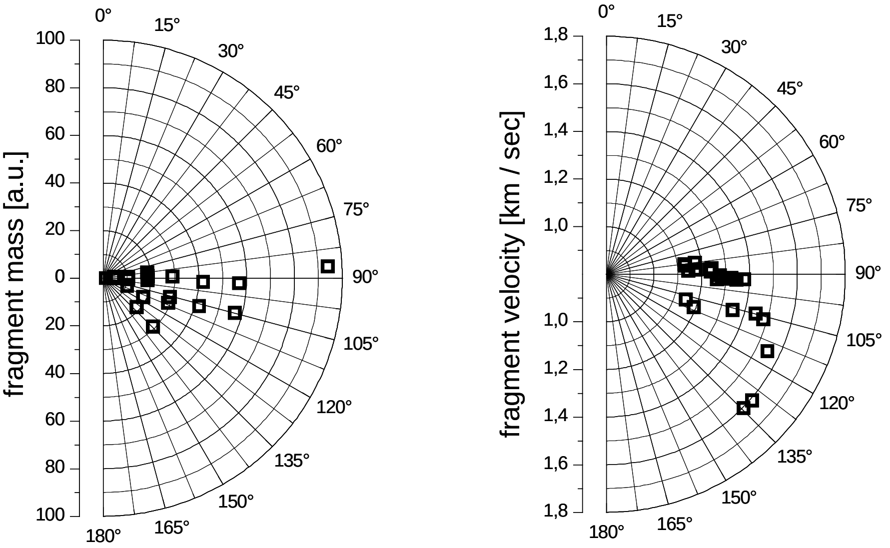

Figure 4. Polar diagrams of the fragment mass versus ejection angle (left side) and the fragment velocity versus ejection angle (right side). The diagrams are calculated on the basis of the 3D reconstruction of the XCT experiment described above.

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