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ULTRASONIC DEVICE DEVELOPMENT FOR SEWAGE VELOCITY AND SEDIMENT CONCENTRATION MEASUREMENTS

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ABSTRACT

A major concern in waste water management is the real time pollutant flow measurement and identification. Traditional acoustic instruments only allow mean velocity or flow measurement. Concentration of solid pollutants, namely suspended sediments, is obtained through dessication of water samples.

In the frame of a technological research and innovation network in water and environment technologies (RITEAU), our research group, in collaboration with industrial partners and other research institutions, has been in charge of the development of a suitable flowmeter : an ultrasonic device measuring simultaneously water flow and concentration of suspended sediments. The current prototype consists of an immersible tight frame containing transducers and acquisition electronics linked to an external platform in charge of data analysis and storage.

After a preliminary instrument description, measurements principles will be exposed. Velocity profile calculation relies on synchronous signal sampling and is based on the treatment of the Doppler information. Multi-frequential acoustic data inversion algorithm, leading to material discrimination and rough concentration estimation of different granular size domains, is based on semi-empirical relations between granular shape and size and frequency obtained through laboratory measurements on calibrated materials. Representative experimental results will be shown as sewer velocity profiles and granulometric concentration for suspended sediments in a wastewater collector.

INTRODUCTION

Measuring flow rates in sewer networks is a crucial aspect of wastewater management. Acoustic flow gauging methods are widely used. Sedimental distribution and concentration are usually obtained through sampling. Real time access to sedimental and flow data would be a major progress in sewage supervision and would allow immediate reaction.

Our research team build a real time ultrasonic flowmeter which allows simultaneous velocimetric and suspended sediments concentration measurements. From 2003 to 2007, this development was granted by financial support of a French RITEAU research project, which lead to the association of 2 research institutes and 2 companies. Fruit of this collaboration is a suitable prototype in a pre-commercial stage.

For developers, contrary to existing commercial flowmeters which often are "black boxes" for the user, mostly totally unaware of exact methods used to perform the measurement, our instrument is based on well known principles and still remains open to implementation of new algorithms or data acquisition protocols.

INSTRUMENT DESCRIPTION

Project goal was to combine in a same instrument possible evaluation of velocity profile up to 1 meter in order to calculate flow and to give an information about the granular distribution of particles in the flow. So, on one hand, Doppler velocity measurements on a distance of a meter require low working frequency in order to minimize beam attenuation and maximize measured velocity. And, on the other hand, the backscattered signal intensity depends on particle radius and intrinsic nature; therefore concentration might be estimated over a given radius domain which is directly linked to beam frequency. Thus, frequencies were chosen in order to be significant for suspended sediments and to allow radius domain overlapping.

Broadband transducers of required frequencies, related to regular sizes of suspended sediments, were especially manufactured. As shown on figure 1, the actual version of the instrument contains 3 transducers of respective central frequency 11 (M11), 4.5 (M4.5) and 1.8 (M1.8) MHz.

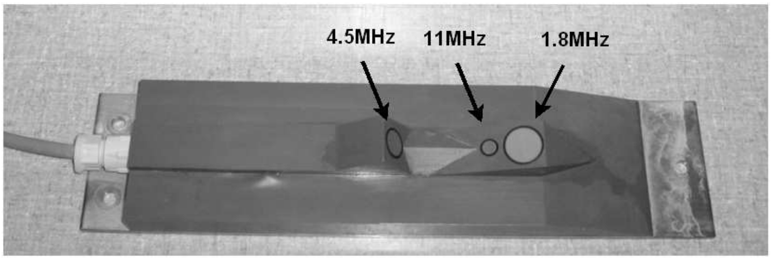

Figure 1.-Transducers set-up.

The M1.8 transducer is used for emission and reception of low frequencies; the M11 is used in emission-reception mode for high frequencies and the last one, M4.5, is only used as receiver for intermediate frequencies at another diffusion angle.
Transducers and front-end electronics, especially self-developed for our instrument, are sealed in a tight immersable frame. Data processing is deported to an external device. The system can work in full autonomy. Online data visualization and analysis can also be done on a connected PC which also allows online data acquisition protocol modification.

ACOUSTIC FLOW MEASUREMENTS

Principle

Mainly, two types of acoustic flowmeters exist. Transit-time ultrasonic ones which are based on the principle that transit time of an acoustic signal along a known path is altered by the fluid velocity. By accurately measuring the transit time of signals sent in both directions along a given path, velocity can be calculated : on one side flow velocity adds to the velocity of sound and substract to it on the other. A similar technique uses the frequency difference between upstream and downstream signals.
Another type of acoustic flow gauging instruments are Doppler flowmeters as our device. Using Doppler effect, they measure the velocity of particles moving with the flowing fluid. An acoustic burst of known frequency is send into the water flow and the combination of backscattered echoes reflected from particles is collected (figure 2). In our case, these measurements are done with the M1.8 transducer which is alternately used in emission and reception mode.
The exploration depth is divided into several volumes by temporal sampling of the echoes [1]. For each depth or spatial volume, the reception of repeated echoes, modulated by the carrier frequency and low filtered, lead to a vector of samples containing the Doppler information (figure 3).

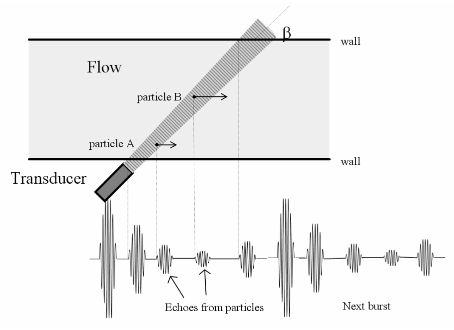

Figure 2.- Measurement principle.

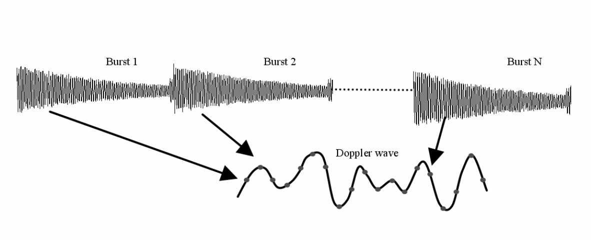

Figure 3.- Doppler extraction.

Several techniques might be used to extract the Doppler information included in each volume's vector of sample [2]. Estimated mean Doppler frequency leads to the fluid's velocity in each volume as shown by equation 1 where V is the fluid velocity, c the speed on sound, f_d the estimated Doppler frequency, f_0 the emission frequency and β the angle between the acoustic beam and the fluid flow (β = 75° for our instrument) :

$$V = \frac{c \cdot f_D}{2 f_0 \cdot \cos\beta} \qquad \text{(Eq. 1)}$$

A velocity profile with good spatial resolution is thus obtained. Flow value is calculated by integration of velocity on the fluid's section. Broadening of the Doppler spectra might be related to size of the measurement volume (associated to beam width and observation time), velocity gradient in the measurement volume or local turbulence.

Experimental results

In order to investigate the instrument's possible limitations, several measurement locations such as rivers and different sewage systems have been explored.

Figure 4 shows an example of Doppler spectrum obtained in a given sewage collector. The instrument was fixed on a metallic plate near the collector's bottom. Velocity measurements were made on a volume line going from bottom to water surface. Strong turbulences are assumed to be generated near the transducer as can be seen on shape of the spectrum.

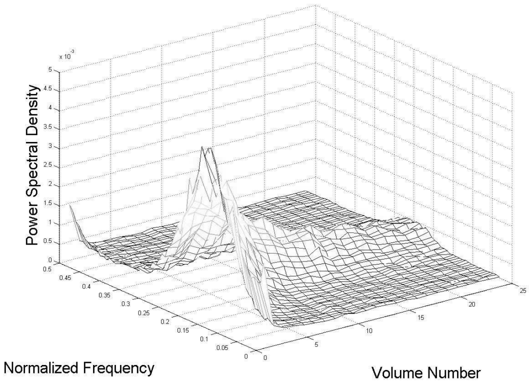

Figure 4.- Typical Doppler frequency in a sewage collector.

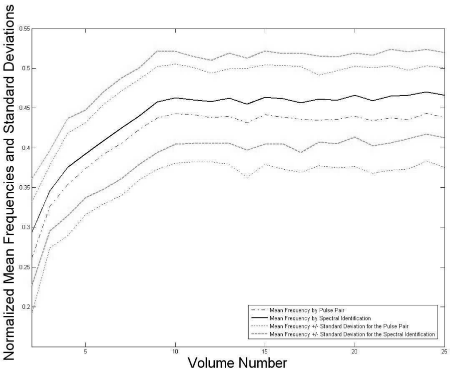

Figure 5.- Comparison between velocity estimators.

Our prototype also allows easy data analysis algorithm comparison. Indeed, two different methods were used to obtain the velocity estimator : the well known Pulse-Pair method and a self-developed Spectral Identification method. Figure 5 shows results obtained on a same flow. Typical shape of a velocity profile for open channel turbulent flow can be recognized. A slight difference on mean Doppler frequency is observed between the two methods. In this specific case, with signal to noise ratio of a few decibels, standard deviation values are lower for the Identification Method [3].

SEDIMENTAL CONCENTRATION MEASUREMENTS

Theoretical background

Use of multiple frequencies and diffusion angles rely on the diffusion theory of rigid spheres [4]. According to this, the intensity of the retrodiffused beam is maximal when, for a given frequency f, the particle radius a is related to frequency through :

$$a = \frac{c}{2\pi \cdot f} \qquad \text{(Eq. 2)}$$

where c is the speed of sound in the medium.

Rough estimation of backscattered signal intensity shows significant contribution in signal intensity for particles with radius in the [a/2; 2a] domain. Theory also foresees angular dependence of scattered beam intensity. Apparatus design rely on these arguments.

In order to use the received acoustic signal for sedimental concentration extrapolation, aim is to link emission voltage Ve,j to reception voltage Vs,j for a given transducer at working frequency j. The reception voltage depends on the encountered particle cloud, divided in n size classes and p types (according to geometrical and intrinsic properties). It can be shown that :

$$\left(V_{s,j}(r)\right)^2 = \left(V_{e,j}G_j\right)^2 c\Delta t_j \frac{3}{32}\left[\sum_{i=1}^{n}\left(\sum_{k=1}^{p}\beta_{vi,j,k}C_{vi,k}(r)\right)\right]\left(\frac{R}{r}\right)^2 g_j^2\left(\frac{r}{x_{c,j}}\right)\exp\left[-2\int_0^r\left(\alpha_j + \sum_{i=1}^{n}\sum_{k=1}^{P}\alpha_{i,j,k}C_{vi,k}(r)\right)dr\right] \qquad \text{(Eq. 3)}$$

where G_j is the electro-acoustic gain of the transducer at frequency j, c the velocity of sound, Δt_j the pulse duration, g_j a transducer near field correction at frequency j, R the transducer radius, r the distance from transducer to the diffusing particles, $x_{c,j}$ the near field distance of the transducer at frequency j, α_j the water attenuation coefficient at frequency j, and finally $\alpha_{vi,j,k}$ and $\beta_{vi,j,k}$, acoustic response coefficients, respectively for attenuation and backscattering, of different particle types of volumic concentration $C_{vi,k}$. Equation (3) can be rewritten as follows :

$$\frac{\left(V_{s,j}(r)\right)^2}{\left(V_{e,j}G_j\right)^2 c\Delta t \frac{3}{32}\left(\frac{R}{r}\right)^2 g_j^2\left(\frac{r}{x_{c,j}}\right)\exp\left(-2\alpha_j r\right)} = \left[\sum_{i=1}^{n}\left(\sum_{k=1}^{p}\beta_{vi,j,k}C_{vi,k}(r)\right)\right]\exp\left[-2\int_0^r\sum_{i=1}^{n}\sum_{k=1}^{P}\alpha_{i,j,k}C_{vi,k}(r)dr\right]$$

$$\frac{\left(V_{s,j}(r)\right)^2}{\left(V_{e,j}G_j\right)^2 c\Delta t \frac{3}{32}\left(\frac{R}{r}\right)^2 g_j^2\left(\frac{r}{x_{c,j}}\right)\exp\left(-2\alpha_j r\right)} = \beta_{v,j}(r)\exp\left(-2\alpha_{v,j}(r)\right) \qquad \text{(Eq. 4)}$$

where $\beta_{v,j}(r)$ is a term related to backscattering and $\alpha_{v,j}(r)$ to attenuation.

Sedimental repartition is obtained by resolution of above equation. All terms of the left part of (Eq. 4) are accessible. $V_{e,j}G_j$ values were obtained trough calibration measurements. The transducer near field correction is based on experimental measurements that can be seen on figure 6. Time thus distance evolution of reception voltage is recorded for several bursts and frequencies and lead to $V_{s,j}(r)$ values.

Accuracy on concentration is directly linked to the good knowledge of coefficients used in (Eq. 4). Acoustic response coefficients depend on particle size, shape, acoustic impedance and observation frequency. A huge variety of suspended sediments occurs in sewage flows. Great disparities in terms of size, shape or density are observed. Their acoustical properties are mostly unknown. Therefore, a simplifying hypothesis was introduced : for a given material, size effects are decorrelated from other effects and can be estimated through the form function of sand [5].

The backscattering term becomes :

$$\beta_{vi,j,k} C_{vi,k} = K_{m,k} C_{mi,k} F_{i,j} \qquad F_{i,j} = \left\langle \frac{f^2\left(\dfrac{2\pi a_i}{\lambda_j}\right)}{a_i} \right\rangle \text{(Eq. 5)}$$

with $C_{mi,k}$ mass concentrations, a_i equivalent particle radii, f the sand form function and $K_{m,k}$ a coefficient named massic response rate. The coefficients $F_{i,j}$ are the mean values of the ratio of form function by particle radius over 4 diameter domains (centered on 30, 70, 170 and 400 µm).

Experimental results

Massic reponse rate of a wide variety of different sediments occurring in sewage has been evaluated through laboratory measurements. Observed values were very disparate, going from 0.4 for sand to 0.01 for cooked and mixed potatoes (figure 7). Nevertheless, some particle types, most representative of particles occurring in sewage, have close values of massic response rate : 0.11 for the loess, 0.1 for paper pulp, 0.15 for excrements and 0.2 for garden ground.

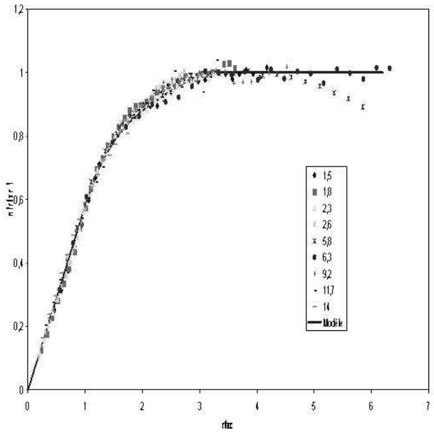

Figure 6.- Near field correction as a function of frequency and r/x$_{c,j}$

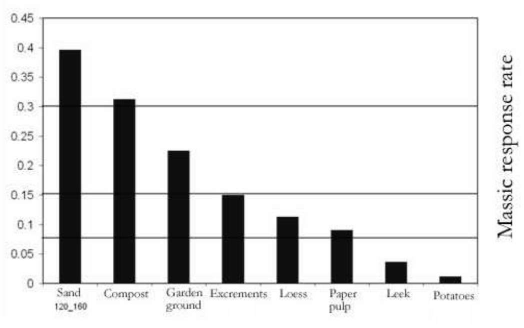

Figure 7.- Massic response rate for different kind of sediments (sand, compost, garden ground, excrements, loess, paper, leek and potatoes from left to right)

More systematic exploration of suspended sediments occuring in sewage like starch and cellulose are foreseen. Comparison between data obtained through several techniques (microscope for good shape knowledge, optical granulometry and turbidity measurements) are planed for global suspended sediments characterisation. Also, further algorithmic studies are on the run in order to include in analysis yet unexploited information such as particle size estimation, a coefficient for measurements at 70° and an attenuation coefficient.

Current state of art let us assume suspended sediments in sewage as a homogenous material of variable granulometry with a mean massic response of 0.1. Following figure shows time evolution over 24h of suspended sediments concentration and flow for the incoming flow of a waste water treatment plant under rainy weather conditions.

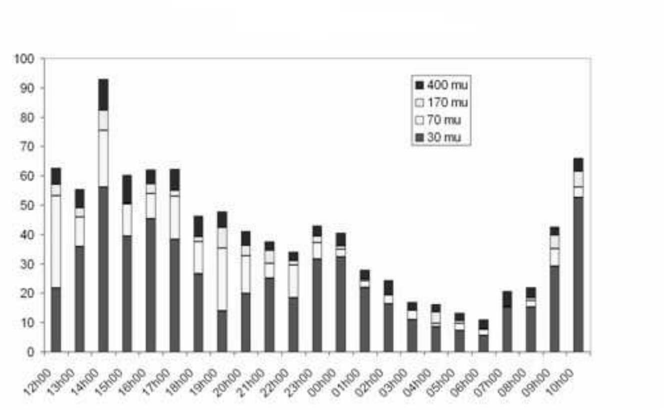

Figure 8.- Time evolution of suspended sediments concentration

Figure 8 shows results in terms of hourly average values. Expected variations are observed, namely nocturnal diminution of suspended sediments concentration related to loss of human activity between 0h00 and 7h00. Finer analysis also shows concentration diminution due to dilution by clear water addition.

CONCLUSIONS

Two prototypes of this instrument currently exist. One is used for laboratory measurements in order to improve knowledge of acoustic response of sewage suspended sediments. The other is used on different sites. For example, over two months, the instrumented was located in a sewage collector of a city, Strasbourg, for real time velocity and water high measurements. Also granulometric measurements were done. First steps in data analysis show that each apparatus is unique on an acoustic point of view. Dispersion on transducers and electronics characteristics generate perceptible differences on the ultrasonic beam and gain : transducer near field corrections which were expected to be similar for transducers of same frequency showed significant differences. Thus individual calibration of each instrument will be required. Another unexpected data feature concerns the diffusion at 70° for which no evolution pattern was observed. Data analysis has still to be completed to allow better tuning of our flowmeter.

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