An Ultrasonic Phased-Array Sensor to Measure the Velocity Profile of Open Channels

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***Abstract*—Ultrasonic phased array technology is applied for water flow measurement. An electronic pivoted beam collects echoes over an initially unknown cross section of a pipe or channel. Filtering the echoes in the time and spatial domain in conjunction with flow models, allows calculation of the velocity profile. The hardware and signal processing are described in this article. Furthermore, the performance is demonstrated in a field experiment.**

***Index Terms*—ultrasound, phased-array, flow measuring, object tracking.**

I. Introduction

Measuring the water flow precisely is of interest, e.g. in wastewater accounting or process monitoring. Here the measurements have to be performed in pipes (completely or partially filled) and open channels. Ultrasonic flow measurement is state-of-the-art [1]. For this technique a train of pulses is first of all sent against the flow direction, and afterwards the upcoming echoes of slip-free flowing particles are evaluated to determine its positions. Finally, the flow velocity can be derived along the beam from the particle positions.

The flow calculation algorithm must be adapted to the actual channel cross section form and size. Moreover, based on the sedimentations, a continuous variation of the channel cross section and flow profile arises over the time. Thus, a sensor system with a single beam has principal limitations. And practical experience shows, that the measurement site is often not optimal with respect to flow homogeneity. Therefore, the mono beam architecture does not cope with advanced requirements. The answer of this challenge is a multi beam technology, which favorably is achieved with phased-array technology. The beam may be pivoted in a section of about $\pm 60°$. This range does not enable to illuminate the whole cross section of a pipe or channel, but is sufficient, to identify the form and the size of the cross section. By collecting enough sampling points, the velocity profile of the flow rate is calculated on the basis of well known flow models [2].

Phased-array beams are relatively broad in contrast to existing mono beam sensors. This leads to a greater number of simultaneous incoming echoes and consequently requires more sophisticated signal processing. Therefore, improved filter methods are needed for time and space domain to track particles within the flow. Reliable tracking requires a high pulse rate, which is in contradiction to range unambiguousness. Additional frequency coding of pulses must be applied.

Determination of velocity may be performed by coherent Doppler processing or incoherent echo detection with particle tracking. This paper is limited to incoherent algorithms. In section II the phased- array preprocessing including echo detection is described. The subsequent signal processing comprises Kalman filtering, probabilistic data association (PDA) filtering and velocity profile calculation. In section III implementation and hardware requirements are analyzed. It is demonstrated, that the whole signal processing may be implemented on a commercial microcontroller. Finally, a performance test of the ultrasonic phased-array technology and the signal processing algorithms on an urban sewage plant is presented in Section IV.

II. Evaluation Process

The presented “incoherent pulse-to-pulse” evaluation method is based on the fundamental idea of target tracking, which is widely used in the radar technology. As the name already indicates, the pulses of the transmission signals is incoherently sent to each other. In this case the Doppler-frequency is not of interest, but rather the transit time between transmitted and received signal respectively its contained echoes. If the transit time τ is known, the particle distance in flow direction to the sensor x_P is calculated by means of the speed of sound c_w and the angle of incidence β in elevation-direction by:

$$x_P = \cos\beta \frac{c_w \tau}{2} \tag{1}$$

That calculation has to be done for each echo or sound-reflecting particle. All variables can be considered as being constant, excepting the acoustic transit time.

To transmit the pulses with a high repetition rate without any spatial ambiguities, the signals have to be coded [3]–[5]. One of the most widely-used coding method is the so called phase-coding, which is often applied in ADCP-measuring systems. However, if the phase randomly varies in steps of $\pm\pi$ a broadband ultrasonic transducer is required in order to follow the phase steps. Hence, a broadband transducer was developed and presented in [6] with a bandwidth of 70% of its centre frequency. Such a broadband transducer is difficult to realize. To overcome this problem, a special

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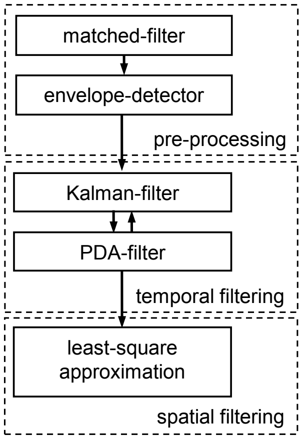

Fig. 1. Filter chain for particle tracking.

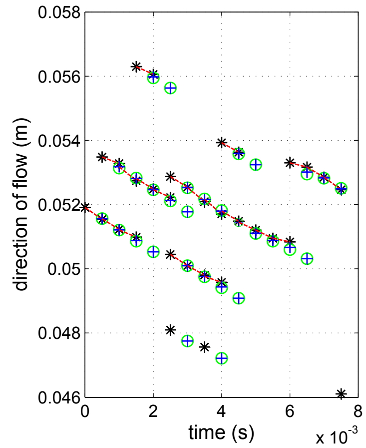

Fig. 2. Tracked streamlines of particles within a flow.

form of frequency coding was developed by [7]. This coding is based on the frequency hopping spread spectrum (FHSS) method, in which its frequency states are combined on the basis of a binary Gold-code sequence. The features of those coded signals are given by a Dirac-shaped autocorrelation and a nearly orthogonal relation to each other. Consequently, these types of signals are ideally suited to detect the transit time of echoes τ by a correlation of transmitted and recieved signal.

The transit time evaluation of the echoes and thus the determination of the particle positions according to (1), are executed in the signal pre-processing. Here, each of the coded transmission signals is implemented in a mirrored form of finite impulse response (FIR) filter coefficients and finally combined to a filter bank. With the help of such a matched-filter bank, the correlation between transmitted and received signal is realized in real-time on a DSP-Board. Envelope-detectors are connected at the filter outputs to detect all echoes within the received signal. Thus, if the transmission signal correlates with an echo in the received signal, the output signal of the filter increases for a short time to a dirac-pulse. Exceeds this peak the established threshold of the envelope detector, the filtered echo is identified as a sound reflection of a particle, and may consequently be used to calculate its distance.

Once the particle positions are known, a temporal and afterwards a spatial filter approach is applied to this information, as illustrated in Fig. 1. The temporal filtering is equivalent to an object tracking method, which extracts the chronological course of particles from the measured values. For this application, the object tracking method is implemented using a Kalman-filter for state-space description and a PDA-filter for data association cf. [8], [9]. With the help of this filter chain, each streamline is represented by a Kalman-filter. As shown in Fig. 2, the evaluation method visualizes not only the streamlines and thus the turbulences of the flow, but also acts as a filter to eliminate faulty reflections from the measurements. Furthermore, there is no restriction of the spatial resolution, due to the fact that the streamlines are tracked individually in the measuring area.

If the filter has adjusted to the course of a streamline, its velocity-state is transferred into a spatial velocity profile. With these measurements and the velocity profile from a model-based computational fluid dynamics (CFD) simulation, a least-square approximation is used to bring both information together. For the following analysis, the mathematical model of the velocity profile of an open channel is defined by [10] and extended to its channel width. The least-square approximation is summarized under the spatial filtering and due to its computational cost of a matrix inversion infrequently calculated.

By knowing the velocity model $f(\vec{v})$ across the whole cross section of the channel A as well as its dimensions, the flow rate Q can be calculated by solving the velocity integral

$$Q = \int_A f(\vec{v})\, \mathrm{d}\vec{A} \tag{2}$$

In contrast to laboratory measurements, the initial velocity of the channel is generally unknown in reality. Therefore, a convergence study was done with different initial velocities and real measurements. The results have shown an errorless flow rate for all varying initial velocities after 100ms. Consequently, there is also a stable velocity profile after that time.

III. Hardware

To realize the measurement task, a modular hardware architecture is used. In principle, the modules are subdivided in a front-end, a digital signal processor (DSP) and a microcontroller. The modules are still separated spatially at the current development status and thus have to communicate by wire. Those three modules are illustrated in Fig. 3. By using a piezo phased-array for the front-end, this acts as an electromechanical transducer with a resonance frequency of 1 MHz. Furthermore, the phased-array transducer consists of 16 individual elements whose main lobe is pivoted by a phase-selective triggering of each element. Measurements of a radiation pattern from a newly developed phased-array transducer have shown a range of $\alpha = \pm 60°$ in azimuth-direction.

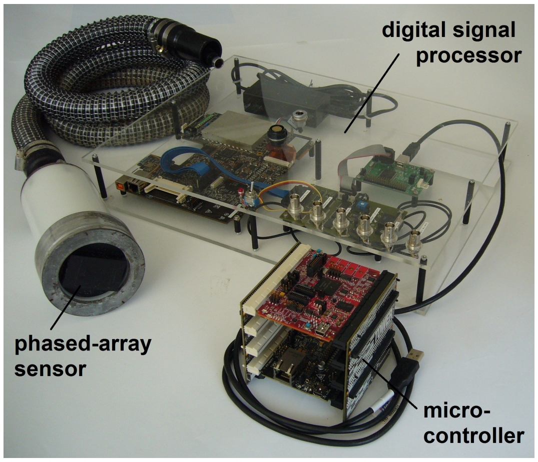

Fig. 3. Sensor-system consisting of a phased-array sensor (front-end), a digital signal processor (DSP) and a microcontroller.

Whereby the receiving level of the main lobe decreases by 2.3 dB at a deflection angle of α =60°.

To transmit or receive the ultrasonic signals on the phased-array transducer in a intermittently way, a DSP unit is used. On one side, the generation of the signal-coding as well as the amplification of the electrical signals occurs on the DSP. On the other side, the pre-filtering, the analog-to-digital conversion, the signal pre-processing and the caching of the measurement data are summarized in this unit. In more detail, the signal pre-processing to determine the particle positions is realized on a field programmable gate array (FPGA) chip of the DSP unit. It means that the matched filter bank, the envelope detector and the calculation of the particle position of the transit time (cf. (1)) are implemented on the FPGA-chip. To reduce the volume of data and its transmission to the microcontroller, only the particle positions are stored in the memory of the DSP unit.

Subsequently, the measurement data from the memory is collected by the microcontroller in a pull-oriented mode. Here, on the microcontroller, the temporal and spatial filtering of the particles is processed. For the temporal filtering, a filter chain consisting of a Kalman-filter and a PDA-filter is applied for each streamline, to track the particles and extract its velocities. The spatial filtering extrapolates the velocity of missing measurement ranges from the cross section of the channel. If finally the whole velocity profile and its cross section are known, the flow rate is computed as described in (2).

Both filter approaches have been implemented and analyzed on a ARM Cortex-M4F processor (Freescale Development Kit K70F120M a) to estimate the computational effort. For this purpose, a channel cross section of 35 cm×45 cm (width × height) is measured by 7 azimuth angles (-30°:10°:30°). 16 measurement intervals within 7 ms are performed for each angle, so that all in all a total number of 11883 particles must be evaluated. Furthermore, it should be noted that for this worst-case scenario the threshold of the envelope detector has been set very low, to increase the number of particles consciously with false detections. The analysis reveals a computing time of 4.1 s for the temporal filtering and for the spatial filtering a time of 0.3 s. The case study shows that the presented evaluation method can be performed in an adequate computing time and is suitable for real-world measurements.

IV. Measurement Results

The following measurements with the described hardware and evaluation method have been done on a pre-filtered inflow of an urban sewage plant. To ensure a clear allocation of the measurement errors from the flow rate, the cross section of the open channel is at first known. The channel has a width of $b = 1600$ mm and at the moment of measurement a fill level of $z = 960$ mm. Additionally, the true flow rate of the channel is known from a magnetic inductive flow sensor by $Q = 1460$ l/s, whose measurement occurs from a pipe after the open channel. The fluid is mixed with small suspended solids, which serve as sound reflectors for the ultrasonic sensor. The sensor system is fixed on the water surface and measures the flow with an angle of incidence of $\beta = 45°$ and an azimuth measurement range of $\alpha = \pm 30°$. To avoid ambiguities of echoes for this measurement depth, two orthogonal coded signals are transmitted at a repetition rate of 1ms.

After a measuring time of 16 ms respectively 16 temporal cycles of filtering, the measured velocity points arises as illustrated in Fig. 4. It clearly shows that even by the help of the phased-array technology a complete scanning of such a large channel width is not possible. However, to guarantee a complete coverage of the measurement, the missing measurement points are extrapolated by the spatial filtering. In addition, the velocity level of existing measurement points is balanced by the processing, to get in the end a homogeneous velocity profile as shown in Fig. 5. Here the structure of the velocity profile overlaps with the simulations and measurements of [11]. Furthermore, the comparison of the flow rates between the magnetic inductive flow sensor and the ultrasonic sensor shows only a deviation of 4%.

V. Conclusion

To measure the flow rate of an open channel in a cost effective way, an ultrasonic phased array sensor with its evaluation method is presented in this article. In contrast to classical ultrasonic flow sensors, it could be shown that this phased-array technology provides a larger measurement coverage of the channel and thus a more detailed reproduction of the velocity profiles. In addition to this technology an evaluation method is presented to detect the velocity of particles within the fluid. For this purpose, a special signal-code is used to identify the positions of reflecting particles, and track its streamline over the time by the help of an object tracking method. With this method, it is now possible for the first time to get a detailed view into the flow behavior of fluids and its velocity. By knowing those particle velocities and projecting them onto the cross section of the channel, the velocity profile and its flow rate can be computed. Combined with simulative

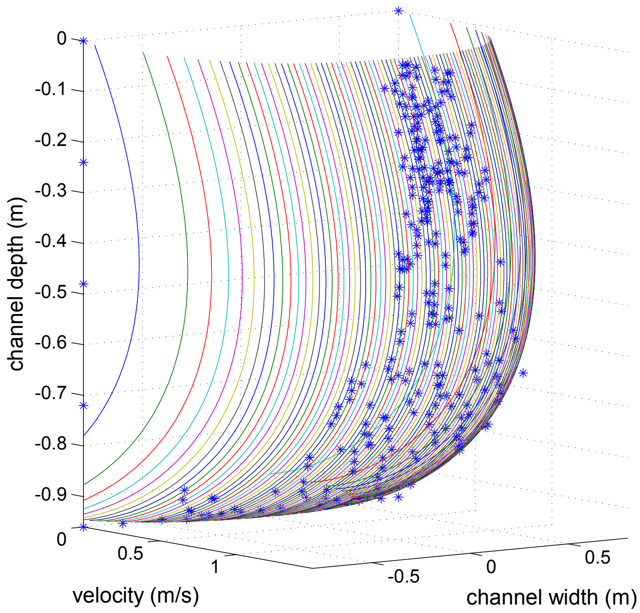

Fig. 4. Measuring results of an open channel from an urban sewage plant. The velocities of each streamline are depicted on the diagram with a *-symbol. Based on those velocities an interpolation has been done.

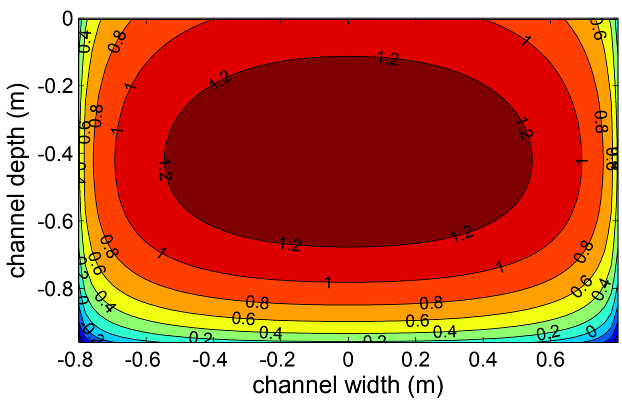

Fig. 5. The approximated velocity profile of an open channel from an urban sewage plant.

information it could be demonstrated, that the flow rate error is only 4% for a real-world measurement in an open channel.

For future work, an improved phased-array transducer with its pivoted range of $\pm 60^\circ$ in azimuth-direction will be used in order to obtain a better coverage of the measurement from the channel cross section. Additionally, it will be tested if a sensor-fusion of multiple phased-array transducers is possible for extremely wide river channels. Furthermore, the existing evaluation method will be expanded by a coherent measurement technique in order to extract more information from the flow behaviour on the basis of the Doppler frequencies.

Acknowledgment

The research is supported by the German Federal Ministry of Education and Research and the Christian-Albrechts-University zu Kiel.

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