

# Gray correlation of speckled high resolution images: an approach to precise deformation measurements with MATLAB

Käferstein, B.

Die Grauwertkorrelation arbeitet mit dem Vergleich von Aufnahmen unterschiedlicher Verformungszustände. Sie bedient sich hochauflösender Kameras und der rechnergestützten Bildverarbeitung. Um die Verformungsvektoren eines Bauteils berechnen zu können, wird eine kleine, aber eindeutig definierte Bildregion vor der Verformung ausgewählt und in der Aufnahme des verformten Prüflings wieder ausfindig gemacht. Der Vergleich wird auf Basis eines Korrelationsverfahrens durchgeführt. Mit zusätzlichen Interpolationstechniken und hochauflösenden Kameras kann eine Auflösung bis zu 1/10000 des Bildausschnittes erreicht werden. Anwendungen sind die Messung plastischer Verformungen oder das Verfolgen von Objekten in Bildsequenzen.

The gray correlation technique works on the comparison of pictures of different deformation shapes. It uses high resolution cameras and computer aided image processing. In order to calculate the displacement field of a specimen, a small but unique region of the object is selected before applying distortion. This area is searched again in the picture of the deformed component. The comparison is based on correlation algorithms. With additional interpolation techniques and high-definition cameras, a resolution up to 1/10000<sup>th</sup> of the section can be reached. Applications are the measurement of plastic deformation or the tracking of objects in picture sequences.

## 1 Introduction

### 1.1 The qualified development tool

It was necessary for the rapid development of the correlation algorithms to use a special computing environment. MATLAB from The Math Works Inc. is installed on the IMW computer systems and has an easy to learn programming interface. It has its own high-performance language similar to C or Pascal for technical computing with predefined algorithms for numerical and large scale matrix operations. The name MATLAB is an acronym for 'matrix laboratory' and features a family of application-specific solutions called toolboxes [1]. Famous

areas in which MATLAB toolboxes apply are signal processing, control system design, neural networks, fuzzy logic and simulation.

### 1.2 The basics of correlation techniques

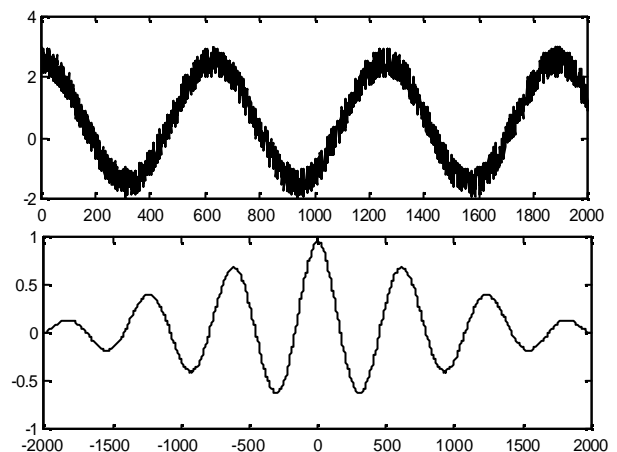
The correlation describes the similarity of objects. The auto correlation is a measure for the self similarity and the cross correlation is a maximum if two objects are nearly identical. For two non-periodic stationary random signals one can define the cross correlation as the scalar product of the reference signal  $x$  and the shifted signal  $y$ , [2]:

$$c_{xy}(m) = \sum_{n=0}^{N-|m|-1} x_n \cdot y_{n+m} \quad \text{Eq. 1}$$

Apparently the cross correlation is maximum if  $x$  and  $y$  have the same sign (phase) and change in the same periodic manner (frequency). Substituting  $x$  for  $y$  leads to the auto correlation:

$$c_{xx}(m) = \sum_{n=0}^{N-|m|-1} x_n \cdot x_{n+m} \quad \text{Eq. 2}$$

Cross correlation and auto correlation depend on the shift  $m$  and are also vectors like  $x$  and  $y$ .



**Figure 1** Vibration signal disturbed by random noise (top) and auto correlation (bottom)

**Figure 1** shows a harmonic vibration disturbed by white noise. The adjacent graph shows the auto correlation signal, which has the same frequency. It is unity if the shift  $m$  is zero. The noise in the signal does not appear regular and with stable phase and

is thus eliminated. Correlation can be used to separate deterministic signals from random signals.

Additionally there is another singleton parameter which is used to measure deviation. The correlation coefficient  $r$  is known from curve fitting and least squares approximations and is applicable for signals and matrices of any dimension.  $R$  is similar to the standard deviation, /3/:

$$r = \frac{\sum_m \sum_n (X_{mn} - \bar{X}) \cdot (Y_{mn} - \bar{Y})}{\sqrt{\sum_m \sum_n (X_{mn} - \bar{X})^2 \cdot \sum_m \sum_n (Y_{mn} - \bar{Y})^2}} \quad \text{Eq. 3}$$

It can be seen that **Eq. 3** refers to the interdependencies of two matrices depending on the individual scattering of each matrix. If both matrices have already high standard deviations the correlation coefficient will be small. The correlation coefficient fits best the requirements and will therefore be used in the core algorithm of the programme.

## 2 The algorithm

### 2.1 Description

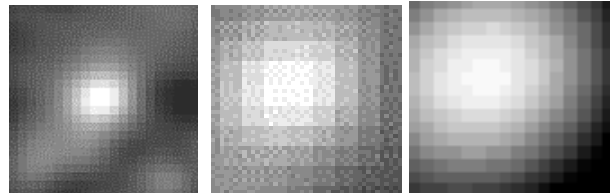
The algorithm itself is quite easy. A predefined section around a specified point of the picture before deformation is selected. A second section of the same size at the same position in the deformed picture is taken and the correlation coefficient is calculated and stored in a matrix  $R$ . The second section will be moved circularly around the specified point till a preselected search area is completely scanned. The position of the maximum correlation coefficient in the correlation matrix leads to the deformation vector in pixels. Using not only one point but a complete grid of points makes it possible to calculate displacement fields and strain distributions. The scale of the object is determined by a metre which was photographed together with the specimen. Now the measurements can be calibrated in metric units.

### 2.2 How to get sub pixel resolution

In order to overcome the fixed resolution of the camera a special interpolation method is used. However the camera has a horizontal resolution of more than 2000 pixels it is sometimes necessary to increase the accuracy by a factor up to ten.

**Figure 2** shows an approach with bicubic spline interpolation. The correlation coefficient is a local peak function around the best fitting position where both sections are coincident. This maximum with its

small surrounding area is cut out and interpolated to increase calculation speed and resolution. The interpolation with a bicubic surface of a finer mesh leads to a new position for the correlation maximum between the original pixels. As the bicubic surface has a limited number of parameters it's necessary to increase the number of input pixels if someone wants to increase the resolution. In practise the upper limit is a fifth of the camera resolution.



**Figure 2** Correlation coefficient matrix. Original state with local maximum (left); zooming in shows the resolution limited by the camera (middle); interpolation by a factor of 2 increases the resolution beyond the physical pixel number (right)

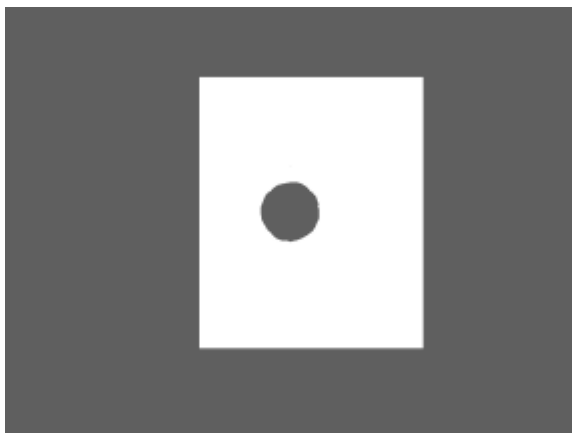
### 2.3 The Implementation

The core function is the gray value correlation 'gwkcalc.m' which reads in the coordinates of the evaluation points and does the calculation of the coefficient  $r$ . Interpolation, picture display, grid overlay and vector output are the main tasks.

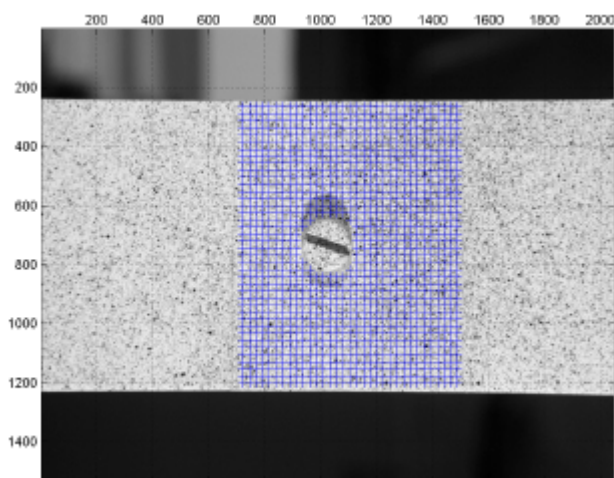
As the system can be used for displacement field analysis and object motion tracking there are two different kinds of input modules for acquiring the evaluation points. 'gmkmeasurepoints.m' displays a picture of the object and reads interactively measurement points from the graphical user interface via the mouse pointer, **Figure 3**. 'gwkmesh.m' reads a black and white picture, **Figure 4**, that serves as a mask to define the region of interest, where a Cartesian mesh is automatically created, **Figure 5**.



**Figure 3** Points which shall be tracked are selected manually /4/



**Figure 4** Masks are used to exclude regions which are not of interest (black)



**Figure 5** Automatic generated mesh using gwkmesh and the predefined mask

The 'gwksettings.m' procedure contains all important preferences like search area, mesh refinement and interpolation options, file names and paths.

In order to display displacement fields and trajectories of points the 'gwkgraph.m' function was implemented. It is used for simultaneous display of contour plots and image data.

The 'gwk.m' is the main program and controls all activities including calculation, scaling to engineering units, output and video sequence generation.

There are a lot of additional helping functions i.e. for MPEG movie conversion, rigid body movement and blur compensation, assemble modules to get animated pictures of the load test, calculation of derivatives, acceleration and trajectories. It is worth mentioning that the 'open' architecture of MATLAB was useful in adapting special graphic functions for own purposes.

## 2.4 Speed and memory considerations

Unfortunately the calculation of the correlation coefficient depends on the search area and the compared section. If the search distance or the section size is doubled the calculation time is fourfold to the previous speed. Additionally all variables have to be cleared manually because MATLAB has no system memory management. In fact the calculation of the aluminium beam in **Figure 7** took more than five hours and 500 MB memory. For this reason some tricks are applied:

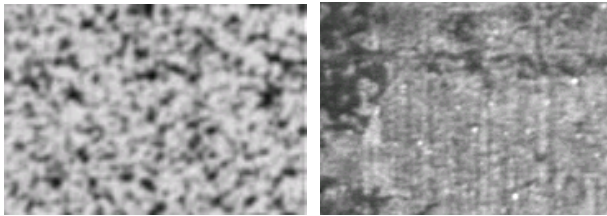
- Large scale rigid body movement must be automatically compensated for at least one reference point. Assume for example a rigid body movement of 10 pixels and a deformation of 5 pixels maximum. Without compensating rigid body movement every evaluation point would need  $15 \times 15 = 225$  calculation runs. If we confine ourselves only to deformation analysis there are  $5 \times 5 = 25$  steps left. That is eight times faster than before!
- The calculated displacement field is assumed continuous so the grid of the evaluation points and the displacement vectors can be interpolated in the same manner like the correlation coefficient matrix.

## 3 The Application fields

The application fields of the system depend on the required resolution. In contrast to other measurement application the resolution of the gray correlation is relative and not fixed. Speckle interferometry for example has a maximum measuring range of about 50 microns, independent of the object size. The gray correlation can measure  $1/2000^{\text{th}}$  of the object size. That can be  $1/1000^{\text{th}}$  mm if used with a microscope or 1 cm if used in crash analysis of cars. The transition is fluent, but gray correlation is mainly used in plastic deformation analysis where other methods fail.

### 3.1 The required surface texture

The correlation is unequivocal if the surface has a random texture. As any regularity or symmetry leads to ambiguities it is not recommended to use gratings or crosses as markers. However sand-blasted, ground or lacquered surfaces have often a suitable quality, **Figure 6**.



**Figure 6** A speckled and a ground surface

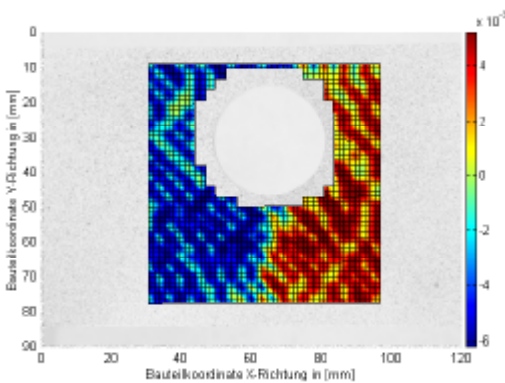
Similar to laser speckle interferometry coherent light can be used to produce a high resolution random texture on objects. Unfortunately decorrelation effects occur due to the change of the illumination direction when the test specimen undergoes deformation. Best results are obtained by careful preparation from far distance with spray cans. To increase the background contrast a white chalk paint can be applied first.

**3.2 Strain and deformation measurement**

If the whole deformation field is measured the strain distribution can be derived by calculating the potential gradient with a build-in MATLAB function.

**3.2.1 Elastic strain of thermosetting plastic**

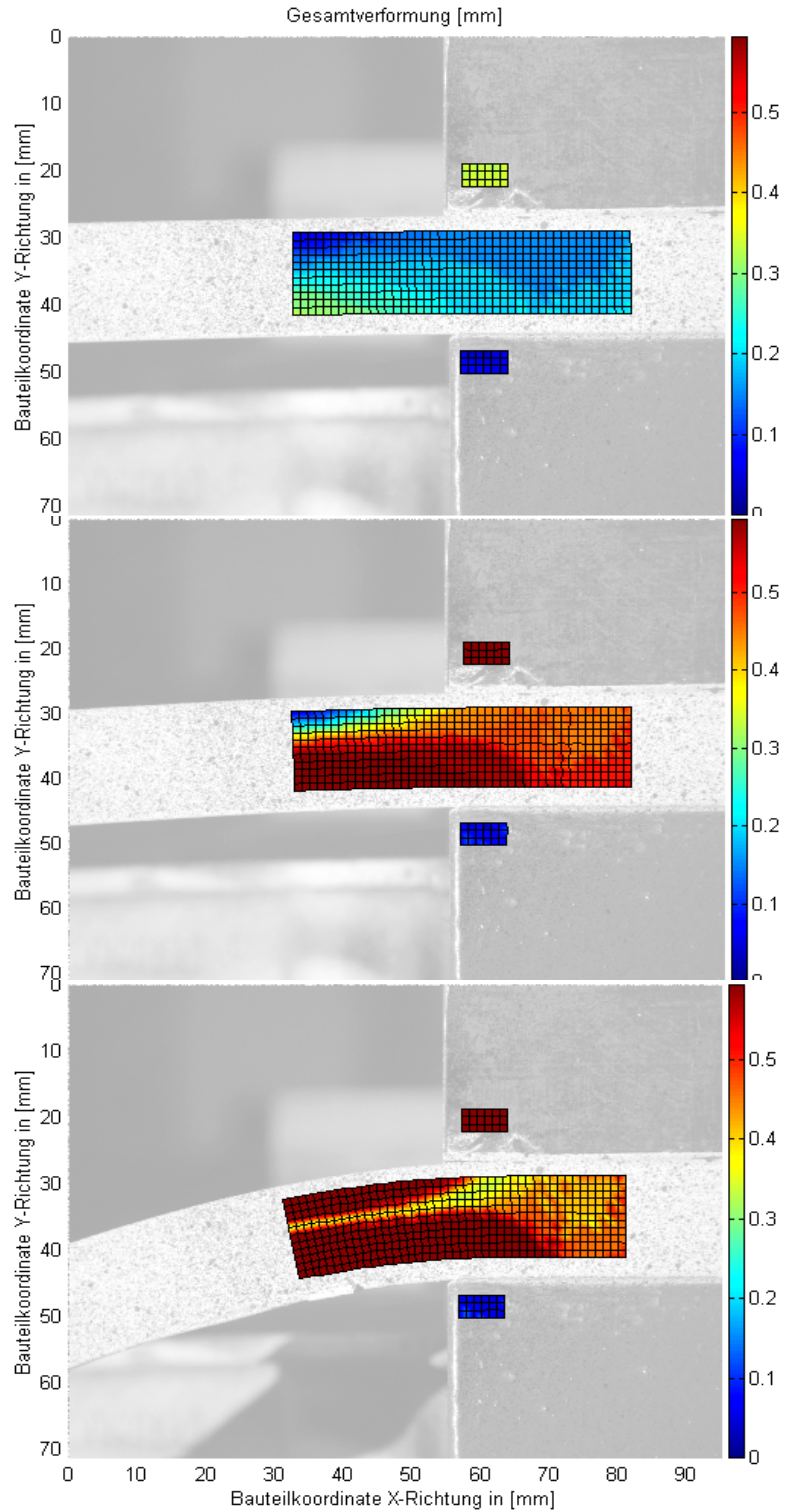
An Araldit (Epoxy resin) plate with an eccentric hole as notch was mounted in a tensile tester. A load was applied in horizontal direction. The deformation was in the elastic range. **Figure 8** shows the yield strain distribution in a selected area around the hole. The spots and discontinuities in the strain distribution indicate that the resolution of the displacement is to small. The overall values reach the lower boundary of the systems capacity.



**Figure 8** Elastic strain of a tensile specimen made of Araldit with eccentric hole

**3.2.2 Plastic deformation measurement**

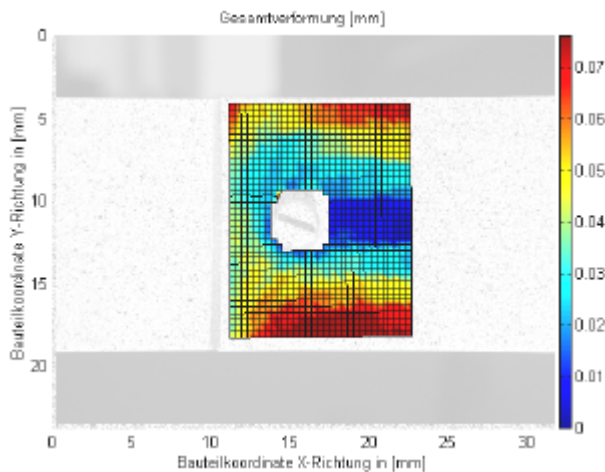
The picture sequence in **Figure 7** shows the bending of a aluminium bar that is clamped in a chuck block. The measurement areas are selected by a mask file. The yield displacement in millimeters is coded in the coloured plot. The small measurement area on the upper jaw shows that it is pushed upward. The neutral fibre forms near the middle of the



**Figure 7** Bending sequence of a plastic deformed and clamped aluminium bar



beam. Even if the displacement is very large, the system is able to follow the specimen. The measurement grid is deformed continuously and undergoes also distortion. Additional points between the grid were calculated with a bicubic spline algorithm to increase the resolution. The patch graphic objects were smoothed with Gouraud shading to obtain a soft light and transition effect for visualization. The background is tinted and shows the current photographs of the deformed shape.

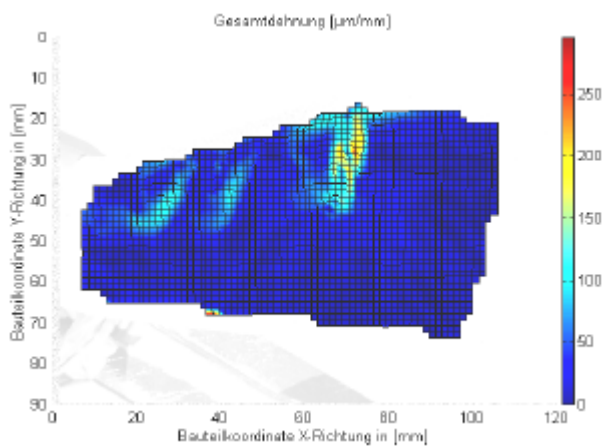


**Figure 9** Remaining deformation of a tensile specimen with screw joint

**Figure 9** shows the deformation of two screwed sheet metal stripes under tension. Local plasticization can be detected around the screw.

### 3.2.3 Detecting flaws of a pressure vessel due to varying wall thickness

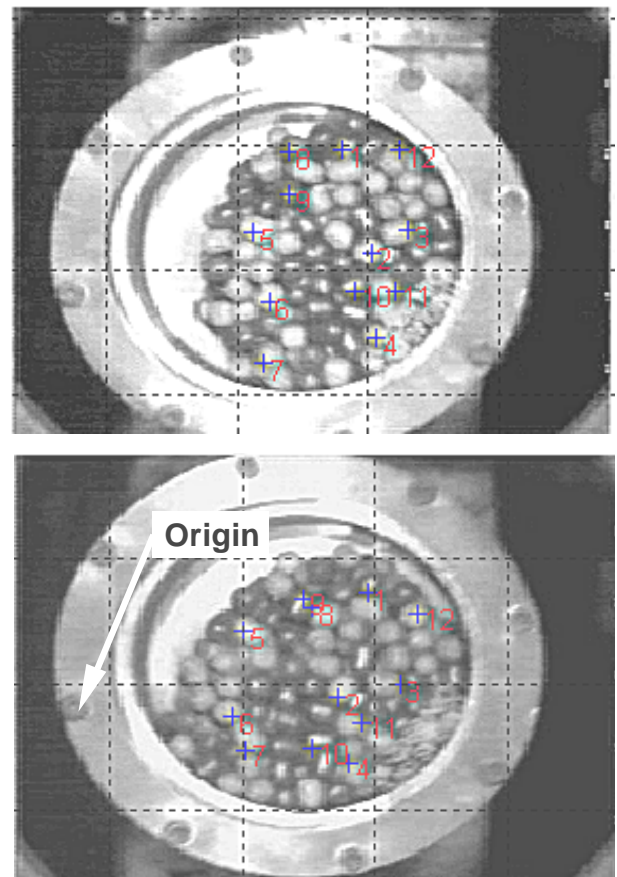
Image correlation can be used to detect flaw in pressure vessels, provided that the deformation is large enough. **Figure 10** shows a plastic vessel with thinned areas in the wall. The regions in the upper half can be identified due to large strains.



**Figure 10** Plastic tank with internal pressure and flaws (just before detonation)

### 3.3 Tracking of objects and determination of kinematic and kinetic parameters

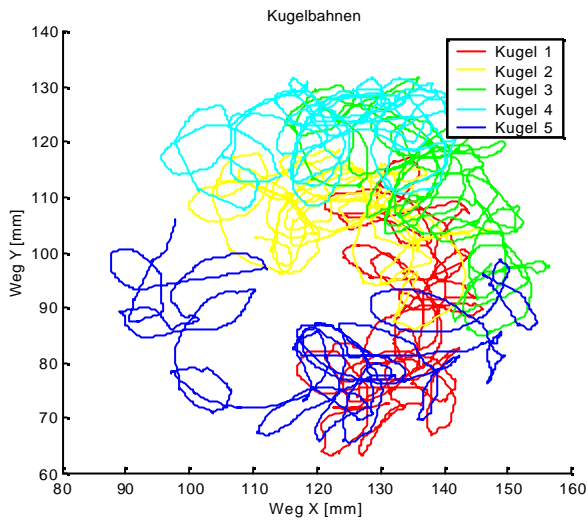
If someone has to measure kinematics the gray value correlation gives an excellent support. The tracking of objects is as easy as the calculation of deformations. Instead of a whole grid the tracking procedure uses a list of single point coordinates. Movie sequences can be evaluated if they are available as MPEG files or as single picture sequences of a common file format. **Figure 11** shows a high-speed record of a vibrating ball mill. The movie was transferred from tape to MPEG with a frame grabber video card. The charge consists of coloured metal balls. In order to increase crushing performance the impact energy of the balls has to be optimised. The first step is to calculate the trajectories. Every discontinuity in the trajectory is a hint to an impact event.



**Figure 11** High speed picture sequence of the charge in a vibrating ball mill

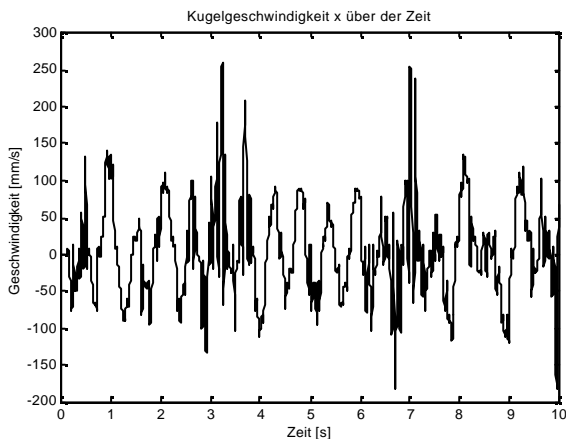
When the time spacing of the frames is equal, the speed and acceleration of the individual balls can be obtained by differentiating the trajectories.

A big disadvantage of the MPEG standard is that it uses lossy compression. Areas in the pictures which move less than a certain limit are assumed to be fixed and the velocity starts to leap.

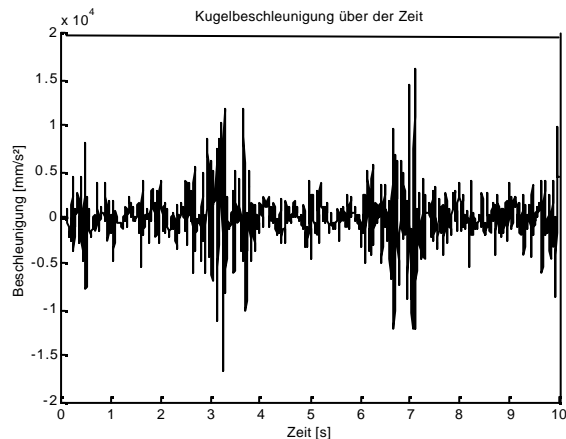


**Figure 12** Motion study of the first five selected balls

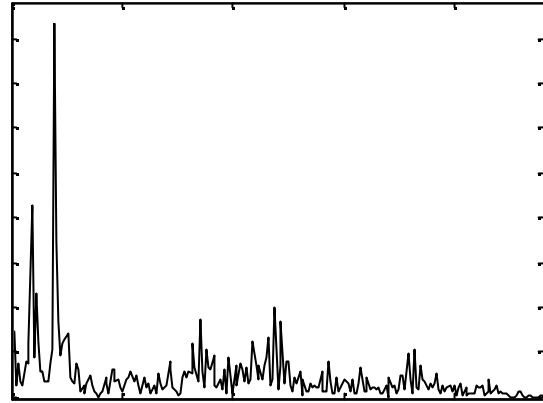
If a ball changes his direction rapidly, **Figure 12**, it probably just bumped against a neighbour or the wall. The mill container itself is following an elliptical trajectory which was eliminated by the rigid movement compensation algorithm. The Origin was set to a head screw on the front, Figure 11.



**Figure 13** Speed in x direction of ball No. 1



**Figure 14** Acceleration in x direction of ball No. 1



**Figure 15** Qualitative Fast-Fourier-Transform derived from the speed of ball No. 1

**Figure 13** to **Figure 15** show derived kinematic parameters.

### 3.3.1 Crash test measurements

The point tracking method can be used in crash test evaluation, too. **Figure 16** shows that even coarse an low resolution MPEG videos give satisfying results.



**Figure 16** Trajectories of points on a car body during a crash test

## 4 References

- /1/ The MathWorks, Inc.: Using MATLAB. Version 5, Natick, Massachusetts, USA, 1999
- /2/ Lüke, H. D.: Signalübertragung. Grundlagen der digitalen und analogen Nachrichtenübertragungssysteme, 7.Auflage, Springer-Verlag, Berlin, 1999
- /3/ The MathWorks, Inc.: Image Processing Toolbox. Users Guide Version 2.2, Natick, Massachusetts, USA, 1999
- /4/ Internet-Seite der Fa. A&O Autoversicherung Oldenburg AG: <http://www.a-und-o.de/supert.html>, Crashtest-Video audia3ct.mpg, Nov. 2000
- /5/ Kieselstein, E. et alt.: Einsatz der Grauwertkorrelation zur Charakterisierung von Faserverbundwerkstoffen. DVM-Tagung Werkstoffprüfung, Bad Nauheim, Dec. 1996