Methods for determining the physical quantities describing the vehicle movement and the driver during a road accident

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Abstract. The paper compares the displacement and speed courses of cars, motorbikes and motorcyclists during a road accident obtained with the use of two measurement methods. In the first method, the course of the impact recorded by a fast camera recording 1000 frames per second was used (“frame by frame” film analysis). In the second method, the courses of accelerations and angular velocities of the objects were used (numerical integration of the recorded courses). The measurements were carried out during crash tests involving a frontal-side collision of two cars or a motorcycle with a car. The results has been shown in the time interval 0-0.5 s. During this period, the following phases of the experiment are observed: vehicle collision and the process of their deformation, the separation of vehicles, the start of independent movement of both vehicles after the collision. The measurement results obtained with the use of both methods are burdened with errors resulting, among others, from limited data sampling frequency, offset errors, calibration errors and sensor noise, duration of the analyzed waveforms. The use of two of the above-mentioned measurement methods simultaneously allows to minimize measurement errors.

Key words: crash test, automotive safety, vehicle testing

1. Introduction
Obtaining physical quantities describing the movement of vehicles and people is of interest to many entities researching: passive safety systems [1, 2, 3], active safety systems e.g. during the modelling of autonomous lane change algorithms [4, 5, 6], dynamics of movement [7], compliance of technological solutions with the applicable standard documents, e.g. LDWS (Lane Departure Warning System), experts analyzing the records of UDS (Unfall Daten Speicher), ADR (Accident Data Recorder) black boxes [8, 9], or road accidents experts [10, 11]. The obtained data is subject to uncertainty due to the limited frequency of data sampling, errors of offset, calibration and noise of sensors, duration of measurements. Therefore, it seems advisable to conduct research focused on determining the uncertainty range of the obtained results of certain physical quantities describing the motion parameters with various methods. The paper compares the course of displacement and velocity of objects during the collision and immediately after the collision, determined on the basis of post-frame analysis of films and
numerical integration of acceleration and angular velocity waveforms recorded during several frontal-lateral collisions of vehicles carried out in the Łukasiewicz Research Network - The Automotive Industry Institute in Warsaw.

2. The aim and scope of this work

2.1. Test objects

The aim of this work is to compare the trajectory courses of cars, motorbike, and motorcyclist during a road accident obtained with the use of two measurement methods based on:

- analysis the course of the impact recorded by a fast camera recording 1000 frames per second ("frame by frame" video analysis);
- analysis the courses of linear accelerations and angular velocities of the objects (numerical integration of the recorded courses - calculations).

Post-impact motion was analyzed. The one frame video in first contact has been presented in Figure 1. Photo a) represent two colliding vehicles under test, photo b) represent motorcyclist hits against a motorcar.

![a) b)](image)

**Figure 1.** The one frame video in first contact; a) a photo of two colliding vehicles under test, b) a photo of motorcyclist hits against a motorcar

2.2. Analysis of the motorcar collision’s

The data acquisition system of the acceleration and angular velocity measurements was located in the trunk of the vehicle in a crash test case. At the stage of recording the measurement results, a 10 kHz filter was used and during the calculations, a 50 Hz filter was used, so that the measurement results were reduced to a frequency band that can be reproduced in the process of modelling and solving equations. The selection of the filter cut-off frequency (tests with 100 Hz and 25 Hz filters were carried out) was a compromise between the expected accuracy of calculations, the possibility of interpreting their results and the possibility of obtaining conclusions relevant and useful conclusions during the modelling and reconstruction of this type of road accidents. Recording cameras the position of the collision vehicles with a frequency of 1000 frames per second were installed above the place of collision and has been presented in the Figure 2a and 2b. Figure 3 represents the silhouettes of the cars at the time of the maximum deformation.
2.3. Analysis of the motorcyclist collision
The data acquisition system of the acceleration and angular velocity measurements was placed in the dummy's head and torso. In addition, the motorcycle and the car have two three-component linear acceleration sensors, the motorcycle - near the centre of mass and on the edge of the seat, and the car near the centre of mass and in the trunk. Accelerations and angular velocity were recorded at a frequency of 10 kHz. In the direction perpendicular to the plane where the motorcyclist was moving, mounted a camera which recorded video at a frequency of 1000 frames per second.
Figure 4. The one frame video under test; a) beginning of the process of a motorcycle impact against the motor car side, b) motorcyclist’s helmet came into contact with the edge of the car roof, c) restitution phase, d) motorcycle lifted to the maximum height

3. Calculations and results

During calculations, the following coordinate systems were used:

- local coordinate systems, rigidly related to the object. The \( O_{ixyz_i} \) coordinate system has the origin of \( O_i \) at the center of the mass of the object “i”, the axis of \( O_i \) is parallel to the longitudinal axis of the object;
- local horizontal coordinate systems related to the object “i”;
- \( O_{GxyzG} \) global coordinate system related to the road.

The relations between the coordinate systems may be described as follows:

\[
\begin{bmatrix}
    a_{xi} \\
    a_{yi} \\
    a_{zi}
\end{bmatrix} =
\begin{bmatrix}
    \cos \Theta_i & \sin \Theta_i \sin \Phi_i & \sin \Theta_i \cos \Phi_i \\
    0 & \cos \Phi_i & -\sin \Phi_i \\
    -\sin \Theta_i & \cos \Theta_i \sin \Phi_i & \cos \Theta_i \cos \Phi_i
\end{bmatrix}
\begin{bmatrix}
    a_{xi} \\
    a_{yi} \\
    a_{zi}
\end{bmatrix}
\]

(1)

\[
\begin{bmatrix}
    \ddot{x}_{Gi} \\
    \ddot{y}_{Gi} \\
    \ddot{z}_{Gi}
\end{bmatrix} =
\begin{bmatrix}
    \cos \Psi_i & -\sin \Psi_i & 0 \\
    \sin \Psi_i & \cos \Psi_i & 0 \\
    0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    a_{xPi} \\
    a_{yPi} \\
    a_{zPi}
\end{bmatrix}
\]

(2)

\[
\begin{bmatrix}
    \dot{\Phi}_i \\
    \dot{\Theta}_i \\
    \dot{\Psi}_i
\end{bmatrix} =
\begin{bmatrix}
    \sin \Phi_i & \tan \Theta_i \cos \Phi_i & \tan \Theta_i \sin \Phi_i \\
    0 & \cos \Phi_i & -\sin \Phi_i \\
    \sin \Phi_i & \cos \Phi_i & \cos \Theta_i
\end{bmatrix}
\begin{bmatrix}
    P_i \\
    Q_i \\
    R_i
\end{bmatrix}
\]

(3)

where:
- \( \Psi_i, \Theta_i, \Phi_i \) – quasi-Euler angles, defining the orientation of the local system \( \{C_a\} \) relative to the global system \( \{O\} \);
- \( P_i, Q_i, R_i \) - components of the angular velocity vector of the body in local coordinate systems.

The trajectory of the car A and B in the global coordinate system has been presented in Figure 3 and the angle of rotation of the cars in relation to the vertical axis has been presented in Figure 4. Continuous lines represents calculations results, pointed line represents results of the "frame by frame" analysis of films from high-speed cameras (high speed cameras).
Figure 5. Trajectory of the collision vehicle: a) vehicle A; b) vehicle B

Figure 6. Time histories of the $\Psi_i$ angle: a) vehicle A; b) vehicle B

Figure 7. An example of the analysis results, a) results of video analysis, b) results of calculations
4. Summary

The method of reconstruction of changes in the positions of cars on the road during a collision, based on the integration of data from acceleration and angular velocity sensors, has given a satisfactory agreement with the results of the analysis "frame by frame" of movies recorded by cameras. A small permanent error in the zero calibration of individual sensors can lead to large calculation errors. Therefore, the work confronted the results of the "frame by frame" analysis of films recorded by a camera with the results of calculations. In all crash tests, the positions of the silhouettes resulting from the calculations were consistent with the positions recorded by the camera in the subsequent phases of the collision. This fact allowed the researcher to consider the results of measurements (acceleration and yaw velocity) as correct, and the applied procedures for determining changes in the location of objects as correct and reliable, and therefore possible to use in other analyses.

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