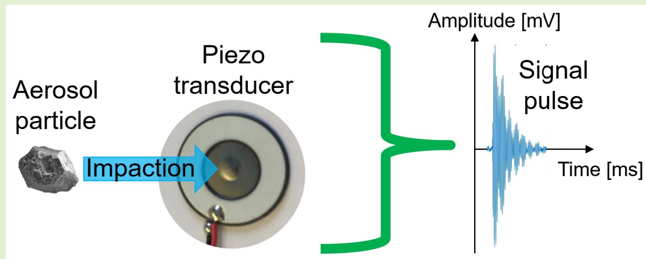
Single Aerosol Particle Detection by Acoustic Impaction

Nadine Karlen, Tobias Rüggeberg, Bradley Visser, Jana Hoffmann, Daniel A. Weiss, and Ernest Weingartner

***Abstract*—A new measurement method has been developed that enables an acoustic detection of individual coarse mode particles (aerodynamic particle diameter > 1 μm) by impaction on a piezo transducer. The aerosol is accelerated and each momentum transfer by a particle is measured as a characteristic pulse in the transducer signal whose amplitude is directly proportional to the particle mass. The current single particle mass detection limit is approximately 50 picograms, which corresponds to an aerodynamic particle diameter of ~5 μm. The measurement technique allows a direct in-situ mass measurement of single coarse mode particles that is unique because it is based on first principles, is relatively simple and less prone to measurement artefacts compared to other methods. This particle mass measurement is independent of assumptions on particle properties like shape, density or refractive index. This technology is of interest for scientific, industrial and health-related monitoring applications as different sources of atmospheric aerosols can be identified via size-resolved mass measurements. Challenges to be overcome include a further lowering of the detection limit, eliminating systematic errors from bouncing phenomena, optimizing the correct mass assignment as well as improving the robustness against sensor vibrations and acoustic noise. In addition, the complete sensor should be portable and affordable. With the future goal to detect submicron particles, coincidence and a reduction of the impactor's cutoff diameter additionally become important issues.**



***Index Terms*— Air pollution, aerosol particles, coarse mode, impaction, acoustic.**

I. Introduction

AEROSOL particles are solid or liquid particles suspended in the air with a particle size of some nanometers to several hundreds of micrometers (Fig. 1). They have distinct optical, electrical, mechanical, physical and chemical properties that characterize their impact on e.g. visibility, the earth's radiative balance and human health [1].

Depending on their diameter, aerosols can be grouped in several modes. Fine particles, i.e. particles with aerodynamic diameters smaller than ~2.5 micrometers, are often of anthropogenic origin (e.g. from combustion processes) whereas coarse mode particles, i.e. particles with aerodynamic diameters greater than ~2.5 micrometers, are mostly generated by mechanical processes [2].

Fine aerosols are increasingly the focus of attention due to their adverse health effects [2]. These particles can enter the human lung or even the blood stream due to their small size and can therefore lead to cancer or organ damage such as in the lung or heart [3].

Beside health effects these particles are also climate relevant. They can remain for weeks in the atmosphere and be transported over wide distances. They directly influence the radiation balance of the sun on earth because they can efficiently scatter and/or absorb sunlight. Aerosol particles change the lifetime, as well as the optical properties of clouds, as they serve as condensation nuclei for cloud droplets [4].

Coarse mode particles also have various impacts that should be investigated more closely: several studies associate high short-term concentrations of coarse mode particles with higher mortality rates and hospitalizations, mainly caused by respiratory diseases due to thoracic deposition of the particles [5]. Coarse mode particles lower the immune response of macrophages in the respiratory tract of the human body and can additionally directly trigger allergic or asthmatic reactions [6]. Furthermore, they can increase the risk for nasal cancer in two ways: some particles such as metal dust are

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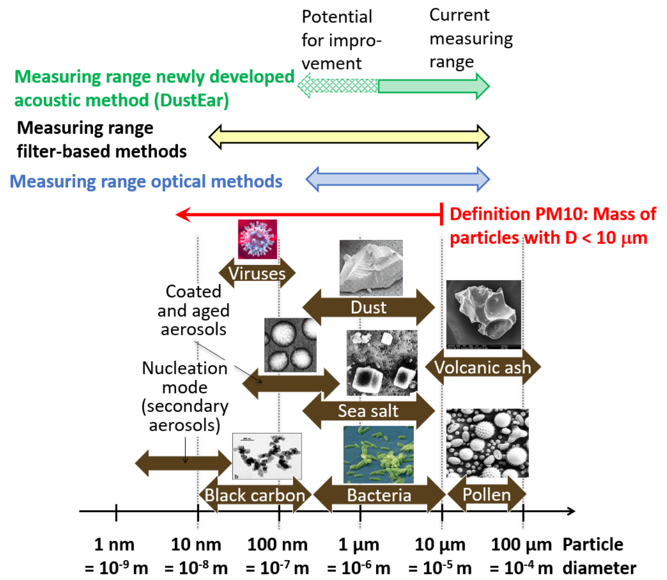

Fig. 1. Size distributions of various aerosols in our atmosphere, definition of PM10 and measurement range of commercialized measurement techniques to characterize PM10.

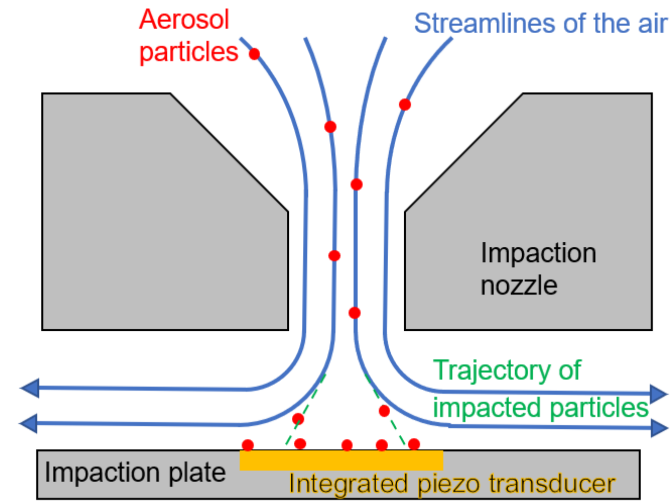

Fig. 2. Principle of operation of the DustEar: Aerosol particles (red) are accelerated in the nozzle and impact due to their inertia on the piezo transducer. This produces a characteristic signal pulse for the impaction of each single particle.

toxic, especially for children [7]. In addition, coarse mode particles such as wood dust can also allow the transport of carcinogenic substances in the respiratory system of the human body. Apart from the health aspects mentioned, coarse mode particles can affect air quality, visibility, climate, ice nucleation and hydrologic cycles [8].

Number and mass size distributions are key properties to understand the above-mentioned impacts of aerosol particles on human health and environment. Nevertheless, most state-of-the-art measurement techniques only allow indirect characterization of particle mass distributions because they analyze related properties such as particle light scattering.

Here we present a new measurement method that allows a direct mass measurement of individual aerosol particles based on first principles. First, we introduce the measurement principle and provide theoretical considerations for the measurement process. Then, we discuss the current results of an initial experimental characterization with well defined monodisperse aerosols. In a next step, we present the current detection limits, which still show great potential to be extended from the current supermicrometer size range into the fine mode. Finally, we have a look at possible applications, further investigations and also future challenges.

II. State-of-the-Art Measurement Methods

There are several methods to monitor the mass concentration or size-resolved distribution of particles larger than 300 nm in diameter [9]:

The most commonly used methods are based on the deposition of particles on a filter and the measurement of their mass in a second step e.g. by weighing or by determining the change in oscillation frequency of a microbalance [10].

Existing alternatives are mostly based on optical measurements where the amount of scattered light from a particle is used as a proxy for particle mass [11], [12]. In this relation assumptions about the density, shape and refractive index of the particles need to be made, however these properties can vary significantly among the measured particles. Therefore, the reliability of intercomparing temporal and spatial air pollution data with optical measurements is limited to some extent.

Other methods use time-of-flight analysis [13] and electric low-pressure impaction [14], characterizing the aerodynamic properties of the particles from which a mass size distribution can be inferred.

III. DustEar Measurement Principle

The principle of operation of the DustEar (**D**irect **U**ltrasonic **S**izing **T**ool with **E**lectroacoustic **A**erosol **R**ecognizer) is illustrated in Fig. 2. First, the aerosol is accelerated in a nozzle. Larger particles with high inertia are not able to follow the streamlines and impact on a piezo transducer that is located behind the nozzle. The air is then drawn evenly across the annulus to the air outlet (Fig. 3), to which a flow regulator (mass flow controller) and external pump (not shown) are connected.

The momentum transfer from the particle to the piezo transducer leads to a single pulse in the transducer signal whose amplitude is proportional to the mass of the impacted particle. This allows a direct and unambiguous correlation between the particle mass and the signal amplitude (see Section VII below).

IV. Existing Acoustic Detection Approaches

In 2007 a patent was granted describing a similar measuring principle as used with the DustEar, but which expired early in 2019 [15]. The idea was never commercialized due to physical limitations. The method focused on the detection of particles with a maximum diameter of 100 μm. Although the possible applications mentioned in the patent are diverse, the intended application of the setup was the detection of abrasive particles

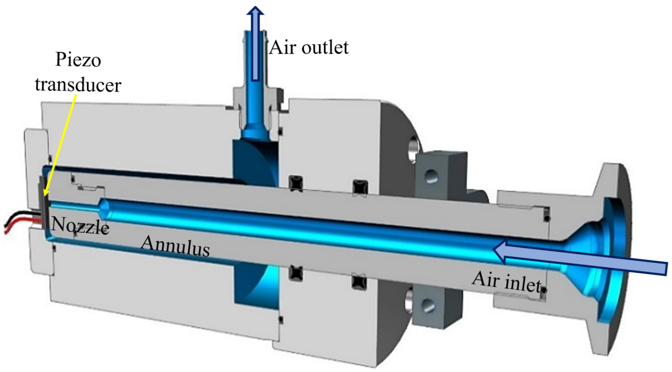

Fig. 3. 3D sectional view of the DustEar: Aerosol enters the DustEar through the inlet (blue arrow), is accelerated in the nozzle and sucked out of the DustEar over the annulus through the outlet (blue arrow). Behind the nozzle the piezo transducer that detects the impacting particles is recessed in the cover to avoid air turbulences.

in optically opaque liquids, especially in the engine oil of diesel locomotives. The motivation was to reliably control the number of particles in the oil in order to extend the time between oil filter replacements.

Several studies describe concepts for acoustic particle detection. To determine the size of aerosols, for example, a piezoelectric film sensor positioned in the air flow measures impact events as individual signal pulses. Salt particles with diameters from 250 to 650 μm were characterized with this method [16]. A demonstrator and experiments with glass beads in diameter ranges of 20 to 250 μm are shown in Hu *et al.* [17]. A similar concept was used to determine particle size distributions with diameters mostly below 200 μm of pneumatically conveyed pulverized fuel. Control of the particle size enables optimal combustion efficiency of the fuel and minimizes pollutant emissions at coal- and biomass-fired power plants. The system is based on acoustic emission detection where peak amplitudes of single signal pulses are analyzed, allowing the velocity and the size of the particles to be determined [18]. Experiments were performed with glass beads with diameters from 20 to 250 μm [16] as well as with willow and miscanthus chips whose diameters ranged from 400 to 6400 μm [19]. Recently, an acoustic method was incorporated into a commercial vacuum cleaner to gain information on the size of house dust during operation. A similar technique was patented in 1997 [20].

Experiments to characterize cosmic dust, space debris and micro-meteoroids with submicrometer sizes and mass of 2 to 100 pg were also based on acoustic particle detection through impaction. However, in this application the microparticles had hypersonic velocities of 2 to 8 km/s. A piezoelectric element measured the particle impulse that allowed real-time information on the particle's kinetic energy [21].

An acoustic approach using impaction was investigated for the characterization of the impact force of liquid droplets. This is of interest for applications like water jet cutting, spray coating or ink jet printing. In an experiment, droplets with diameters of around 3 mm hit a piezoelectric film. The output voltage of the generated signal pulse was found to be proportional to the respective impact force [22].

These methods were used to detect comparatively large particles. However, the DustEar setup presented here has the potential to measure single, fine aerosol particles after further optimization steps. In addition, it directly measures the mass of the particles, so that the composition or density of the particles does not need to be known or assumed. Furthermore, due to an adapted impactor design, the impact velocity profile of the particles will be further improved. Finally, the piezo transducer does not interfere with the air flow because the transducer is recessed, preventing turbulence that would lead to higher noise levels.

V. Theory on Particle Impaction and Momentum Transfer

In the following, we describe the physical processes that are important for the DustEar measuring principle.

In a first step, the particles must be accelerated to their final velocity v_p (= velocity of the air flow v_{air}) in the nozzle in front of the impactor. To achieve this condition, the acceleration distance must be sufficiently long so that also the larger respectively heavier particles reach this final velocity and can thus be measured in a defined manner. By knowing the particle's maximum size respectively mass that should be detected and its desired final velocity, the minimum nozzle length can be determined. It is equal to the acceleration distance s which is given by

$$s = v_p \cdot \tau = v_{air} \cdot \tau = v_{air} \cdot m_p \cdot B \quad (1)$$

with

$$B = \frac{C_c}{3 \cdot \pi \cdot \eta \cdot d_{p,a}} \quad (2)$$

where $d_{p,a}$ is the aerodynamic particle diameter that is represented by the geometric diameter of a sphere with unit-density and the same gravitational settling velocity as the described particle [23]. τ is the duration it takes to accelerate a particle to the air's velocity, called the relaxation time. It depends on the mass m_p and mobility B of a particle that is influenced by the aerodynamic particle diameter $d_{p,a}$. C_c is the Cunningham correction factor and η the dynamic viscosity of the gas [24].

In a next step, the particles are impacted on the piezo transducer. Whether a particle follows the air streamlines or is impacted depends on the aerodynamic diameter of the particle, which can be calculated [23] from the geometric diameter:

$$d_{p,a} = d_p \cdot \sqrt{\frac{1}{\chi} \cdot \frac{\rho_p}{\rho_0} \cdot \frac{C_c\left(d_p\right)}{C_c\left(d_{p,a}\right)}} \quad (3)$$

$d_{p,a}$ = Aerodynamic particle diameter [m]
d_p = Geometric particle diameter [m]
χ = Shape factor [-], is one for spherical shape
ρ_p = Particle density [kg/m^3]
ρ_0 = Reference density of 1000 kg/m^3
C_c = Cunningham correction factor [-]

An important parameter is the cutoff diameter d_{50} that defines the size of the particles with a collection efficiency of 50%. This diameter is defined by eq. 4 and depends on the impactor design, the velocity of the particle, C_c and the properties of the gas [25].

$$d_{50} = \sqrt{\frac{9 \cdot \eta \cdot Stk_{50} \cdot d_j}{\rho_p \cdot \upsilon \cdot C_c}} \tag{4}$$

d_{50} = Cutoff diameter [m]
d_j = Nozzle diameter [m]
ρ_p = Reference density of 1000 kg/m^3
η = Dynamic viscosity of the gas [Pa·s]
υ = Particle velocity [m/s]
Stk_{50} = Stokes number for 50% collection efficiency [-]

For a cylindrical nozzle design the recommended square root value of the 50% Stokes number is $\sqrt{Stk_{50}} = 0.49$ [25].

Particle impaction leads to a momentum transfer to the transducer which is described in the following as a simple spring-mass system. The signal amplitude u, which is proportional to the piezo transducer's displacement, can be described with a homogeneous differential equation of second order with constant coefficients:

$$\ddot{u} + 2 \cdot \delta \cdot \dot{u} + \omega_{res}^2 \cdot u = 0 \tag{5}$$

Solving this equation leads to the following equation for a signal pulse with a damped oscillation:

$$u(t) = U_0 \cdot e^{-\delta t} \cdot \sin(\omega_{res} \cdot t) \tag{6}$$

The angular frequency ω_{res} depends on undamped natural frequency ω_0 of the oscillator and the damping factor δ:

$$\omega_{res} = 2 \cdot \pi \cdot f_{res} = \sqrt{\omega_0^2 - \delta^2} \tag{7}$$

This leads to the following final equation for damped oscillation:

$$u(t) = U_0 \cdot e^{-\delta t} \cdot \sin\left(\sqrt{\omega_0^2 - \delta^2} \cdot t\right) \tag{8}$$

Because we only analyze the maximum signal amplitude of each signal pulse (see Chapter VI), we are interested in the maximum measured voltage amplitude U_0 of our signal. This value is a function of the impedance Z of the transimpedance amplifier of the piezo transducer and the current I_0 that is the quotient of charge displacement ΔQ and time difference Δt:

$$U_0 = Z \cdot I_0 = \frac{Z \cdot \Delta Q}{\Delta t} \tag{9}$$

The charge displacement can be expressed with the piezoelectric constant d_{ij} of the piezoelectric effect and the force difference ΔF that acts on the piezo crystal:

$$\Delta Q = d_{ij} \cdot \Delta F \tag{10}$$

If the piezo crystal is assumed to behave like a spring obeying Hook's law, the force difference can be expressed as the product of the spring constant k and the displacement Δx :

$$U_0 = \frac{Z \cdot d_{ij} \cdot \Delta F}{\Delta t} = \frac{Z \cdot d_{ij} \cdot k \cdot \Delta x}{\Delta t} \tag{11}$$

The ratio $\Delta x / \Delta t$ is interpreted as membrane velocity υ'_M after the impulse transfer. This leads to

$$U_0 = Z \cdot d_{ij} \cdot k \cdot \upsilon'_M \tag{12}$$

By assuming an inelastic momentum transfer, the following equation for impulse conservation apply:

$$m_p \cdot \upsilon_p + m_M \cdot \upsilon_M = m_p \cdot \upsilon'_p + m_M \cdot \upsilon'_M \tag{13}$$

where m_p is the mass of the impacting particles and m_M the mass of the transducer membrane. υ_p and υ_M are the particle respectively membrane velocity before the impaction on the transducer. υ'_p and υ'_M are the mentioned velocities after impaction.

With the assumption that the particle sticks to the membrane after the impulse transfer, the simplification of $\upsilon'_M = \upsilon'_p$ leads to:

$$m_p \cdot \upsilon_p + m_M \cdot \upsilon_M = \upsilon'_M (m_p \cdot + m_M) \tag{14}$$

Eq. 14 solved according to υ'_Mleads to:

$$\upsilon'_M = \frac{m_p \cdot \upsilon_p + m_M \cdot \upsilon_M}{m_p + m_M} \tag{15}$$

Assuming that $m_M \gg m_p$, the sum in the denominator simplifies to m_M. This leads to the following approximation:

$$\upsilon'_M = \frac{m_p \cdot \upsilon_p + m_M \cdot \upsilon_M}{m_M} \tag{16}$$

Since the piezo membrane is stationary before the momentum transfer, υ_M is zero and the equation is further simplified to

$$\upsilon'_M = \frac{m_p \cdot \upsilon_p}{m_M} \tag{17}$$

Inserting eq. 17 in eq. 12, results in

$$U_0 = Z \cdot d_{ij} \cdot k \cdot \frac{m_p \cdot \upsilon_p}{m_M} = Z \cdot d_{ij} \cdot m_p \cdot \upsilon_p \cdot \frac{k}{m_M} \tag{18}$$

The term $\frac{k}{m_M}$ is given by the resonance frequency f_{res} of the piezo transducer:

$$f_{res} = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{k}{m_M}} \text{ or } \frac{k}{m_M} = 4 \cdot \pi^2 \cdot f_{res}^2 \tag{19}$$

This leads to the final relationship between measured voltage maximum, particle mass and piezo transducer properties:

$$\underline{\underline{U_0 = 4 \cdot Z \cdot d_{ij} \cdot m_p \cdot \upsilon_p \cdot \pi^2 \cdot f_{res}^2}} \tag{20}$$

This calculation was performed for inelastic impaction, i.e. the particles stick to the impactor surface. However, if the particles bounce off the impactor surface, the momentum transfer is elastic. In this case the signal amplitude is a factor of two higher compared to the inelastic case, since the momentum transfer is twice as large.

It is remarkable that with the assumptions made, the maximum of the measured signal amplitude is directly proportional to the particle mass at a constant particle velocity.

VI. Experimental Characterization

First characterization experiments of a DustEar prototype setup were carried out in a laboratory fume hood with continuous air filtering and circulation to prevent the inhalation of aerosol particles. Well defined test particles were dispersed with a small scale powder disperser (TSI Model 3433) and connected to the analyzing instrumentation (see Fig. 4). To be

TABLE I
MONODISPERSE CALIBRATION DUST PARTICLES

Sample number	1	2	3	4	5	6	7
Description	CalDust 1100	CalDust 2000	Monodisperse Silica Microspheres			Spherical Micro Particles	
Manufacturer	Palas GmbH		Cospheric			Palas GmbH	
Geometric mean diameter	1.1 µm	2.5 µm	3.62 µm	4.08 µm	7.75 µm	10.3 µm	20.56 µm
Density	2'000 kg/m³		1'800 kg/m³			1'180 kg/m³	
Standard deviation	n.a.		0.18 µm	0.11 µm	0.29 µm	2.59 µm	4.56 µm
Material	Silicon dioxide (SiO_2)					PMMA	

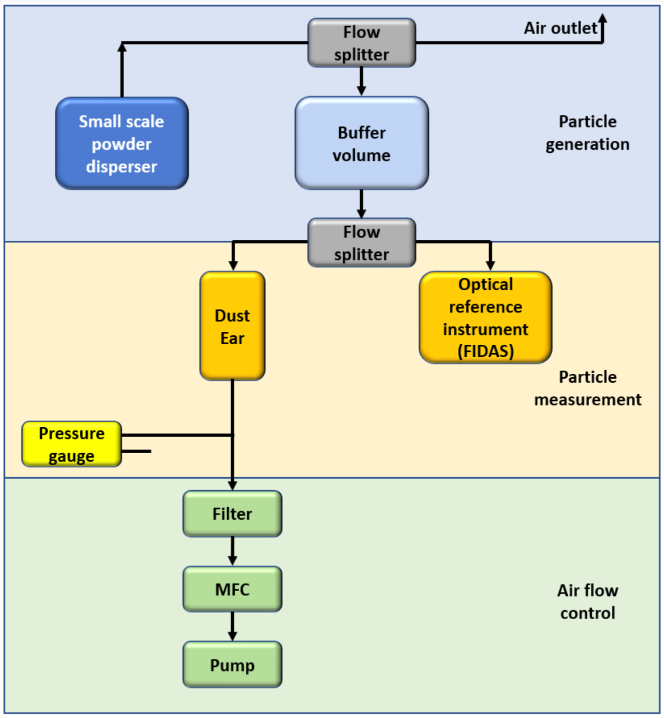

Fig. 4. Overall measurement setup with particle disperser, buffer volume, reference instrument and DustEar with external mass flow controller (MFC) and pump.

able to interpret the measured signals correctly, the characterization of the DustEar setup was done with test particles of a known size distribution and known density (see Table I). Knowing these two parameters, the real mass distribution of the measured particles was calculated. The particle size distribution was verified with a reference measurement with the Palas Fidas Dust Monitor System (Fidas 100) that measures particle number size distribution based on light scattering of individual particles. Because the test particles have a spherical shape and a known refractive index, the measured size distribution of the optical reference instrument allows a reliable crosscheck.

A fraction of the aerosolized particles (flow rate ca. 17 LPM) were first fed into a buffer volume (ca. 30 L) that allows stable conditions and minimizes rapid variations in the particle concentration (see Fig. 4). One part of this flow (4.8 LPM) was fed into the optical reference instrument Fidas 100. The other fraction of the buffer volume flow is drawn through the DustEar with an external pump (Rietschle CLFG 41) and a mass flow controller (red-y smart controller GSC) to allow defined impaction conditions. Here the flowrate was varied between 1 and 10 LPM, depending on nozzle diameter and investigated impactor parameters. By operating the reference instrument and the DustEar in parallel it can be ensured that time-dependent concentration changes do not influence the comparison. Care was taken to ensure that isokinetic conditions prevailed, i.e. there were no significant impaction losses at the flow splitters.

The critical DustEar impactor dimensions such as nozzle diameter, distance between nozzle and impaction plate as well as air flow rate were chosen according to Marple and Lui's recommendations for impactor design [26] and adapted to the setup used.

When designing the impactor, three important boundary conditions must be taken into account that influence each other:

- A low cutoff diameter d_{50} of the impactor that allows measurements of the intended size range
- A high particle velocity to obtain a high signal amplitude (low detection limit)
- A suitably guided and restricted air flow in the DustEar to avoid turbulence and minimize noise

We have performed various tests with different impactor designs and a range of piezo transducers with resonant frequencies between 7 kHz and 3 MHz. In the following we present the results which showed the best signal to noise ratio: a nozzle diameter of a few millimeters and an acceleration length of a few centimeters with an air flow of a few LPM. These parameters limit the upper aerodynamic particle diameter size that can be correctly detected to about 15 μm, because in this design larger particles are not accelerated to air velocity and will therefore be falsely identified as smaller particles. The cutoff diameter of this setup was around 1 μm, which corresponds to the current physical detection limit. The measured data were recorded with a piezo transducer with a resonance frequency of around 100 kHz.

A typical signal of recorded voltage U is illustrated in Fig. 5. It can be divided into a characteristic amplitude increase (red) and decrease (yellow) of the signal envelope. It is assumed that in our setup (metal plate with piezo transducer ring) the increase is caused by the energy transfer from a longitudinal to a radial oscillation. This effect was

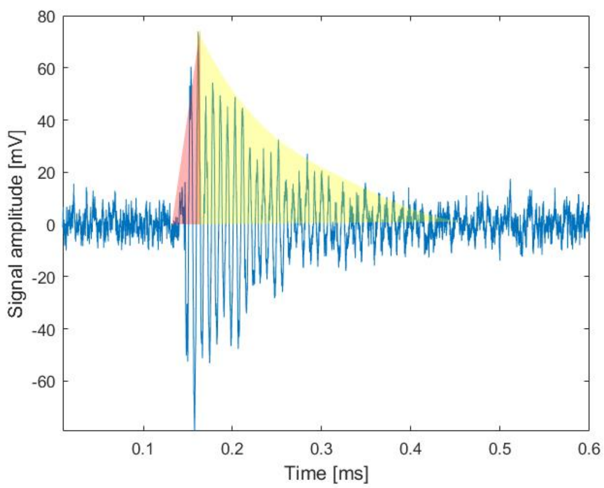

Fig. 5. Raw data of a typical signal pulse from a particle with an aerodynamic diameter of 11.19 μm. It is assumed that the amplification (red) of the signal envelope at the beginning can be interpreted as the transformation of the stored energy from a longitudinal to a radial oscillation. At the interface between the amplification and the exponential attenuation (yellow) of the signal envelope, all energy is stored in the radial oscillation and will then be attenuated over time.

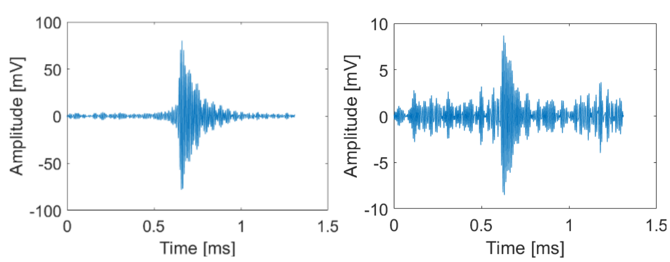

Fig. 6. Signal pulses (bandpass filtered) of particles with an aerodynamic diameter of 11.19 μm (left) and 5.47 μm (right). The signals show the same characteristic shape and the signal amplitude depends on the particle size, respectively, particle mass. Signal noise with an RMS value of a few mV defines the current lower detection limit.

not seen with other piezo transducers whose oscillation mode was directly excited by the particle impact. The decrease is caused by an exponential damping of the radial oscillation with the damping factor δ that was introduced in eq. 6. The used frequency in the ultrasonic range enables a good signal to noise ratio because there are fewer noise sources at ultrasonic frequencies. However, the piezo transducer is still sensitive enough to detect signal pulses from micrometer sized particles.

The signal of the piezo transducer is bandpass filtered with a passband in the range of the resonance frequency. The amplitude of the filtered signal is then evaluated.

VII. Results

Seven types of monodisperse calibration dust particles made of silicon dioxide (SiO_2) or polymethyl methacrylate (PMMA) were used for the proof-of-concept (see Table I).

In Fig. 6 two typical examples of signal pulses are shown. It is clearly seen that the signal amplitude depends strongly on the particle size. It is also evident that the signal pulses have the same characteristic shape, which simplifies the signal recognition in a following development step.

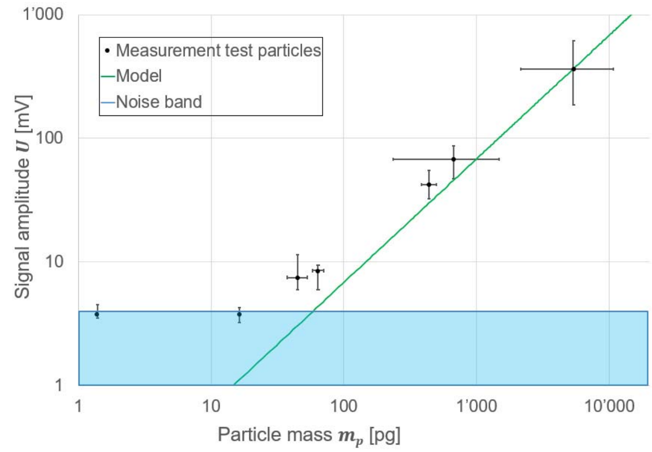

Fig. 7. Linear relationship between signal amplitude and particle mass, visualized as model (green) showing the best linear fit to the measured data (black). The noise band (blue) restricts the current detection limit to about 50 picogram which is mainly due to electronic noise.

Measurements with the final impactor settings, the chosen piezo transducer and the above-mentioned seven calibration dust particles showed a linear relationship between the particle mass and the signal amplitude, as predicted by theory, see eq. 20. The linear correlation is illustrated in Fig. 7: the measurements of the calibration dusts are plotted in black with error bars in the x-direction that represent the half width of the corresponding size distributions. The error bars in the y-direction represent the corresponding distributions of the measured signal amplitudes. The green line is the best linear fit of the measured data. The points are mainly above the fitted line because the fit is forced through the origin. The noise band (that is measured without particles) is marked as a blue area. It allows an estimation of the actual detection limit: with the setup used, individual particles with a mass down to about 50 picograms can be measured. This corresponds to an aerodynamic particle diameter of $\sim$5 μm. We found that the main source of the current noise is caused by the electronics and data acquisition and will be further improved in a next development step.

A first application for measuring aerosol size distributions of droplets was also demonstrated. A handheld nebulizer produced water droplets that were drawn in through the inlet of the DustEar. The measured signal peak values were transferred to a droplet mass distribution with the linear model of Fig. 7. With knowledge of the droplet density the number size distribution is derived, see. Fig. 8.

A complication in the current setup is that the velocity of the particles depends on their radial position in the impaction nozzle. This results in a measured distribution of peak voltages U_0 even if the particles are all monodisperse. To investigate the existing flow profile at the end of the impactor nozzle, CFD simulations with COMSOL Multiphysics® of the current impactor were done. Fig. 9 (left) shows the modeled particle velocity profile at the exit of the nozzle. There is too little residence time of the air in the nozzle to establish a parabolic velocity profile. However, the particles have no uniform velocity. To analyze the particle's velocity frequency distibution,

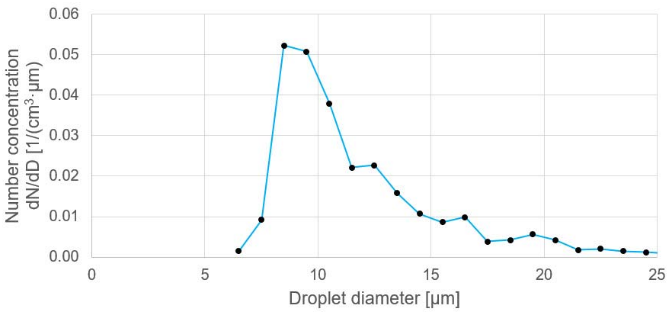

Fig. 8. Size distribution of nebulizer spray droplets, determined with DustEar setup by spraying towards the instrument's inlet.

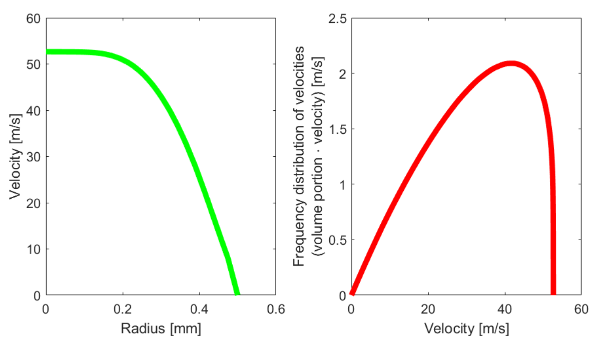

Fig. 9. Left: Velocity profile at the nozzle exit in the DustEar, showing that not all particles have the same velocity. Right: Resulting frequency distribution of particle velocities at the nozzle exit.

each area portion in the nozzle with the same air respectively particle velocity was multiplied with the corresponding velocity. The result is a particle velocity frequency distribution at the nozzle exit (Fig. 9, right). It can be seen that there is an accumulation towards higher velocities.

In a next step, DustEar measurements with test particles of Sample 5 in Table I (Fig. 10, bottom) were compared with the expected impulse transfer (Fig. 10, top). The latter was derived from the known mass distribution of the test particles and the modeled velocity profile of Fig. 9. It can be seen that the modeled and measured particle distributions of a monodisperse aerosol are similarly broadened. The modes of the size distributions match with the linear fit of Fig. 7.

Another effect that might be expected to cause a broadening of the signal distributions is that particles may not all impact on the centre of the piezo transducer respectively may not all impact perpendicular to the impactor. However, for the piezo transducer used, the CFD simulations show that the airflow has a nearly constant profile diameter until it hits the transducer surface. In addition, the nozzle diameter is relatively small compared to the sensitive piezo transducer area (see Fig. 11). This indicates that all particles impact perpendicular to the air stream on the sensitive transducer area.

VIII. Fields of Application

Since the presented technique can directly detect the momentum transfer and thus the mass of a particle, it is possible to collect further information about different types of coarse mode particles, which is useful in a wide context

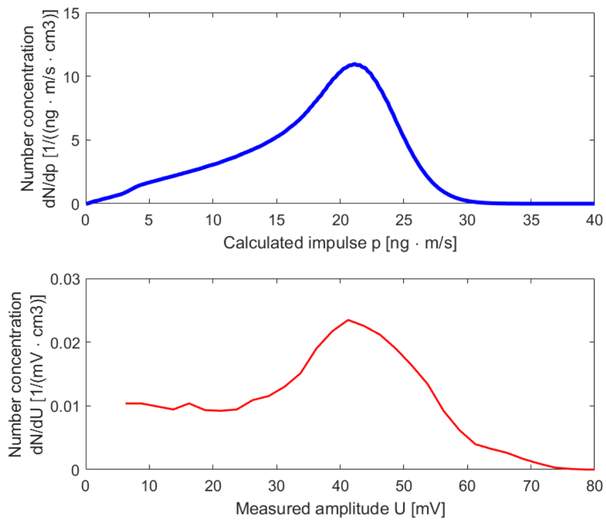

Fig. 10. Top: Calculated impulse distribution of the test particles of Sample 5 in Table I using the velocity profile of Fig. 9. Bottom: Corresponding measured signal distribution.

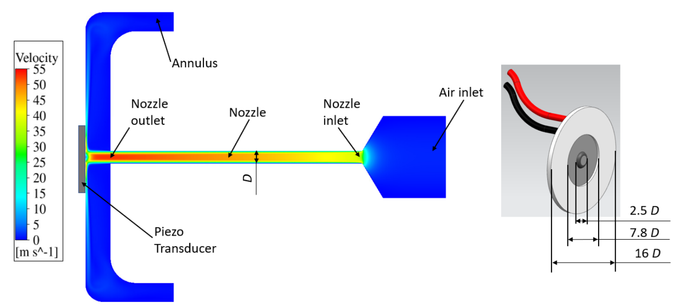

Fig. 11. Left: CFD Simulation of the velocity profile before, in and at the exit of the impactor nozzle with an inner diameter D = 1 mm. Right: Drawing of the piezo transducer showing that the sensitive surface area (grey) is much larger than the flow profile diameter.

of different application areas. As a concrete example, the DustEar can be used in a measurement setup to detect the mass of pollen or volcanic ash but also to characterize fog, ice crystals or nebulizing systems. Fig. 8 shows the potential for robust measurements of liquid aerosols and droplets. Furthermore, it can give information about coarse mode particles in industrial processes such as powder coating, bulk material processing or toner handling. In addition, the DustEar setup can be used for quality control of drug processing or to assess air quality in clean rooms. It can also be integrated into a testing setup for coarse dust filters or protective masks by employing a DustEar before and after the filter in a bypass of the main volume flow. Finally, it can be used to investigate questions concerning the bouncing properties of coarse mode particles. This can be realized with two DustEars connected in series, where the fraction of particles bouncing off the piezo transducers is determined by comparing the two DustEar readings. This can be of interest for airbrushing applications to know if the paint in a setting has already dried by the time the spray hits the surface. Another application is related to the study of mixed-phase clouds in which supercooled cloud droplets (sticky) and ice crystals (bouncy) are present [27].

In general, DustEar can be used for source apportionment studies due to the size-resolved data. If the detection limit can be lowered to 300 nm, there are multiple interesting fields of application ranging from a long-term PM10-monitoring sensor to a reference standard in metrological applications, to a reference device for low-cost optical PM sensors and to stand-alone lab instruments that may combine the acoustic detection method with existing characterizing techniques (e.g. optical methods).

IX. Challenges

As mentioned at the end of the previous section, multiple interesting applications require a lower detection limit of 300 nm in particle diameter. Compared to the existing prototype, this means an improvement of the lower detection limit by a factor of 10 in terms of diameter is required. This translates to a factor of 1000 in terms of particle mass or signal amplitude. To achieve this level of sensitivity, several challenges have to be overcome, which are being investigated in a current project. One challenge is the impaction of submicrometer particles (lowering d_{50}) as they follow the streamlines in the actual impactor setup (see Fig. 2). To overcome this problem, a low-pressure impactor setup is currently being investigated, where the particle impaction takes place in low vacuum. This ensures a lower cutoff diameter due to the increase in air and thus particle velocity caused by the reduction in air density and flow turbulence. This enables an increase of the particle impact on the transducer respectively of the signal pulse amplitudes for a given particle mass. In addition, other transducers optimized for the detection of particle impact signals and for use in low vacuum are being tested. Furthermore, the transducer needs to be robust enough against sensor vibrations and environmental noise. An optimized electronic design as well as data acquisition and processing enlarges the signal to noise ratio, e.g. with optimized filtering algorithms, pattern matching or optimized electronic components. When interpreting the signal amplitude, it must be taken into account that elastic and inelastic impulse transfer differ in signal amplitude by a factor of two. This makes a correct interpretation of the actual particle mass difficult. However, it must be stated that mainly larger, micrometer-sized particles are expected to bounce off, as the smaller particles stick due to Van-der-Waals forces. To avoid such systematic errors, particles must be prevented from bouncing off the surface, e.g. by applying vacuum grease to the impactor plate.

In the present prototype, the particle distributions of a monodisperse aerosol exhibit a significant broadening. To allow a correct particle mass assignment, a uniform velocity profile is needed. This will be investigated in a next prototype by using another nozzle design. The alternative is to use an inversion algorithm to reconstruct the correct particle mass distribution out of the signal amplitude histogram.

In addition, there are several challenges that will arise in the future for the application of the prototype as a commercialized product. The sensor needs to be portable and low-cost, which places high demands on the pump. In particular, pulsations must be avoided, as these can lead to misinterpretation of the piezo transducer signal. Furthermore, the DustEar sensor must be designed for long-term measurements in harsh environments. There the challenge of cleaning the transducer arises.

Finally, if the detection limit is lowered to 300 nm, it needs to be considered that the particle concentration for submicron particles in the environment is much higher than for the coarse mode particles. Therefore, coincidence problems have to be overcome. In the current measurement setup, the signal envelope length is approximately 0.5 ms. If we assume a maximum particle frequency of one particle per ms to avoid coincidence, a maximum particle concentration of 40 cm^{-3} can be detected with the current air volume flow. However, there are coincidence corrections that can be used to separate the signals.

X. Further Investigations

We are in the process of improving the current setup: minimizing the detection limit to particle diameters of 300 nanometers should extend the measuring range to the fine particles and allow a representative determination of PM10 concentrations (see Fig. 1). Then the DustEar setup can be employed in air quality monitoring stations, as it provides a reference measurement to ensure that PM10 limit values are met. These values are defined as a mass concentration that can be directly measured with the DustEar. PM10 includes the health relevant particle fraction that can penetrate deep into the human body and lead to serious diseases or organ damage as explained in the Introduction.

At the moment, the following main investigations will be carried out: optimization of the soft- and hardware structure and a redesign of the impactor as explained in Chapter IX. These improvements are focused on enabling long-term measurements and a direct characterization of the mass of single particles with diameters down to some hundreds of nanometers.

As a future step, a miniaturization of the setup can be considered, e.g. by using piezo MEMS ultrasonic transducers. Furthermore, it can be investigated whether there is a possibility to characterize not only the mass, but also the latent heat transfer during the impaction on the piezo element by taking advantage of the pyroelectric effect of the transducer. Such heat transfer is released during phase changes of the particles (crystallization or evaporation). This may allow to distinguish e.g. ice crystals from (supercooled) droplets.

XI. Conclusion

A new, robust and cost-effective method was investigated to characterize the mass of single aerosol particles directly and in-situ. A measurement setup as well as data analysis and calculations were reviewed. The combination of theoretical and practical approaches allows an evaluation of the potential of this new measurement technique.

A detection limit was achieved that corresponds to a particle mass of around 50 pg respectively an aerodynamic particle diameter of $\sim 5\ \mu m$. The advantage of this technique is that the determined particle mass is independent of assumptions on the particle shape and density.

In addition, the particle mass is measured in-situ and is not affected by evaporation or condensation artefacts as long as the sampling line of the DustEar is not changing the chemical composition of the measured aerosol. This allows to measure volatile particles correctly. We have found that DustEar can also be used to measure micrometer-sized droplets which offers the possibility to use it as a simple tool for a fog monitor.

DustEar is expected to be more cost-effective than the existing filter-based techniques. Furthermore, it can serve as an alternative or reference instrumentation for optical low-cost devices. The operation principle of DustEar allows a direct measurement of the mass of single particles and mass-resolved particle characterization provided that particles are accelerated to a uniform velocity profile. This is an advantage as particle mass is of interest e.g. due to regulatory concentration limitations. Furthermore, DustEar is immune to artefacts experienced by filter-based sensors, which suffer from systematic errors due to evaporation or condensation of semi-volatile gases on the filter. This property is essential for the comparability of spatially and temporally distributed data.

A necessary condition for a traceable measurement is a uniform velocity profile that is investigated in a next step.

In conclusion, DustEar combines the advantages of the state-of-the-art measurement methods in a simple, robust setup. Thus, as a comparable reference device that allows reliable long-term measurements it can open the field for a denser PM monitoring network.

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