Technologies and experience with monitoring sediments for protecting turbines from abrasion

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Abstract. Abrasion of turbines by sediments is a constant threat in high head and high sediment load situations. It is widely recognized that larger grains cause abrasion, although no consensus on a critical size exists. Grain hardness plays a second key role. Thus monitoring of sediment concentration is highly desirable, particularly with attention paid to the large grains. This has recently become possible with LISST instruments that use laser diffraction (LD) technology. These in-line instruments measure multi-angle laser light scattering, which is converted to a particle size distribution in a pre-defined size range. In order to reach high concentrations, the instruments incorporate auto-dilution capability. The data are transmitted to the control room. Provided software displays concentration history in up to 4 size classes, and the software is capable of generating alarms when sufficiently high concentrations occur. Since no definition exists for this sufficiently high concentration, in this paper we propose an objective criterion based on the rate of revenue generation contrasted with rate of cost of turbine repair. This simple idea helps guide the plant operator to set shut-down thresholds during sediment transport events. We also introduce a lower cost, high-frequency pulsed acoustic sensor for sediment monitoring. The rather lower accuracy of this device is offset by its lower cost that is suitable for small plants.

1. Introduction
It is known that sediments cause abrasive damage. It is recognized that, generally, large grains do more damage than smaller ones. Grain hardness and water velocity play a role, and the type of turbine plays a role, e.g. Peltons suffer more severe damage than Francis. A few formulations relating rate of abrasion and these 3 parameters have been proposed [1] [2] [3]. Verification and broad acceptance remains in progress. Consequently, no generally applicable formulation exists that relates suspended sediment size and concentration with instantaneous rate of turbine abrasion. Lacking such guidance, plant operators face the question: so, under what conditions of grain size and concentration should I shut down power generation? This paper describes measurement technologies, and then proposes a simple guide.

Given that grain size is important, monitoring technologies must measure size-specific concentration of sediments running through turbines at any time. So far, only one technology has emerged that can do this with accuracy. This technology is laser diffraction, embodied in the LISST-Hydro and LISST-Infinite instruments (Sequoia Scientific, Inc., Bellevue, Washington, USA). Installations in Latin America and in the Himalayas have been operating for a few years. The technology has been proven, though in one case in the Nepal Himalayas, extreme conditions produced damage to the water lift pump of the instrumentation itself (clogged sample pump). In all cases, rapid rise (hour time scale) and slower decline of sediment concentrations have been found to be typical. In one case, a turbine operator provided numbers on turbine repair cost as related to volume of sediment passage between maintenance stoppages. As our first key contribution, here we present an objective strategy to set alarms that guide turbine shut-down only when rate of loss of revenue is exceeded by rate of cost of repair.
The laser diffraction instruments that sort the total concentration into 32 precise size classes are found by some small plants to be expensive. For this application, we introduce a newly developed high-frequency acoustic back-scatter instrument, LISST-ABS for monitoring of suspended sediment concentrations. Though not as accurate or size-sorting as laser diffraction, it is none-the-less far superior to optical turbidity type sensors used in some countries. The LISST-ABS sensitivity (output per unit mass concentration) is relatively flat over 30-400 microns showing only ±30% variation from its mean value over this range (and as square-root of diameter for larger sizes). In contrast, optical turbidity sensors lose sensitivity to large grains as 1/diameter, i.e. sensitivity to 400 microns is a factor of 14 lower than that for 30 microns, effectively making turbidity blind to large grains – precisely the grains of relevance to abrasion! The LISST-ABS, though less accurate than laser diffraction, is thus by far better suited to abrasion warning instrumentation than optical turbidity meters. This paper has the first description of use.

2. Sediment monitoring technologies – a review

Here we offer a summary view of available technologies. There also exists ISO-11657-2014 standard applicable to the present need. A slightly more detailed review is offered by [4] and [5]. The methods considered here are (i) optical turbidity; (ii) acoustic back-scatter; and (iii) laser diffraction.

2.1 Optical Turbidity

Although primarily a visual measure of suspensions as implied by the name turbidity, optical turbidity has been in widespread use as a surrogate for (indicator of) suspended sediment concentration. Its acceptance is rooted in two facts: first, it is relatively inexpensive, and second, it is simple. As such, standards developed for measuring the optical turbidity are often mis-interpreted to validate turbidity sensors as qualified surrogates. The main problem with use of optical turbidity is the change in sensitivity with changing grain sizes. The sensitivity (output volts/unit mass concentration) of optical turbidity sensors varies inversely with grain diameter, 1/d. [The 1/d dependence is noted in ISO-11657-2014]. There is a large body of literature reporting this difficulty (e.g. see [6], figure 6). Consequently, in any mixture, fine particles produce disproportionately large part of the output signal, while coarse grains are relatively ignored. In monitoring for sediments, a small concentration of fine particles may cause high apparent turbidity, though there may be little or no large grains which are the ones that cause damage. The high apparent turbidity may generate false alarms. Conversely, even a high concentration of large grains may not generate alarms, subjecting the turbine to abrasion. It is precisely this reason – lower sensitivity to the damaging large grains – that renders turbidity mismatched for turbine abrasion monitoring. While choosing turbidity for reasons of low cost, the plant operators should bear in mind the cost of the turbines that they intend to protect. A small saving in instrumentation cost can expose the turbines to danger. Unfortunately, despite this hazard, some plants are known to use turbidity sensors.

2.2 Acoustic Backscatter Sensors

These are acoustic ‘turbidity’ sensors. In a manner similar to optical turbidity sensors, they sense the strength of sound backscattered to the transmitter. Analogous to radar, a pulse of high frequency sound is transmitted, and the sound pressure backscattered to the transmitter is sensed and stored. There are similarities to optical turbidity, but also differences. Whereas optical scattering is almost always in the geometric scattering regime (i.e \( ka > 1 \), where \( k \) is \( 2\pi/\lambda_o \), \( \lambda_o \) being optical wavelength and \( a \) being particle radius), acoustic scattering is mostly in the Rayleigh regime (i.e \( k_o a \ll 1 \), now \( k_o \) is defined for acoustic wavelength \( \lambda_o \), or at best in the transition regime (i.e \( k_o a \sim 1 \)). In the Rayleigh region, whether for optics or acoustics, scattering increases rapidly with \( ka \). When \( ka \approx 1 \), the scattering strength per unit mass of particles becomes nearly constant – a very desirable quality. At still larger grain sizes, in the geometric regime, \( ka >> 1 \), the amplitude of scattering – which is the quantity sensed by radar or acoustics
– decreases as $a^{-1/2}$. [Optics involve sensing intensity, so the dependence to size is $a^{-1}$]. This relationship is displayed in figure 1 for an 8MHz system, which is an unusually high frequency employed in the LISST-ABS described later. Common acoustic frequencies range from 0.5 to 4MHz, for which the transition to Mie scattering happens at inversely larger sizes, e.g. for 1MHz, the transition occurs at $a = 240$ microns.

![Figure 1: Optical (red), acoustic backscatter (blue), and laser diffraction (magenta) sensitivity variation with grain size. The acoustic response is shown for an 8MHz system in water; where $ka = 1$ occurs at $a = 30$ microns. (left) linear Y-axis; (right): logarithmic Y-axis. The figures clearly shows that 8MHz acoustic backscatter system (LISST-ABS) is sensitive to large grains, suited for abrasion protection.](image)

Many users of acoustic Doppler current profilers (ADCP), also record the backscatter signal strength (pressure), e.g. [7][8]. Inversion of these signals requires at least 2 frequencies, given the two unknowns that determine signal strength, i.e. grain size and concentration. There is a large body of literature in this field [7]. More recent literature is reviewed in [9], where the authors have considered the performance of these methods in study of river columns and noted errors that arise in bi-modal situations which are typical of rivers. The inversion is not yet routine, despite several decades of research work. [A recent announcement of a 4-frequency acoustic system capable of producing particle size distribution in 32 size classes, proved misleading on closer examination. After all, how can 4 measurements lead to solving for 32 unknowns?]

Multi-frequency acoustic backscatter systems for grain sizing began with the pioneering work of Hay and Sheng (1992). These systems can obtain a mean size, and a mean concentration at multiple points along a beam. However, the processing of data is not yet routine. In particular, the results in situations such as rivers, where the size distribution is bi-modal, are questionable. Furthermore, the ‘flat’ region of acoustics in figure 1 on right, being dependent on frequency occurs starting at $a = 240$, 120, 60 microns for 1, 2 and 4MHz. In other words, most sediment grains remain in the Rayleigh regime, where little additional information is added by adding other frequencies. By choosing 8MHz as the operating frequency, the LISST-ABS can observe particles in the 60-500 micron diameter range reasonably accurately.

### 2.3 Laser Diffraction

Laser diffraction (LD) is a widely used technology for measuring particle size distributions. Its operating principle is simple. If one measures $n$ parameters, one can solve for $n$ unknowns (with some restrictions related to noise). In the case of LD, the measurements are light scattering intensity into $n$ angles. The name diffraction comes from the original observation that at small forward angles of laser light scattering, particle composition is not of importance in determining the multi-angle scattering, scattering is dominated by diffraction for which only particle size matters. That result made the technique broadly useful. However, LD mostly remains a laboratory technology due to sensitive optical alignments. Its
introduction to hydropower benefits from LD’s first adoption to measuring particles on coastal ocean floor by the present authors [10]. This original application required ruggedization and automation which later carried over to the present application. In figure 2, we show a schematic of the optics that were built into every early LD system made by Sequoia Scientific, Inc. Newer modern LD systems depart from the restriction of small forward angle scattering, although the name LD remains convenient. Measurements of scattering at wider angles permit extracting information on finer particles. Current field systems can measure size distribution covering the range 0.3 to 500 microns.

In figure 2, a collimated laser shines through the water. Particles in water scatter light. The forward scattered light is gathered by a lens. Rays scattered at a particular angle from the axis reach a focal plane detector at the same angle from lens centre. Thus, distance $r$ along the detector plane becomes scattering angle in air, $\tan^{-1}(r/f)$ where $f$ is lens focal length. [Due to refraction at the test cell receiving window, the scattering angle in water follows, from Snell’s law, as $\sin^{-1}[\sin(\tan^{-1}(r/f))/1.33]$, or for small angles, $\tan^{-1}(r/1.33f)$. A series of concentric silicon photosensitive rings at the focal plane sense scattering into multiple angle sub-ranges. The photocurrents are amplified and stored. A hole in the detector at the focal spot permits the focused beam to pass through. Its power is sensed and stored. The reduction of this power due to particles is used in the processing of stored data to de-attenuate sensed scattered light, and to invert for particle size distribution. From a typical set of measurements from a ring detector, a size distribution can be measured in one scan. With averaging to smooth results – mainly due to particle concentration fluctuations, a typical PSD can be measured in a few seconds.

3. Instrument Systems

We describe two instrument systems based on laser diffraction, i.e. the LISST-Hydro and LISST-Infinite, and the LISST-ABS acoustic backscatter system. LISST is a trademark of Sequoia Scientific, Inc.

3.1 LISST-Infinite and LISST-Hydro

These laser diffraction instruments are made specifically for hydropower plants. The instrument reads the 32-ring detector outputs and the optical transmission (power through the hole in centre of ring detector, see figure 2). This firmware then computes the particle size distribution (PSD) and the total concentration and stores that to a file. The reading of this data file and graphic display of the data are performed by a second software LISST-Viewer.
- Display up to 5 instruments on a summary page, with auxiliary data and warnings;
- Strip charts for each instrument on a separate tab; each tab shows 4 strips – total, fine (<75 microns), medium (75-200 microns) and coarse fractions (>200 microns).
- Setting of sediment concentration alarms for each size class on each instrument, independently;
- Audible alarms, with built-in features so operator cannot easily ignore the event;
- Full 32-size class PSD display for any point on the chart, with forward-back buttons for easy comparison of changes over time;
- Option to view the optical background for each data; this background arises from scattering off windows (see figure 2), and it grows with fouling of windows; the background is used to alert operators to clean these optical windows;
- LISST-Viewer auto-start. In the event of a power loss to the computer, the software will launch when an operator logs on at restoration of power. This feature reduces loss of data and missed warnings.
- Alarms when sediment concentration trends suggest anticipated exceedance of alarm thresholds; and similarly, ‘all clear’ alerts for when decreasing trends from an active event indicate when concentration will reach below alarm levels.

The LISST-Viewer is designed with the intent that multiple work stations may view the data from an installation. For instance, if the data are saved on a shared server or a cloud such as Dropbox, multiple users can launch LISST-Viewer on their desktops and keep an eye on conditions at an installation. This feature also enables the manufacturers to keep an eye on the health of the equipment if access to data is permitted by plant operators.

In some hydro plants, MODBUS is used for data display. Software for delivering data from the instrument via MODBUS is available. However, in this case, the setup of alarm thresholds and warnings are based on the total concentration alone, giving up the advantages of laser diffraction.

3.2 LISST- ABS: a High Frequency Acoustic Backscatter System

The LISST-ABS is a high-frequency system, operating at 8MHz. The choice of this high frequency was based on the characteristic response to particles of different sizes, as shown in figure 1. At 8MHz, the Rayleigh scattering region (ka << 1) extends to about 30 micron diameter. In this region, the sensitivity varies strongly with grain size. In contrast, the sensitivity varies little with size from ~30 to 500 microns. This is almost exactly the range of sizes of hazardous particles from point of view of turbine abrasion. As such, the acoustic backscatter measurement is quite well matched to the needed data on coarse particles alone. This is a distinct advantage of LISST-ABS over all optical turbidity sensors, which are more sensitive to fine particles. The LISST-ABS does not have an upper or lower size limit for observable particles. The sensitivity declines as \( d^{0.2} \) for acoustic scattering for larger particles.
The LISST-ABS is a single-point sensor, intended as a replacement for optical turbidity sensors. Field data collected by USGS scientists at the Elwha river in Washington State is shown in figure 3. This is a site of a major dam removal in the year 2012, resulting in large sediment loads fed by silt accumulated in the reservoir over a century [12].

The LISST-ABS can be mounted so that its face is flush with a wall of a waterway, draft tube or turbine intake. However, pressure management may be necessary to match the instrument’s upper limit.

4. An Installation and Example

4.1 Location
The LISST-Infinite or –Hydro instruments can be installed near the draft tube, tailwater channel, or near the intake to the turbine. Water must then be drawn and delivered to the instrument. If installed near turbine intake, a pressure reduction system may be necessary, whereas there is reason to believe that particles may be altered (broken) in passage through a turbine and hence water drawn at the draft tube may not give a true size distribution (Sultan Alam, private communication). In [11], the authors argue to the contrary, but only for particles smaller than 20 microns. Such small particles mostly do not impact on the turbine parts, and hence are not subject to breakage. The pressure reduction system design is non-trivial, as conventional valves are themselves subject to abrasive destruction.

4.2 Example Data
The LISST-Viewer, with capacity to handle upto 5 instruments, displays data on a computer screen in 2 formats. In one, a summary view of all 5 (or if a smaller number are installed, then all) is displayed, figure 4. This is suitable for an operator’s quick glance. On this display, the total concentration is displayed, and then also the percent-to-alarm for each of the size classes. Furthermore, the level of the
auxiliary clean water tank which provides water to the instruments to zero the measurement is displayed. Any faults in operation are indicated in a box on the right of the Clean Water tank level indication (not shown).

Figure 4: The summary view of up to 5 instrument systems. In case of more than one instruments being monitored, similar figures repeat below this one, all in one window.

The history of data of any of the up to 5 instruments is accessible from the same screen by choosing an instrument from the tabs, figure 5. The time base is expandable. Each of the 4 strips on the chart can have its own alarm level setting. To avoid false alarms, only after 3 consistent readings exceed alarm levels does the alarm sound. And to ensure that a sleepy operator doesn’t merely shut off the alarm and go back to sleep, the alarm sounds a second time for any event, so that the operator has 2 chances to deal with the situation. Again, double-clicking on any point of the chart opens a window with the corresponding particle size distribution, figure 6. This same window also shows other information regarding data quality.

All data are saved in ASCII files each month. These data can be processed according to user preferences for periodic reports to plant management etc.
Figure 5: Strip chart display of history of concentrations for a single instrument. The charts show concentrations in, from bottom to top, all, fine (<75), medium (75 to 200) and coarse (>200 µm) fractions. [note: the alarm levels are set extremely low here; the operator was playing.]

Figure 6: The size distribution (and cumulative distribution, red line) corresponding to a data point on the chart shown in Fig. 4. Although the strip charts show only 3 size bands, this high resolution size data has value in future research and analyses to relate sediment concentration and abrasion rates.
5. A strategy for turbine shut-down decision-making in excessive sediment load

The question an operator inevitably asks is: ok, so you are telling me the sediment concentration in ppm. What do I do? “At what ppm should I stop the turbine?” In answer, we offer the following strategy which makes a direct and *instantaneous* comparison of loss of revenue due to plant stoppage with loss of value of turbine due to abrasion.

Often, either by specification of a turbine maker or from empirical data, it is known that a turbine will cost so much for so many tons of sand passing through. Of course, these tend to be approximate numbers, but they can serve as a guide.

Let the turbine life, before rebuilding be expressed as $N$ tons of sand passing through. And let the cost of repair and rebuilding the turbine at the end of this be $S$ dollars. One then computes the instantaneous flux of sand as the current flow-rate $Q$ (m$^3$/sec) times the current sand concentration $C$, (tons/m$^3$). This instantaneous sand flux is the product $CQ$ (tons/sec). The corresponding instantaneous cost in dollars is $S(CQ)/N$. If $R$ is the revenue generation rate in dollars, it follows that when the revenue rate is less than the instantaneous cost of sediment damage, i.e. when

$$R < SQ/C/N$$

(1)

the plant operation is no longer profitable. This is an objective criterion to stop the turbine if cost is the sole basis for this decision.

We recognize that exact numbers for $N$ in tons are not usually available, and as of today, the damaging grain size-threshold is also not known. Besides, the composition of the suspended sediment, in particular the quartz content, is important in determining $N$. Thus, in the absence of direct data, alternate sources of information may be available from historical records (e.g. manual sampling). This uncertainly in $N$ can be absorbed into an ‘uncertainly’ parameter $\sigma$ which has a value 1 when $N$ is firmly known, and may be adjusted depending on the uncertainty in $N$. Combining, when the parameter

$$R < S QC/ (\sigma N)$$

(2)

turbine shut-down can be sensible. This threshold can be used to determine a critical concentration level, $C_{\text{crit}}$ which can be set as the alarm level for high-concentration shut-down:

$$C_{\text{crit}} > \sigma NR/(QS)$$

(3)

As an example, if a million tons of sand can pass through a 100MW turbine with a flow rate of 10 m$^3$/s before a repair cost of $2M occurs:

$$N = 10^6 \text{ tons;}$$
$$Q = 10 \text{ m}^3/\text{sec;}$$
$$R \text{ (100MW at S0.02/kWh)} = 2,000 \text{$/hr;}$$
$$S \text{ (cost of repair)} = $2M;$$

then, assuming an uncertainty factor $\sigma = 2$;

$$C_{\text{crit}} = 55g/L, \text{ or 55,000 ppm.}$$

(4)

That is, when this turbine reaches a sand concentration of 55,000ppm, it is no longer profitable to operate it. An effective instrument system would be programmed to sound an alarm at such concentrations. Of
course, there can be other societal considerations or contractual obligations to continue turbine operation.

The above guidance is based on the assumption that abrasion rate is linearly proportional to concentration and flow rate. In contrast, if a linear relation with concentration and a third power relation with velocity is used [13], Eq. (3) needs to be adapted considering the type of turbine. The need for further research is clear. More advanced models are incompatible with the idea of a fixed amount of sediment passing through the turbine until a major overhaul.

6. Conclusion
Technologies are now capable of real-time monitoring of sediments striking turbines and displaying the data to a plan operator. With the best available models relating sediment concentration to abrasion rate, we have offered a method to objectively decide when it is economical to stop production of hydro power.

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