Acoustic measuring techniques for suspended sediment

P Gruber1, D Felix2, G Storti3, M Lattuada4, P Fleckenstein3 and F Deschwanden1

1 Competence Center for Fluid Mechanics and Hydro Machines (CC FMHM), Hochschule Luzern (HSLU), Technikumstrasse 21, CH-6048 Horw, Switzerland
2 Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zürich, Hönggerberg-ring 26, CH-8093 Zurich, Switzerland
3 Institute for Chemical and Bioengineering, ETH Zürich, Vladimir Prelog Weg 1-5/10, CH-8093 Zurich, Switzerland
4 Adolphe Merkle Institute - Nanoparticles Self-Assembly, Université de Fribourg, Chemin des Verdiers 4, CH-1700 Fribourg, Switzerland; formerly at ETH Zürich

Abstract. Acoustic signals can be used in various ways for suspended sediment monitoring. One possibility which lends itself particularly well in the context of hydropower plants (HPPs), is to use installations for acoustic discharge measurement (ADM). Such installations already exist at waterways of many HPPs. Similar to certain turbidimeters, the attenuation of the forward scattered signal travelling through the water-sediment mixture is correlated with suspended sediment concentration (SSC). This correlation can be based on reference SSCs, e.g. from gravimetric analyses of bottle samples. Without the need of additional sensors and practically maintenance-free, this method is used successfully in the HPP Fieschertal to warn the HPP operator of high SSC to prevent excessive turbine abrasion.

Acoustic methods and systems that allow for estimating both SSC and particle size distribution (PSD) are under development. The simultaneous determination of SSC and PSD is not possible using a single frequency. Therefore, multi-frequency approaches are investigated for generally scattered signals. When backscattered signals are used, a stronger frequency dependency can be exploited. However, the reliable simultaneous determination of particle size (and distribution) and concentration is still a major challenge due to a low signal-to-noise ratio and an ill-posed problem of estimating concentration and size from recorded signals. The optimal setup configuration (angles, frequencies) for such a system is not unique and further investigations are recommended.

1. Introduction

In various high- and medium head hydropower plants (HPP) worldwide, e.g. in the Alps, the Andes and the Himalayas, fine sediment particles (silt and fine sand) contained in the water poses at least temporarily a problem in terms of damaging turbines and other equipment due to abrasion. Typically, the mass concentration of suspended solids (SSC) covers a wide range, from less than 0.1 g/l to 10 g/l or occasionally even 100 g/l. To prevent excessive damage it is recommendable to close intakes and to shut down the turbines if SSC is higher than typically 1 to 10 g/l, depending on the HPP. Abrasion depends not only on the SSC but also on the particle size distribution (PSD). Therefore there is an interest to monitor both SSC and PSD continuously and in real-time.

SSC and PSD of sediment particles in water can be measured in many ways. [1] gives a good survey of various methods with their advantages and disadvantages.

---

[1] Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Published under licence by IOP Publishing Ltd
In the laboratory, SSC can be determined by weighing of the water-sediment samples and the dried residues after filtration or evaporation of the water from water samples. This gravimetrical method is still the reference. PSD can be measured in the laboratory by sieving (typically above 40 µm), sedimentation methods (hydrometer), laser diffraction and analysis of microscope images. However, no continuous real-time measurements are obtained from laboratory analyses.

For on-line SSC monitoring, two techniques are widely used: optical backscatter and optical transmission. The outputs of such turbidity meters (e.g. in Formazine Nephelometric Units FNU) need to be converted to SSC which depends unfortunately on particle size, shape and color. For on-line SSC and detailed PSD monitoring, Laser In-Situ Scattering and Transmissometry (LISST) devices have become available [2]. Felix reports on the application of a number of the mentioned and other methods for online SSC and PSD monitoring [3], [4].

In two-phase suspension systems like silt-water mixtures, ultrasonic signal characteristics can also be used to obtain information about SSC and PSD. The advantages of the acoustic methods are: non-intrusive and rapid on-line measurements even under optically opaque conditions. On the other hand, air bubbles may strongly affect the measurements.

Acoustic techniques use the backscatter or forward scatter of pulsed acoustic bursts. Forward scattering can be exploited in installations for acoustic discharge measurement (ADM) based on the acoustic transit time (ATT) method. Such installations exist in many HPPs and can also be used – after a calibration – to estimate SSC or PSD, but not both [5].

In acoustic backscattering techniques, the intensity of the backscattered signal also depends on SSC, PSD and frequency. By using multiple frequencies (often with acoustic Doppler current profilers) basically both SSC and information about the PSD can be determined with little calibration [6], [7], [8], [9], [10]. Most backscattering applications are reported from open waters like rivers, channels, lakes or seas. Problems still exist with the accuracy and repeatability of simultaneous SSC and PSD measurements.

The present paper deals with acoustic measuring techniques for SSC and PSD. First, physical models on the interaction of acoustic signals with solid particles in water which are suited for suspended sediment monitoring are described. A selection of models is presented, one for forward scattering and one for general scattering. Then SSC monitoring exploiting the attenuation of forward scattered signals as can be measured with ADM installations is presented. A comparison between the model prediction and measurements from a field study at HPP Fieschertal is shown and discussed. In a final section the opportunities for a simultaneous estimation of SSC and PSD by acoustic methods are presented.

2. Physical background

2.1. Overview on wavelength regimes and models

The scatter of acoustic signals at individual particles in motion is widely known and described in literature [11], [12]. Theoretical models for determining the wave propagation speed and the attenuation of the sound wave as a function of particle concentration and size are derived from the interaction of the incoming sound wave with the particles (forward and backward scattering, absorption).

These models can be simplified by classification of different wavelength regimes dependent on the particle size (particle radius $a$) and the wavelength $\lambda$ of the incoming sound wave. In figure 1 the boundaries of the three regimes are displayed in double logarithmic scales. In ADM applications the frequency lies for ATT installations typically between 200 kHz and 2 MHz and the particles’ radius between 0.5 µm and 500 µm. This means that the models for the long wavelength regime (LWR) are applicable for most of the cases in the described context. In the LWR regime, visco-inertial and thermal effects dominate while in the SWR regime the scattering effect is dominant. In the intermediate IWR regime, all effects play a role and the most complex models must be applied.
Models for only spherical particles were considered. There are two groups of models: The first group includes models based on the two-phase approach, such as the one developed by Atkinson and Kytömaa (AK) [13]. This model provides accurate relationships for the attenuation and the sound speed in a suspension, if the particles are not large compared to the sound wavelengths (LWR). However, it cannot be used to describe backscattering since the propagation and attenuation of sound waves is considered only in the forward direction. A similar model by Urick treats only the attenuation of the forward scattered wave but in a larger particle range [14].

The second group of models considers the scattering behavior of individual particles by solving the equation of wave propagation inside and outside the particles. They can cover single scattering as well as multiple scattering (which is extremely challenging). This group of models includes those developed by Faran [15], Epstein-Carhart-Allegra-Hawley [16] (ECAH), Allegra and Hawley [17] and Hay and Mercer (HM) [18]. The advantage of these models is the accurate description of the scattering behavior of particles combined with the possibility to include elastic, viscous and thermal effects simultaneously. The three models differ only in the underlying approximations and will be discussed in more detail.

2.2. Attenuation and far field function

The Atkinson-Kytömaa (AK) model was chosen out of the first group as the appropriate model for the visco-inertial effects [5], [19]. From the second group, the Faran model was chosen for the scattering effects [20]. Both models can be combined to model both effects. The more complicated models like ECAH and HM cover a greater range and take into account all major physical effects of acoustic wave interaction with a single spherical particle. The number of required model parameters however is very high for these models and not adequate for monitoring applications.

In the present application, the effect of the particles on the sound speed in the suspension is not exploited. The main quantities of interest are the attenuation and the far field function. The attenuation can be modelled for all physical effects while the far field function $|F_\infty|$ exists only in the models of the second group. In the range of interest, the far field function is similar for all examined models. Therefore, the model with the lowest complexity, i.e. Faran was chosen. For the application in connection with ADM installations, only the attenuation is of interest. For small values of $2\pi a/\lambda$, the Faran model underestimates strongly the attenuation while for large values of $2\pi a/\lambda$, the AK-
model is underestimating the attenuation. In the present application, the long wavelength regime corresponding to small values of \(2\pi \cdot a/\lambda\) is relevant. Thus the AK-model is used for the attenuation.

2.3. Attenuation and excess attenuation

The absorption of a plane acoustic wave in a two phase liquid–solid suspension is composed of three terms: the attenuation in water \(\alpha_l\), the attenuation of particles \(\alpha_s\) and the attenuation due to the water-particle interaction, the so called excess attenuation \(\alpha_{ex}\):\[
\alpha = \varphi \alpha_s + (1 - \varphi) \alpha_l + \alpha_{ex}
\]
with \(\varphi\)=volume fraction of particle concentration [-] \(\alpha\) (1)

As \(\varphi\) is usually small in the described application, equation (1) is approximated by \(\alpha = \alpha_l + \alpha_{ex}\).

The acoustic signal emitted from the sensor propagates spherically and is reduced with increasing distance \(x\) from the transducer. As this is a pressure transducer, the amplitude \(A\) of the acoustic pulse in the far field is proportional to the acoustic pressure. \(\alpha\) is normally expressed in Neper/m (Np/m) or dB/m (1 Np = 8.686 dB):

\[
A = \frac{K_T}{x} e^{-\alpha x} = \frac{K_T}{x} e^{-\alpha_s x} e^{-\alpha_l x} \quad \varphi << 1 \quad \text{with} \quad K_T = \text{sensor constant} \quad (2)
\]

\(\alpha\) depends very strongly on the frequency \(f\). The attenuation increases basically with \(\sim f^2\) for \(\varphi < 0.05\) (corresponding to SSC < 125 g/l) and the particle size range of interest in the described application. The dependency of the attenuation on the particle diameter is complicated. Comparisons have been done [21] between Urick’s and the AK-model. The agreement in the low diameter range is good, while for diameters larger than 100 µm the AK-model is no more valid and underestimates the attenuation (figure 2a). Urick’s and the AK model show for small particle diameter (< 1 µm) an attenuation increase with \(\sim d^2\) and for medium size particles (1 µm < d < 100 µm) an attenuation decrease proportional to \(\sim 1/d\), while for larger particles the attenuation increases with \(\sim d^3\) according to Urick’s model. In the range of interest for the described application, the excess attenuation is practically proportional to SSC (figure 2b) and approximately proportional to \(\sim 1/d\) as mentioned above.

![Figure 2. Excess attenuation \(\alpha_{ex}\) for mineral particles (\(\rho_s = 2500 \text{ kg} / \text{m}^3, \ c_s = 5000 \text{ m/s}\)) at 1 MHz; a) for SSC = 20 g/l as function of particle diameter, b) as a function of SSC for various particle diameters (the smallest diameter d = 5 µm corresponds to the line with the steepest slope and vice versa).](image-url)
Natural suspended sediment particles do not have a single size, i.e. they are not mono-disperse. For graded particles, it is not obvious to calculate the excess attenuation from the PSD. The naïve way of calculating a volume- or mass-averaged particle size and then using this diameter in a mono-disperse model is not accurate enough. For $\text{SSC} \leq 50$ g/l as in this application, the following approach was used: For each diameter class of the PSD the excess attenuation is computed and added to obtain the excess attenuation of the particles of all sizes. Then, an equivalent average diameter is determined which leads to the same attenuation. This equivalent average diameter can then be used in mono-disperse models (AK, Urick).

2.4. Inferring SSC or average particle size from excess attenuation

The main problem when exploiting the forward scattering for sediment monitoring is that there exists an infinite number of combinations of SSC and particle diameter leading to the same excess attenuation (figure 3a). This means that the inverse problem does not have a unique solution. SSC can be calculated if the particle size is known, or the size can be calculated if SSC is known. Figure 3b shows the considerable influence of the actual particle diameter on the SSC if SSC is inferred from a measured excess attenuation and an assumed reference size. If the actual diameter is smaller than the reference, the SSC estimate is too high, and vice versa. The deviation of SSC is proportional to $d_{ref}/d$.

![Figure 3](image)

**Figure 3.** a) Pairs of particle diameter and SSC leading to the same excess attenuation (the highest value of $\alpha_{ex}$ corresponds to the line with the steepest slope and vice versa). b) Over- or under-estimation of SSC if the particle diameter differs from the assumed reference diameter; both diagrams calculated with the AK-model.

3. SSC Monitoring based on ADM installations

3.1. Acoustic discharge measurement

The multipath acoustic discharge measurement (ADM) based on the acoustic transit time (ATT) method is a well-established method for accurate discharge measurement especially in large conduits and channels. On each path between two transducers, the transit times of acoustic signals travelling in both directions are determined, from which the averaged axial path velocities are calculated. The discharge, i.e. the volumetric flow rate is calculated by integrating the path velocities over the area of the cross section.

The method allows to measure at a high temporal resolution not only the flow velocities of each path but also the sound speed $c$ and the attenuation $\alpha$ of the acoustic pulses at all paths easily. The sent
acoustic signal is characterized basically by its frequency, power (amplitude) and duration. The duration can be parameterized by the number of bursts. Normally ADM systems operate with a single frequency, typically at 500 kHz or 1 MHz. Beside the sound speed \( c \) and the attenuation \( \alpha \), the signal shape and the frequency content can also be analysed.

3.2. AK-model for SSC monitoring or field calibration

Figure 4a shows the principle way how the AK-model can be used for SSC monitoring. For given particle parameters (mainly diameter, shape and density as well as sound speed) an SSC can be obtained from the measured excess attenuation, as described in section 2.4. Information on particle size, shape and density can be obtained from laboratory analyses of bottle samples.

Another way besides the inverse use of the AK-model is to work with a field calibration: A relation between the attenuation and SSC is established by comparing gravimetrically determined SSCs and measured attenuations at corresponding times (figure 4b). This involves also some effort because bottle samples have to be collected and analyzed in the laboratory, but is relatively simple and includes all effects (e.g. also of non-spherical particle shapes which are difficult to parametrize).

![Figure 4. a) Application of the AK-model for SSC monitoring: The measured attenuation \( \alpha_{ex} \) is post-processed in an inverse AK-model with assumed particle properties to obtain SSC. b) Damping of the acoustic signal \( \delta \) (from single-frequency forward scatter method) as a function of the gravimetrically determined reference SSCs (SSC_G, below 4 g/l), measured in the waterway of the HPP Fieschertal in 2013, with a linear fit.](image)

3.3. Field study: Setup and Methods

In an interdisciplinary research project on hydro-abrasive erosion on turbines of HPPs, SSC and PSD in the waterway of HPP Fieschertal in Valais, Switzerland, have been measured and analyzed since 2012 [13]. The water used in this HPP originates from a highly glaciated catchment and is known for relatively high SSC (approx. 0.5 g/l on average, 5 g/l exceeded several times a year). Among other measuring techniques, the method of acoustic single-frequency attenuation based on an ADM installation as described in section 3.1 has been employed [4] [Felix et al. 2016]. A standard 4-path ADM installation with two measurement planes has already been existing at the top of the penstock (inner diameter 1.95 m). The path length is 2.27 m and the frequency of the signals is 1 MHz. The only modification which was required to use the existing ADM installation (Risonic from Rittmeyer) also for sediment monitoring was to define the amplitudes of the received signals at the four paths as additional outputs and to feed them in the data acquisition system.

For this ADM installation, equation (2) can be rewritten for a fixed distance of \( x = 2.27 \) m as follows:

\[
A = K_x \cdot 2.27 \ m \ e^{-\delta} \quad \text{where} \quad K_x = \frac{K_x}{2.27 \ m} e^{-\alpha_{ex} 2.27 \ m} \quad \text{and} \quad \delta = \alpha_{ex} \cdot 2.27 \ m \quad (3)
\]
The damping $\delta$ is a dimensionless quantity. Equation (3) for $A$ was applied to two cases: first with clear water ($A_0, \delta = 0$) and then with an actual SSC and thus $\delta > 0$. The ratio of the amplitudes in the two cases is:

$$\frac{A}{A_0} = \frac{K_{x=2.72 m} e^{-\delta}}{K_{x=2.72 m} 1} = e^{-\delta}$$

(4)

A linearization of the exponential function (for $\delta \ll 1$) yields:

$$\frac{A}{A_0} \approx 1 - \delta \quad \delta \approx 1 - \frac{A}{A_0}$$

(5)

The amplitudes of the signals were measured in Volts. The damping $\delta$ varies between 0 (clear water) to 1 (the sent signal does not reach the receiver on the other side of the acoustic path).

The value of $A_0$ was calculated from the recorded amplitude of the received signals in clear water conditions for each path. From the time series of the measured amplitudes $A$, the damping $\delta$ was calculated according to equation (5) for each path. Then the time series of plausible $\delta$ obtained from the various paths were averaged and filtered to reduce noise. The damping was correlated with gravimetrically determined reference SSCs from bottle samples (figure 4b). Reference SSCs were obtained from the weight of samples before and after evaporation of the water (no filtration) and by deducting the concentration of dissolved minerals (<0.08 g/l). For SSC below 4 g/l, a linear relation was obtained as predicted by the AK-model (figure 2b). The linear relation was applied to convert the time series of $\delta$ to SSC. For comparison, SSC was also determined from density measurements using a Coriolis Flow and Density Meter (CFDM) installed on a sampling pipe close to the ADM [4]. In addition, PSDs were measured using LISST.

### 3.4 Field study: Results and Discussion

Normally, the particles in the water were relatively fine, i.e. $d_{50} \approx 15 \mu m$ (mainly medium silt). The $d_{50}$ denotes the particle size which is not exceeded by 50% of the particle mass (median particle size). Coarser particles up to $d_{50} = 100 \mu m$ were present at higher SSCs of e.g. 10 g/l. However, high SSCs were not always associated with larger particles, also due to different reasons for high SSCs (flood vs. resuspension events).

The SSCs from the acoustic method corresponded generally well with the SSCs from gravimetry and CFDM (figure 5b). However, in periods with higher SSCs, the SSC from the acoustic method was considerably lower than the references. These temporary deviations are mainly attributed to the effect of particle size variations (figure 5a) on the acoustic damping as predicted by the AK-model. The applied conversion of $\delta$ to SSC (figure 4b) is mainly based on the usually prevailing small particles in the SSC range below 4 g/l and does not reflect the situations with temporarily coarser particles at higher SSCs. In the example of figures 5a and 5b, $d_{50}$ measured by LISST increased in two events from 15 to 40 or 55 $\mu m$, respectively, leading to underestimations of the SSC from the acoustic method by a factor of 2 to 3.5. Because the correlation between SSC and $d_{50}$ is quite weak at this study site, it is not possible to find a conversion from $\delta$ to SSC which would always yield unbiased SSCs. In situations with a higher degree of correlation between SSC and $d_{50}$, a non-linear conversion from $\delta$ to SSC could be applied compensating the undesired effects of $d_{50}$-variations on SSC.

Another reason for the underestimation of higher SSC with the acoustic method is the behaviour of the measuring system. While the relation between $\delta$ and SSC for a given particle type is approximately linear up to some g/l, it is nonlinear at higher SSC and approaches a saturation (figure 5b).

During a major flood event with an estimated return period of 20 years, high SSCs of up to 50 g/l occurred in the penstock of HPP Fieschertal [4]. The high SSC during the flood was also calculated using the pressure method (the CFDM has not yet been installed in 2012). In the pressure method, the effect of suspended sediment on the mixture density and on the pressure measured at the downstream end of the penstock is exploited [4]. The value of the peak SSC of 50 g/l was verified by some bottle
samples and Imhoff cone measurements during the event. Based on the data recorded during the event, the measuring performance of various devices for suspended sediment monitoring at high SSC was studied.

The upper limit of the typical measuring range of turbidity meters, i.e. 4000 FNU, indicated in figure 5b, was exceeded during several hours. However, a special type of turbidity meter (Optek TF16-N with flow cell F20), allowed measuring the turbidity during the whole event (figure 5b). This device measures NIR attenuation over an optical path of only 10 mm; turbidity is expressed in terms of concentration units CU. The time series of the acoustic damping is also shown in figure 5b. The scaling of the vertical axes was adjusted to facilitate a visual comparison. The acoustic damping during this event corresponded generally well to the turbidity, except for very high damping of $\delta > 0.95$, when the strength of the received signal tended to 0 ($\delta = 1$). In this event, the upper limit of the SSC measuring range of the acoustic system was between 15 and 20 g/l. This limit is not generally valid, since it depends on the particle properties, the power and the frequency of the sent acoustic signal, as well as the path length; as described by the AK-model.

**Figure 5. a)** Time series of the median particle size $d_{50}$ and **b)** corresponding SSC time series from the acoustic method (single-frequency forward scatter), from CFDM and from gravimetric analysis of bottle samples, measured in the waterway of the HPP Fieschertal during four summer days. **c)** Time series of acoustic attenuation and turbidity measured at the same location during the major flood event in 2012 (modified from [22]).

### 4. Monitoring of SSC and PSD

Acoustic methods and systems which allow for estimating both SSC and PSD are under development and start becoming to be available commercially. The simultaneous determination of SSC and PSD is not possible using a single frequency. Therefore, multi-frequency approaches are investigated for generally scattered signals. When backscattered signals are used, a stronger frequency dependency can be exploited [6], [8], [7], [10], [9], [23]. However, the reliable simultaneous determination of particle size (and distribution) and concentration from generally backscattered signals, i.e. solving the inverse problem based on measurements, is a major challenge. For monitoring purposes, an accuracy of ±20 % for SSC and $d_{50}$ would be sufficient. To the authors’ knowledge, this goal has been achieved so far only for specific cases. The main problems are:

- the low signal-to-noise ratio requiring intensive averaging of the signals,
- the inversion problem is ill-posed, this means that a unique determination of SSC and PSD is difficult even under ideal conditions (no noise),
- the values of at least three parameters are to be determined simultaneously (SSC, $d_{50}$ and a parameter for e.g. the width of the PSD).

The ill-posedness of the inversion problem can be reduced by finding
• an optimal set of sensors (frequency, bandwidth),
• an optimal installation configuration (angles, forward/backward combinations of sensors),
• a robust mathematical inversion and optimization method.

5. Conclusions
In the Fieschertal field study it was confirmed that the single-frequency acoustic method based on the acoustic discharge measurement (ADM) installation allows to measure SSC up to 15 g/l of mainly medium silt. The correlation between the attenuation of the acoustic signals and the SSC was established based on gravimetrical analysis of bottle samples. The attenuation of the forward scattered signals predicted by the AK-model was confirmed by the measurements. At low SSC, say below 0.5 g/l of silt, the signal-to-noise ratio is low requiring filtering and averaging of measurements, and optical methods may be more suitable. Above approx. 0.5 g/l of medium silt, the performance of the acoustic method is similar to widely used turbidity meters. The upper limit of the SSC measuring range of the acoustic method with the described setup is higher than the one of widely used turbidity meters. This acoustic method offers the advantage that no additional sensors are required in HPPs having similar ADM installations, the measurements are spatially well averaged (over the path length and optionally over several paths) and refer to the sediment-laden water directly in the waterway. Like this, there is no need for sampling pipe installations which require maintenance and may be prone to clogging or to potentially non-representative sampling. The field test confirmed that practically no maintenance is required, since acoustic systems are less sensitive to fouling than optical ones. Similarly to turbidity meters, the SSC obtained from this single-frequency acoustic attenuation method is biased by PSD variations if these are not correlated to SSC. Thus, the SSC measuring uncertainty is higher if the particle sizes are not well correlated to SSC.

The Faran model has been presented which allows to predict the backscattered signals in terms of SSC and PSD. Main output quantities of this model are the far field function and the attenuation. As the Faran model and the AK-model describe different physical effects for different application ranges, a combination of the two models is proposed. The simultaneous determination of SSC and PSD from measurements of forward- and backscattered acoustic signals at several frequencies remains a field for improvements.

Acknowledgements
The support of the Fieschertal field study by swisselectric research, the Swiss Federal Office of Energy (SFOE) and the HPP operator Gommerkraftwerke AG are gratefully acknowledged. Thanks go to Endress+Hauser, Sigrist Photometers and Rittmeyer for lending measuring equipment. Furthermore, the support by the Swiss Commission for technology and Innovation CTI in the two projects “Nr. 7947.2: Empfindlichkeit der akustischen Durchflussmessung auf Verschmutzung (Sensitivity of ADM to suspended sediment)” and “Nr. 13223.1 PFFLR-IW: Evaluation of forward and backward scattered acoustic signals to determine the flow and the particle, respectively bubble concentration in water”, as well as the contributions of all project partners are acknowledged.

References
[1] Wren D, Barkdoll B, Kuhnle R and Derrow R 2000. Field Techniques for Suspended-Sediment Measurement, J. of Hydraulic Eng. 126(2): 97–104
[2] Agrawal Y C and Pottsmith H C 2000. Instruments for Particle Size and Settling Velocity Observations in Sediment Transport, Marine Geology 168: 89-114
[3] Felix D, Albayrak I, Boes R M, Abgottspon A, Deschwanden F and Gruber P 2013. Measuring Suspended Sediment: Results of the first Year of the Case Study at HPP Fieschertal in the Swiss Alps, Proc. Hydro 2013, Innsbruck, Austria, paper no 18.03
[4] Felix D, Albayrak I, Abgottspon A and Boes R M 2016. Real-time measurements of suspended sediment concentration and particle size using five techniques. Proc. 28th IAHR Symposium
on Hydraulic Machinery and Systems, Grenoble, IOP Conf. Series

[5] Costa L I, Storti G, Lüscher B, Gruber P and Staubli T 2012. Influence of solid particle parameters on the sound speed and attenuation of pulses in ADM, J. of Hydrologic Eng. 17(10): 1084-1093

[6] Thorne P D and Hanes D M 2002. A review of acoustic measurement of small-scale sediment processes, Continental Shelf Research, 22(4): 603-632

[7] Skripalle J, Hies T, Liu Y and Nguyen H H 2012. Application of multifrequency acoustics to estimate concentration of suspended sediments from Jurong lake Singapore, Proc. 17th Intl. Seminar on Hydropower Plants, Bauer C and Doujak E (eds.), Vienna, Austria: 725-737

[8] Moore S A 2012. Monitoring flow and fluxes of suspended sediment in rivers using side-looking acoustic Doppler current profilers, PhD thesis, University of Grenoble, France

[9] Thorne P D and Hurther D 2014. An overview on the use of backscattered sound for measuring suspended particle size and concentration profiles in non-cohesive inorganic sediment transport studies, Continental Shelf Research, 73: 97–118

[10] Jourdin F, Tessier C, Le Hir P, Verney R, Lunven M, Loyer S, Lusven A, Filipot J F and Lepesqueur J 2014. Dual-frequency ADCPs measuring turbidity, Geo-Marine Letters 34(4): 381–397

[11] Dukhin A S and Goetz P J 2002. Ultrasound for characterizing colloids: Particle sizing, zeta potential, rheology, Elsevier, Boston

[12] Rossing T D 2007. Handbook of Acoustics, Springer, New York

[13] Atkinson C M and Kyttömaa H K 1992. Acoustic wave speed and attenuation in suspensions, Int. J. Multiphase Flow 18(4): 577–592

[14] Urick R J 1967. Principles of underwater sound for Engineers, McGraw-Hill, New York

[15] Faran Jr J J 1951. Sound scattering by solid cylinders and spheres, J. Acoustical Society of America, 23(4): 405-418

[16] Epstein P S and Carhart R R 1953. The absorption of sound in suspensions and emulsions, J. Acoustical Society of America, 25(3): 553-565

[17] Allegra J R and Hawley S A 1972. Attenuation of sound in suspensions and emulsions: Theory and experiments, J. Acoustical Society of America, 51(5.2): 1545-1564

[18] Hay A E and Mercer D G 1985. On the theory of sound scattering and viscous absorption in aqueous suspensions at medium and short wavelengths, J. Acoustical Society of America, 78(5): 1761-1771

[19] Lüscher B and Gruber P 2010. Silt monitoring via ultrasonic signal analysis, Proc. IGHEM Conference, Roorkee, India

[20] Fleckenstein P, Deschwanden F, Storti G, Lattuada M and Gruber P 2014. Ultrasonic characterization of Silt Suspensions by Backscattering, Proc. 9th Intl. Symposium on Ultrasonic Doppler methods for fluid mechanics & fluid engineering, Strasbourg, France

[21] Lüscher B 2008. Abschlussbericht KTI-Projekt 7947.2: Empfindlichkeit der akustischen Durchflussmessung auf Verschmutzung (Sensitivity of ADM to suspended sediment, unpublished, in German)

[22] Felix D, Albayrak I, Abgottspon A, Boes R M and Gruber P 2012. Suspended Sediment and Pelton Turbine Wear Monitoring: Experimental Investigation of various Optical and Acoustic Devices and Beginning of the Case Study at HPP Fieschertal. Proc. 17th Intl. Seminar on Hydropower Plants, Vienna, Austria: 483-494

[23] Deschwanden F 2015. Evaluation of forward and backward scattered acoustic signals to determine the particle parameters in water, Semester thesis, HSLU Luzern, Switzerland (unpublished)