J. Forstner, R. Benning, J. Procelewska, A. Osorio Nesme, M. Mauermann, T. Hanke, J.-P. Majschak and A. Delgado

Novel Approach for Detection of Foreign Particles in Beverages

Foreign particles in food and beverages constitute a serious problem to industry, due to company image and legal responsibility, and the consumer, whose health might be threatened. In this case random testing does not suffice and every container has to be individually tested for absence of such particles. Consequently, there is an urgent need for a reliable, fast and low cost system, which can be automated and which can be applied to filled and closed containers. The presented paper describes a system, which is based on rotatory movement of bottles. Due to their importance glass and PET bottles were used as examples for the approach, forcing particles like glass splinters to move to the wall. Multiple contacts of the particle upon the wall follow from this proceeding and are recorded by a piezo sensor. After processing the resulting signals allow the detection of glass particles with dimensions down to 1 mm x 1 mm x 1 mm in aqueous liquids, like water, beer, butter milk or orange juice. Besides the costs an advantage of the system lies in the characteristic that an optical access is not necessary, both with respect to the material of the bottle and the contained liquid.

Descriptors: foreign particles, food, beverages, multi contact, detection system, piezo sensor

1 Introduction

Foreign particles in food or beverages pose an important problem. For the consumer their existance can result in injuries if they are ingested or even swallowed. For the manufacturer, filler or bottler a case of a foreign particle can lead to legal consequences due to actions for damages or economic disadvantages by decreasing sales or removal from trade chains. Consequently, the test of control samples is not sufficient and every single bottle or container has to be tested. The necessary effort is illustrated by the following numbers of produced containers for food and beverages. In the year 2008 approximately 4.8 billion new beverage cans and 9.3 billion new bottles and bins were manufactured.

Due to these considerations a reliable system for detection of foreign particles, which is capable of testing every single bottle in real time is of vital interest for food and beverage industry. At present there are different approaches to solve this problem. The systems in use often, but not exclusively, depend on optics, ultrasound, X-ray or metal detectors [1–8]. For the latter a clear disadvantage is the restriction to metal foreign particles. Other materials, especially glass splinters, which are of particular interest in the food industry, can not be detected, although they constitute the most prominent case. Optical systems, normally based on CCD cameras, are only applicable for transparent bottles and ingredients. Consequently, their use for products like coffee, cappuccino etc. is not possible. Furthermore, the realisation of optical detection is often technically demanding as additional illumination is needed and one single camera normally is not enough to cover the complete test item. Similar restrictions hold for the other mentioned alternatives. Apart from the difficulties to inspect the complete volume within a reasonable time, the need for specifically trained personnel, the influence of environment, e.g. temperature, or mere limitations with respect to the detected materials are serious disadvantages of these systems [3, 7, 8].

As a consequence of the current situation it was the aim of the research project described in this paper to develop an automated low-cost system, which is able to detect foreign particles in food, and which can be integrated into existing equipment in the filling process. A necessary characteristic of the considered food is the capability of flowing. A further aspect is the independence from optical accessibility. Primary goal was to prove the principal applicability of such a system. The detailed realisation was intended to be done in cooperation with partners from industry. The system should enable a detection rate of 100 %. This means that a particle is detected in at least 100 runs while in at least 100 runs at identical conditions but without particle there is no false positive signal. The detection rate consequently depends on particle size, material, liquid and experimental parameters.

To be sure that a contamination after the detection process is impossible, the system should be placed after closing the container. The final system uses the fact that in a rotating fluid a foreign particle with a density higher than that of the fluid is transported to the wall of the container. This is of interest for the most interesting case of a glass splinter within a glass bottle. The multiple contacts

Authors

Judith Forstner[1], Dr. Rainer Benning[1], Dr. Joanna Procelewska[1], Dr. Anuhar Osorio Nesme[1], Marc Mauermann[2], Tilo Hanke[2], Prof. Jens-Peter Majschak[2], Prof. Antonio Delgado[1];
[1] Friedrich-Alexander-Universität Erlangen-Nürnberg, Chair of Fluid Mechanics, Erlangen; corresponding author: Judith.Forstner@lstm.uni-erlangen.de;
[2] Fraunhofer Applications Center for Processing Machines and Packaging Technology AVV, Dresden

of the particle with the inner side of the wall cause oscillations of the bottle that can be detected by suitable means.

Numerical simulations were carried out in advance to estimate the resulting forces and an applicable location for the sensor with respect to different rotational velocities. On this basis an experimental setup was designed to develop the detection sensor and signal processing.

2 Materials and methods

2.1 Numerical calculations

Numerical calculations were carried out using the software ANSYS CFX 11.0 (ANSYS Germany GmbH, Otterfing).

A basic model of a returnable bottle for mineral water with a volume of 0.5 l was defined. Two different meshes were generated for the bottle, see figure 1, a coarse one using 52,476 tetraeders with 68,915 nodes (figure 1, left) and a fine one applying 673,056 hexaeders with 684,188 nodes (figure 1, right).

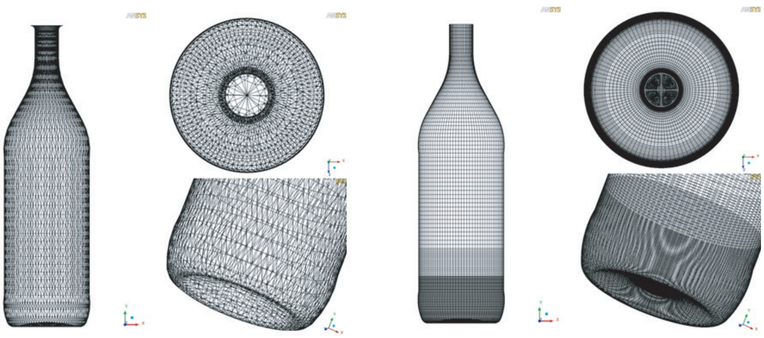

Fig. 1 Two meshes of different resolution for simulation of the bottle. The coarse one (left) is composed of 52,476 tetraeders, the fine one consists of 673,056 hexaeders

As the fine mesh gives more precise results but leads to a higher computational expense the fine mesh was only applied to the lower part of the bottle. Further properties of the materials from ANSYS CFX 11.0, library materials, are given in table 1.

The simulated fluid was assumed as Newtonian and isothermal, flows were treated as laminar.

The simulation of particles in the fluid was performed using the Lagrangian tracking model, which integrates particle paths through the discretized domain. Individual particles are tracked from the injection position until they leave the domain or some integration criterion is reached. The particle displacement is approached by using a forward Euler integration of the particle velocity over the time step. ANSYS CFX 11.0 allows simulating both spherical and non-spherical particles with different diameters. However, only non-spherical particles with ellipsoidal form can be simulated, making it difficult to reproduce particles with sharp edges.

ANSYS CFX makes use of an element-based finite volume method for discretizing the spatial domain using a mesh. The fluid governing equations for mass, momentum and energy are integrated over each discretized control volume. For transient simulations, the unsteady term is approximated by means of a second order backward Euler scheme. Discretization of the advection term was done by the High Resolution Scheme, which is essentially of second order [9].

For the presented simulations the discrete time step was chosen to be 0.005 s. This selection permits a detailed analysis of the particle in short times. The maximum residual level considered in this work was 1.0e-4.

The simulations dealt with two different alternatives that were considered as suitable for an active positioning of the particles at the wall of the bottle and for a following implementation into an industrial filling line. In the first case a bottle filled with fluid and foreign particle is linearly moved with constant acceleration, in the second case the bottle rotates with constant angular velocity around its longitudinal axis. In both cases the following parameters have to be determined

- the necessary time, which the particles need to reach the wall at constant acceleration with respect to their starting position.
- the minimal acceleration, which is required to move the particles to a defined position at the wall.

Due to the advantages for implementation a target of the simulations was to gain knowledge to which extent already existing equipment in a filling line, e.g. labelling unit or bottle inspector, are suited for integration of the developed system. Consequently, the behaviour of foreign particles in a rotating glass bottle, filled with water, was investigated.

For the foreign particles a spherical shape with diameters of 0.5, 1.0 and 1.5 mm was chosen. Angular velocities of 400, 600, 800, 1,000 and 1,200 rpm (revolutions per minute) were applied as rotational speeds. At time t = 0 the fluid was defined to be in rest and all particles lying at the bottom. This corresponds approximately to the situation at the entrance of a bottle inspector.

Table 1 Material properties for numerical simulations, taken from ANSYS-CFX 11.0, library materials

property	water	glass
density [kg/m³]	997	2,500
dynamic viscosity [kg/m s]	0.00089	–
temperature [K]	293.15	–
coefficient of thermal expansion [1/K]	0.00021	–

2.2 Sensors

For the described experiments piezo sensor membranes of type EPZ-35 (Ekulit Elektrotechnik, Ostfildern) were used. The technical data are given in table 2.

Table 2 Technical data of applied piezo sensors

Type	EPZ-35
resonance frequency	2.9 kHz
impedance	200 Ohm
capacity	26,000 pF

2.3 Data processing

The signals from the piezo sensor were amplified and filtered by an individually adapted electronic circuit, developed at the workshop of the Chair for Fluid Mechanics, University of Erlangen-Nuremberg, which includes high-pass filter, low-pass filter and a notch filter. This eliminates all potentially disturbing signals from the used motor or other components of the experimental setup. Finally, the signals were Fourier transformed on a PC, using MATLAB (MathWorks, Ismaning).

2.4 Design of experimental setup

After defining a rotational acceleration as method for positioning of the particles a experimental setup was designed and built up.

As a result of the conception phase the selected approach, see figure 2, was realised in an experimental setup, depicted in figure 3, for further investigation of the detection method.

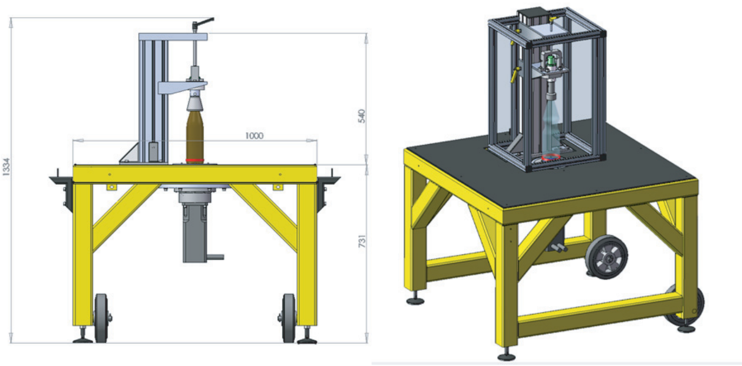

Fig. 2 CAD model of the experimental setup, numbers refer to lengths in mm

The following boundary conditions were taken into account:

- direct drive of the bottle by servo motor (M5061, Eduard Bautz GmbH & Co.KG, Weitenstadt),
- control of motor by digital servo controller (SCE953, Eduard Bautz GmbH +Co. KG, Weitenstadt),
- simple definition of experimental parameters, e.g. rotational speed, acceleration time,
- simple fixation of the bottle,
- use of standard parts of a labelling machine for bottle fixation,
- use of gum surface for minimisation of the slip of bottle and drive during motion and for a simple decoupling of vibrations,
- data and energy transfer by a precision slip ring transmitter (Type 5, Michigan Scientific, Milford, USA),
- use of a coaxial cable for data transfer to avoid data corruption.

Fig. 3 Fixation of the bottle into the rotating equipment

The piezo sensor was fixed in the middle of the bottom of the bottle, see figure 4 (left). This alternative also has the advantage of an easier integration into the disc drives, see figure 4 (right), of existing rotational equipment.

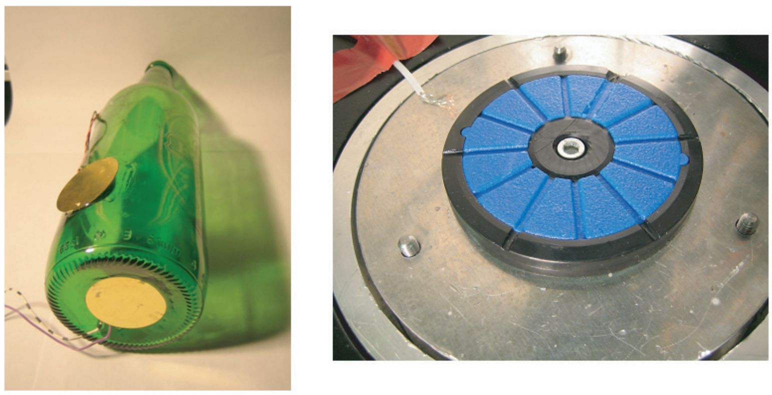

Fig. 4 Fixation of the sensor to bottle bottom (left) and rotating drive (right) as possible location for piezo sensor integration into existing bottle inspectors (type carousel machine)

The necessary electronic equipment of the system was also fixed to the bottle at a side position due to reasons of easy accessibility.

To validate the functionality of the experimental setup numerous experiments were carried out. Both glass bottles and PET bottles were used. To simulate practical conditions not only various liquids, see table 3, but also foreign particles, different with respect to

Table 3 Experimentally used liquids and their rheological characteristics

medium	viscosity μ [mPas]
water	1.0
orange juice	1.7
beer	1.2
saccharose solution (50 w%)	15
saccharose solution (60 w%)	56
sunflower oil	60
butter milk	shear thinning
smashed tomatoes with pieces	–

Fig. 5 Applied model particles: glass particles and steel spheres of different sizes

material, shape and size were tested. These are shown in figure 5. The dimensions of the glass splinters varied between approx. 1 mm x 1 mm x 1 mm and 8 mm x 5 mm x 3 mm. The splinters were generated by breaking a glass bottle and choosing particles of appropriate dimensions. Thus, the shape is not well defined but can be assumed to be realistic. Furthermore, steel balls with diameters of 1.5 mm and 3 mm were used.

3 Results and discussion

3.1 Positioning of particles

Figure 6 exemplarily shows the trajectories obtained by numerical simulation for a spherical glass particle with a diameter of 1.0 mm and a rotational velocity of 1,000 rpm. The simulated time was 0.5 s.

Simulations of linear acceleration showed that the necessary length for reaching an arbitrarily defined height, in this case 0.0032 m, exceeds practically applicable values. This especially holds for small particles, e.g. 0.5 mm in diameter. Results are shown in figure 7.

As a final conclusion all experimental investigations were done with rotating bottles.

3.2 Experimental results

In the numerical calculations a multiple contact of the particles, see figure 8, with the wall of the bottle is obtained.

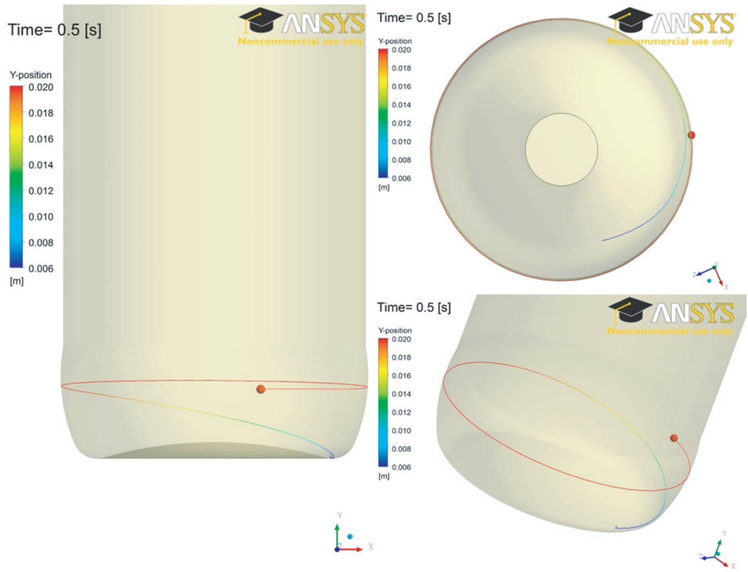

Fig. 6 Trajectories for a spherical glass particle with a diameter of = 1.0 mm and a rotational velocity of 1,000 rpm. The colour scale indicates the height of the particle from the bottom of the bottle.

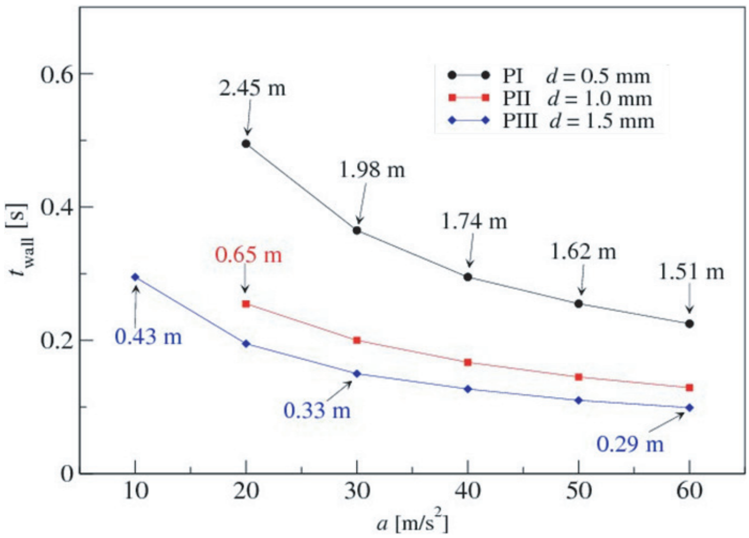

Fig. 7 Dependence of the necessary time for reaching a defined height of a particle (0.0032 m) in the bottle from applied acceleration. Additionally, the covered distances of the bottle are given

In the experimentally obtained spectra, see figures 9 to 11, several peaks can be identified. Each peak corresponds to a contact between particle and wall. This proves that the numerically predicted multiple contacts occurs in reality and can be recorded with the used measuring electronics.

Figures 9 to 11 depict different spectra before software processing. Figure 9 shows the difference of spectra without and with foreign particle in a glass bottle filled with water. The used glass splinter has dimensions of 1 mm x 1 mm x 1 mm. While the spectrum without particle only shows noise (figure 9, left), the presence of the splinter leads to multiple peaks (figure 9, right). These can be assigned to the multiple contacts of the particle at the inner side of the wall.

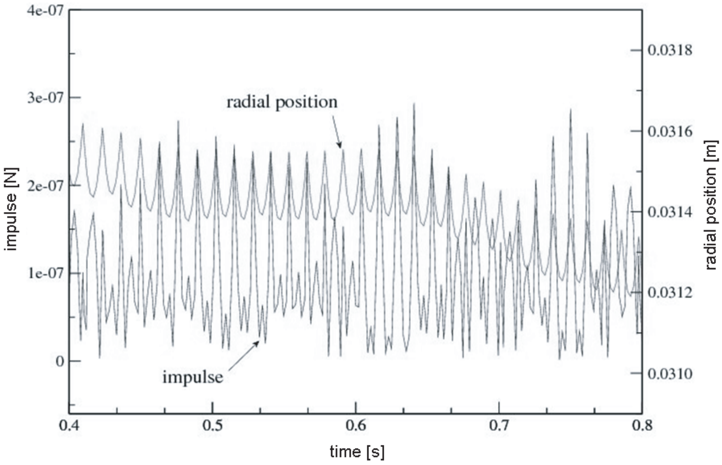

Fig. 8 **Numerically calculated impulse and radial position of a particle with a diameter of 0.5 mm at a rotational velocity of 1,000 rpm. The peaks indicate the multiple contacts to the wall. The different radial positions are caused by differences of the simulated bottles inner radius at various heights.**

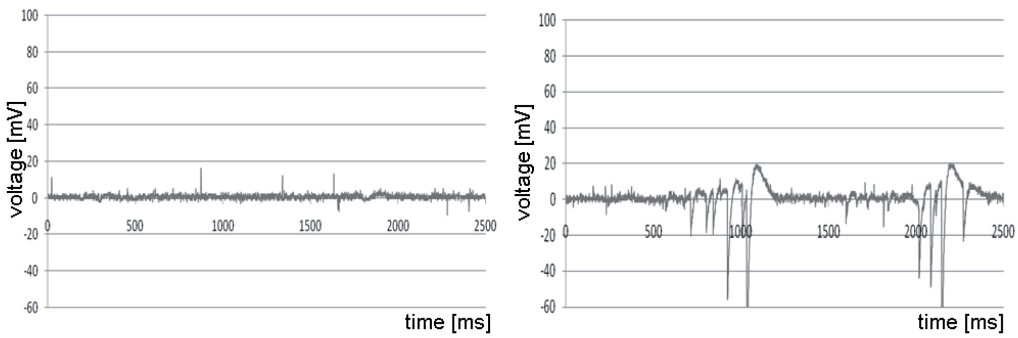

Fig. 9 **pectra before software processing. Glass bottle with water, 1,000 rpm, without (left) foreign particle and with (right) foreign particle (glass splinter, 1 mm x 1 mm x 1 mm)**

It was observed that even very small particles are detected in the different types of bottles and liquids. Furthermore, the experiments showed that asymmetric particles like glass splinters result in clearer signals than steel balls (not shown). This can be explained by the fact that the used glass splinters hit the wall more often than the balls. The latter tend to roll along the wall after a certain time and exert a smaller impulse upon the bottle.

A further question concerns the liquids, in which foreign particles can be detected with the developed approach. Although water represents an important part of beverages, there are also non-newtonian liquids and beverages containing pulp. To investigate the influence of both characteristics butter milk and orange juice were used. While butter milk exhibits a non-newtonian, in this case sheer thinning, behaviour, orange juice contains pulp. Figure 10 depicts typical spectra for both cases. The results show that the principle detection of small particles is still possible. The signal in the case of orange juice is clearer than that of butter milk. Due to the rheological characteristics the signals for butter milk are less distinct but clearly observable. This fact indicates that a more sophisticated data processing should be developed to enable a reliable and robust detection.

Further experiments to increase complexity were carried out with smashed tomatoes. This experimental item not only contains pulp but also kernels with dimensions in the range of small foreign particles. The results (not shown) indicate that kernels also excite signals. Future investigations will be carried out to find an approach for differentiating between the signals of hard foreign particles and comparatively soft kernels.

Additionally, glass and PET bottles were compared as the importance of the latter increases. There is a principle difference of the spectra, shown in figure 11. In the case of PET peak heights are drastically lower and the necessary detection time is higher. These effects can be assigned on one hand to the different elastic moduli of both materials. While the elastic modulus of glass is approx. 40 kN/mm² or higher, depending on the specific kind of glass, the value for PET only is about 4 kN/mm². On the other hand the wall thickness of a PET bottle is smaller than that of a glass bottle. Both factors lead to a decreased stiffness of the PET bottle, resulting in a higher absorbance of the foreign particles impulse instead of transferring it to the sensor.

However, there is no principal restriction of detection as the material based deviations only influence peak distribution and height of the amplitudes. Although the experiments showed that higher numbers of revolutions per minute also caused a higher number of contacts, it could be proven that industrially applied velocities are sufficient for a reliable detection.

It has to be mentioned that the times given in figures 9–11 refer to experiment time, which includes start and acceleration of the bottle. The necessary detection time was estimated to be in the range of approx. 0.5 s in the laboratory experiments. There was no precise determination intended as this was defined to be a goal of investigaions in industrial environment.

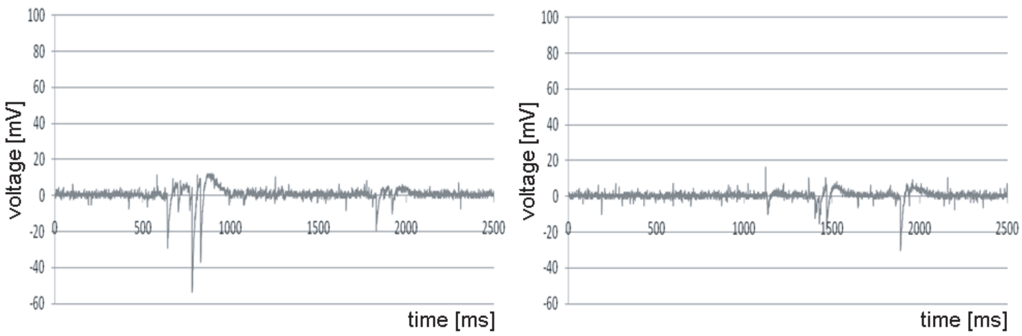

Fig. 10 **Spectra before software processing. Glass bottle with glass splinter (1 mm x 1 mm x 1 mm), 1,000 rpm, orange juice (left) and butter milk (right)**

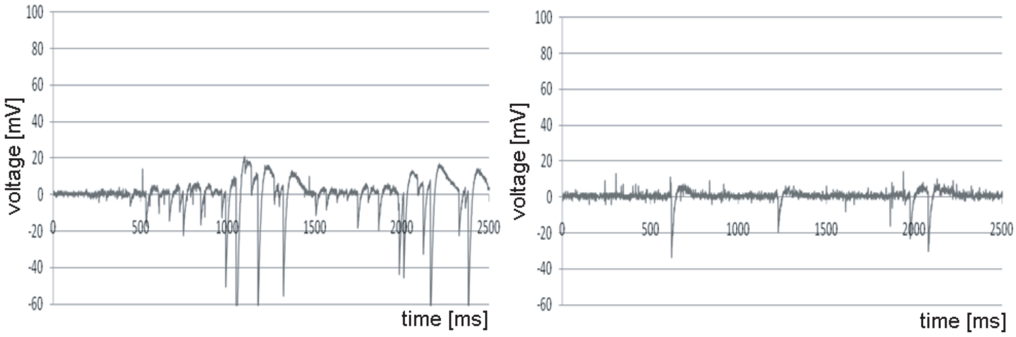

Fig. 11 Spectra before software processing. Glass (left) and PET (right) bottle with water, glass splinter (1 mm x 1 mm x 1 mm), 1,000 rpm

The experiments validated that the investigated aqueous liquids enable correct results of the measurement. This also holds for beverages with carbon dioxide. The comparison of water with beer exhibited no significant differences with respect to the detection rate. It can be concluded that this statement also holds for other liquids of similar characteristics.

4 Conclusion

The investigations showed that the detection of foreign particles is possible on the basis of forced multiple contacts between particle and wall of a bottle. Additionally, the subsequent recording by piezo sensors offers a reliable and comparatively cheap alternative to existing detection systems.

During the experiments it was proved that the system is capable of detecting glass splinters of the relevant dimensions of 1 mm x 1 mm x 1 mm and bigger with detection rates of 100 % in aqueous liquids. Further investigations suggest that these rates can also be achieved for beverages with a more complex rheological behaviour. Similar considerations hold for such applications where the food includes desired particles, e.g. fruit kernels in smoothies. Such problems can be solved by a sophisticated data processing, taking into account the size and the shape of the recorded spectra caused by different particle characteristics.

Present investigations deal with the further development of the system. The sensor is no longer fixed to the bottle but is permanently implemented into the center of the disc drive, which rotates the bottle. First results show that there is no deterioration concerning the detection performance.

Additionally, the sensor system is tested in industrial scale equipment. Here the necessary detection times and the achievable detection rates under these conditions are in the focus. Furthermore, the required integration expenses will be estimated. A further question concerns the influence of inevitable noise in industrial environment, e.g. caused by collisions of bottles, onto the system. As the measurements are not based upon acoustic but on mechanical phenomena, an influence of noise is not expected.

Further work includes the evaluation of the spectra on the basis of artificial neural networks of multilayer perceptron type trained by a BFGS (Broyden-Fletcher-Goldfarb-Shanno) algorithm. First results show that glass splinters with a dimension of 1 mm x 1 mm x 1 mm or bigger in water, orange juice and butter milk can be reliably detected. Furthermore, beverages and food, containing pulp and fruit kernels in the same order of magnitude of the foreign particles, will be investigated. A target will be to find out whether a differentiation of the peaks caused by kernels and foreign particles will be possible.

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