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An Algorithm to Minimize the Zero-Flow Error in Transit-Time Ultrasonic Flow Meters

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***Abstract*—Transit-time ultrasonic flow meters are widely used in industry to measure fluid flow. In practice ultrasonic flow meters either show a zero-flow error or suffer from a significant random error due to a limited signal-to-noise ratio, requiring a significant amount of averaging to achieve good precision. This work presents a method that minimizes the zero-flow error whilst keeping the random error low, independent of the hardware used. The proposed algorithm can adjust to changing zero-flow errors while a flow is present. The technique combines the benefits of two common methods of determining the transit-time difference between the upstream and downstream ultrasonic waves: cross-correlation and zero-crossing detection. The algorithm is verified experimentally using a flow-loop. It is shown that the zero-flow error can be greatly reduced without compromising the random error or increasing circuit complexity.**

***Index Terms*—cross-correlation, flow measurement, reciprocity, transit-time, ultrasonic flow meter, zero-crossings, zero-flow error.**

I. Introduction

TRANSIT-TIME ultrasonic flow meters are used to measure fluid flow in a large range of industrial applications where the temperature and type of liquid often vary considerably. The transit time difference (TTD) between the upstream and downstream signals is a measure of the flow velocity. The fundamental idea behind ultrasonic flow meters is that the only non-reciprocal effect in the system is the flow itself [1]–[3]. However, in practical flow meters, an offset in zero-flow conditions is often found, causing a flow velocity to be measured, even in the absence of flow. This offset error is often referred to as the zero-flow error. The offset error can originate from a slight non-reciprocity in the circuit, caused by an impedance mismatch between the transmit and receive circuit. Other sources of offset error are temperature changes [4] (and the associated changes in material properties of the components), temperature differentials across the flow meter and variations in material properties or the liquid over the flow meter geometry. Due to process changes (e.g. variations in temperature or the liquid properties) the offset error can change in operation. Hence, it is important to minimize the magnitude of the error.

Minimizing the offset error is commonly done by matching the impedance of the receive circuit to the impedance of the transmit circuit, in order to maximize the reciprocity of the measurement system [3], [5], [6]. This method is good at reducing the offset error, but a residual offset usually remains.

Industrial flow meters are usually specified for a range of flow velocities, where the accuracy of the lowest flow speed determines the minimum time-difference that has to be detected. For example, in a flow meter that spans a range from 0.1 m/s to 100 m/s with a 5% accuracy, an error below 5% of 0.1 m/s is required, corresponding to a time difference of 0.18 ns in water for a 40 mm inner diameter pipe (with the transducer at a 45° angle). For a transmit signal with a center frequency of 2 MHz this results in a very small phase difference of 360 ppm of the wavelength. Detecting phase differences that are that small imposes stringent requirements on the electronics and algorithm that are used to calculate the flow. Small errors in the measurements can therefore quickly have a significant influence on the calculated flow velocity.

Two methods that are often used to calculate the phase difference or transit-time difference are zero-crossing detection and cross-correlation. As mentioned in [5], zero-crossing based detection often results in a lower offset error, whereas cross-correlation based methods produce results with lower random error. The latter is caused by the fact that cross-correlation uses information contained in the complete waveform of the received signal rather than just one point. An alternative approach was presented in [7], where the transducers were excited with a fixed frequency until a steady state was reached. The excitation frequency was tuned to calibrate the offset error. Although an interesting approach, its practical applicability is limited as calibration must be performed in zero-flow conditions and the transducers have to be separated by a significant distance to prevent interference of reflected waves. Similar to cross-correlation, an algorithm that uses time and phase domain signals was proposed in [8], with the main objective to be less sensitive to changes in the waveform shape.

Cross-correlating the upstream and downstream signal with their averages has been proposed to increase the measurement precision, because the average has a better resemblance to the waveform than the upstream and downstream signals mutually, because they might differ in amplitude and frequency [9]. Unfortunately, also this method requires recalibration in zero-flow conditions. Other work proposes to compare the measurement to the analytical solution of an oscillator model [10] or reconstructing the signal based on a signal model [11], mitigating the drawbacks of averaging. This method, however, still faces the drawback of the higher offset error commonly seen in cross-correlation measurements.

Thus, an algorithm that minimizes the offset error without compromising on the random error, that does not require calibration measurements, is desirable. This work proposes a method that combines the benefits of zero-crossing and

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cross-correlation methods to obtain flow measurements with a minimized absolute error in combination with a small random error, while being able to adjust for changes in the offset error over longer term as caused by environmental changes such as changes in temperature and pressure.

II. Simulation model

In order to simulate the upstream and downstream signals, the transducers are modeled using the KLM-model [12] in combination with a voltage source V_{in} and a source impedance R_{tx} representing the transmit circuit. The receive circuit impedance is modeled by the load impedance R_{rx}, as shown in Figure 1a. The cable capacitance and piezo capacitance are modeled by C_{p} and the two resonant branches represent the upstream (A) and downstream (B) transducer, coupled by an acoustic transmission line. Because we are only interested in the waveform shape and phase difference between the upstream and downstream signal, the KLM-model can be simplified by removing the acoustic transmission line and replacing it by its characteristic impedance Z_{tl} (Fig. 1b). The current in the transmit branch, I_{pulse}, is proportional to particle velocity in the acoustic domain. The acoustic pressure at the receive side of the transmission line is modeled as a voltage source, V_{pulse}, with a source impedance equal to the transmission line impedance Z_{tl}. The transformers and transmission line impedances can be replaced by an inductor when I_{PZT} and V_{pulse} are moved to the other side of the transformer and the values of the RLC-branch are adjusted accordingly. The adjusted component values are denoted $R_{\mathrm{A'}}$, $L_{\mathrm{A'}}$ and $C_{\mathrm{A'}}$. Similarly the receive side can be simplified as well. The resulting circuit model consists of two Butterworth-van-Dyke models [13], where the voltage source at the receive side is proportional to the current through the transmit transducer. The resulting simulation model is shown in Figure 1c.

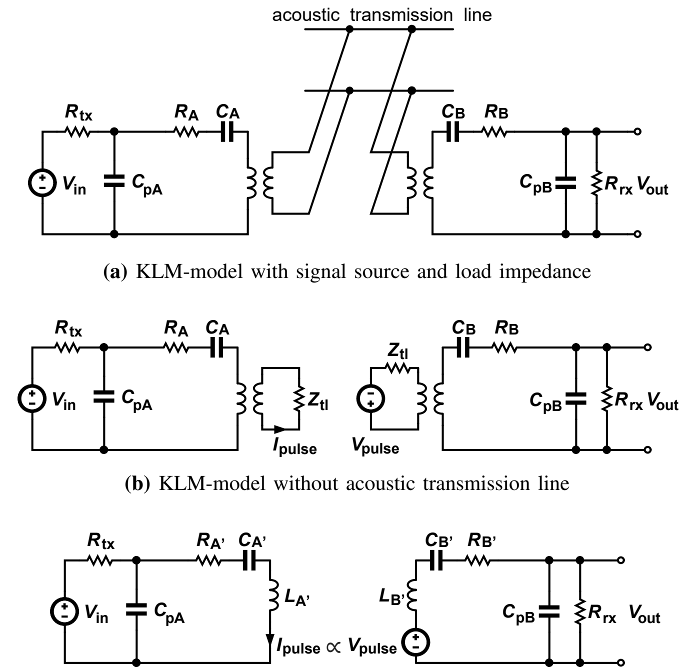
The component values of the Butterworth-van-Dyke model were determined by analyzing the impedance of a 10 mm PZT disc, and curve fitting the model parameters. The resulting parameters are shown in Table I. Transducer B is assumed to be equal to transducer A except for a 5 % mismatch in C_{B}. To simulate the upstream and downstream waveforms the parameters of the two transducers A and B are interchanged.

III. Error Sources

In transit-time ultrasonic flow meters two main error sources that are affecting the flow measurements can be distinguished: The offset error, which appears as an offset to the measured flow, and the random error which influences the precision of the measurement and shows as a randomly distributed deviation from the actual flow velocity.

TABLE I: Fitted model parameters for Butterworth-van-Dyke model

R	L	C	C_{p}
20 Ω	46 µH	139 pF	0.55 nF



(a) KLM-model with signal source and load impedance

(b) KLM-model without acoustic transmission line

(c) Simplified KLM-model

Fig. 1: Simulation model based on simplified KLM-model.

A. Offset Error

It is well known that the offset error is minimized by making the system as reciprocal as possible [14]. When the transducers or the circuit impedances are equal, the system is fully reciprocal and no offset error is present [3]. In a practical system a mismatch between the transducers will always be present. To minimize the offset error, one thus has to make the impedance of the transmit circuit and the impedance of the receive circuit equal and preferably both significantly lower or both significantly higher than that of the transducer [3], [5]. In practice it is not always trivial to make the circuit impedances equal, especially in mass-produced devices where batch variations have a significant impact on the performance. In those cases, often an offset error still exists. The offset error is simulated by introducing a mismatch between the transmit circuit impedance (R_{tx}) and receive circuit impedance (R_{rx}), as well as introducing a mismatch between the two transducers.

The offset error can be considered as a systematic error on the measurement: even with averaging, this error can not be reduced. Using the simplified KLM-model, an example upstream and downstream waveform are simulated, as shown in Figure 2a. For illustration purposes a large mismatch between R_{tx} and R_{rx} was used. As evident from the figure, the upstream and downstream transient waveforms differ slightly in amplitude and shape. Although the difference looks small in the figure, it introduces a significant error in the flow-measurement. This error becomes evident when looking at the instantaneous phase difference, or more practical, at the zero-crossings of the two waveforms. Figure 2b shows the transit-time difference calculated using zero-crossings detection. Note how the transit-time difference increases over time, eventually

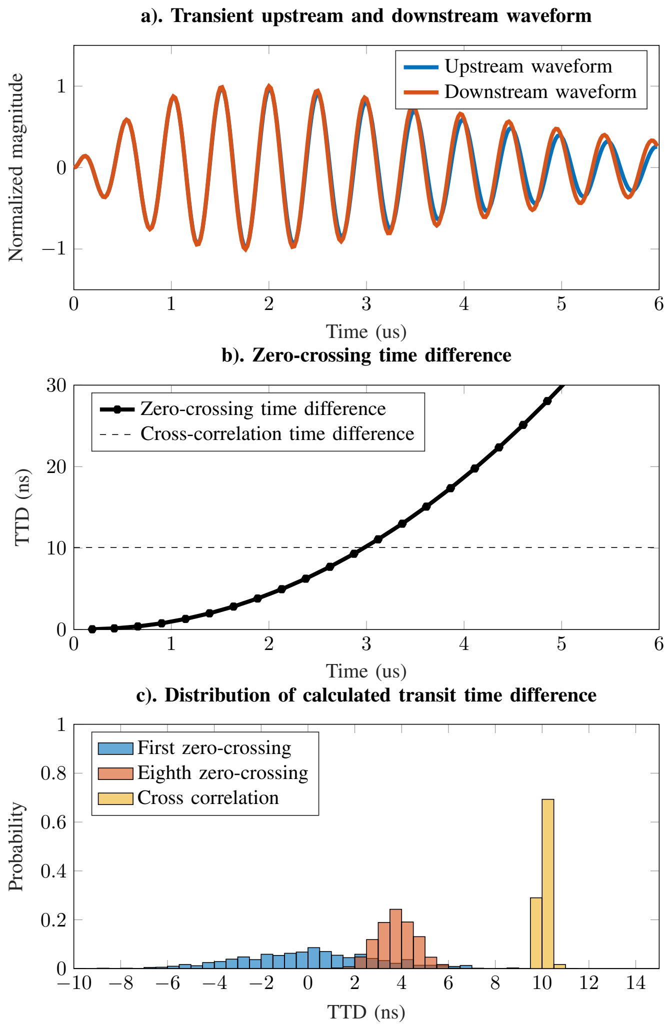


Fig. 2: Simulated upstream and downstream signals for $R_{\mathrm{tx}} = 50\,\Omega$ and $R_{\mathrm{rx}} = 20\,\Omega$, excited with a single square pulse: a). Transient waveforms b). Upstream-downstream time-difference (markers represent zero-crossings) and c). Probability distribution of the transit-time difference obtained using the zero-crossing and cross-correlation based algorithms for 2000 simulated waveforms with 30 dB SNR.

converging to a linear increase with time associated with the resonance-frequency difference between the transducers. The best estimate of zero flow can therefore be found early in the waveform, where the signal's amplitude is low. This is contradicting with the requirement of a high signal-to-noise ratio (SNR), as the best SNR can be obtained when a high signal amplitude is available. Therefore in practical systems that use zero-crossing detection, a trade-off is made between taking an early zero-crossing and having a good SNR.

The commonly used alternative to detect the phase difference between the upstream and downstream signal is by cross-correlating the signals. Cross correlation between two discrete signals f and g is defined as:

$$(f \star g)(\tau) = \int_{-\infty}^{\infty} \overline{f(t)} g(t+\tau)\, dt \tag{1}$$

where $\overline{f(t)}$ denotes the complex conjugate of $f(t)$. In essence cross correlation delays one of the waveforms (waveform g in equation (1)) and results in the highest magnitude when both waveforms resemble each-other best. The delay τ that results in the maximum value is assumed to be the phase difference of the two waveforms. With a phase shift that increases over time, as we saw in Figure 2b, the delay τ that results in the best resemblance between the waveforms f and g will be at a point in time where significant phase shift is present between the waveforms (as indicated in Figure 2b by a dashed line). This effect will generally cause the cross-correlation to result in a higher offset error than the zero-crossing detection result.

B. Random Error

In Figure 2c the probability distribution of 2000 simulated transit-time differences is shown for the first zero-crossing, for the eighth zero-crossing and for cross-correlation, based on a signal with 30 dB SNR. Clearly visible is the reduction of the random error when using a zero-crossing in the higher-amplitude part of the waveforms (here the eighth zero-crossing) and an even smaller deviation when cross-correlation is used.

Depending on the algorithm used to detect the transit-time difference, the random error varies. Especially in time-domain methods like zero-crossing detection, a low SNR can significantly degrade the precision of the measurement. The SNR can be improved by applying averaging, however the improvement when taking the average of N measurements is only $\sqrt{N}$ [15], so a starting point with a better SNR is beneficial.

Minimizing the random error is important to get a good measurement precision. The random error can be dominated by many sources ranging from thermal noise and clock jitter to turbulence in the flow. To guarantee a good SNR one would like to use a high amplitude transmit signal, however industrial meters are often limited in voltage to guarantee intrinsic safety. Moreover, short well-defined transmit waveforms are commonly chosen. Common transmit waveforms are a single square pulse [16] or a single-cycle sine. Although it is possible to obtain reasonable results with these methods, they suffer from low SNR because the transmit signal contains limited energy [17]. As an alternative, significantly longer transmit waveforms have been proposed, to be able to measure in a steady state [18], but with the drawback that the transducers must be far apart to not be affected by interference of reflected waves. Ideally one would like to use a transmit waveform that contains a significant amount of energy and is easy to cross-correlate to achieve a low random error on the transit-time measurements. From imaging physics, it is well known that the waveform can be optimized to improve the SNR when using cross-correlation [19].

To further improve the cross-correlation result, the receive waveform can be compared with a high SNR version of the signal [9], [10], such as an averaged waveform.

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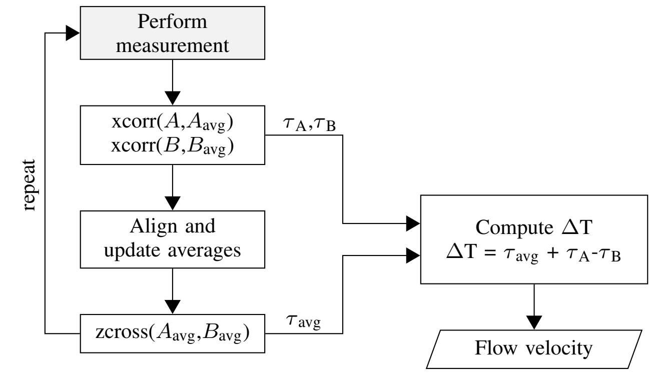

Fig. 3: Diagram showing the steps of the algorithm.

IV. Algorithm

Processing the measurement data in such a way that the offset error is calculated using zero-crossings, while the flow measurement is based on cross-correlation, combines the benefits of both techniques. An algorithm can thus be designed that removes the offset error caused by the cross-correlation operation. Because changes in the offset error are generally slow (e.g. due to temperature change), the zero-crossing calculation can be performed on an averaged signal, reducing the noise on the offset correction signal.

A diagram showing the steps of the proposed algorithm is shown in Figure 3. By means of a moving average, high SNR versions of the upstream and downstream waveforms are collected: A_{avg} and B_{avg}. Since the flow velocity can change over time, waveforms A and B have to be time shifted before they can be included in the moving averages. The required time shift can be determined by means of a cross-correlation between those waveforms and their respective moving averages:

$$\tau_A = \text{xcorr}(A, A_{\text{avg}}) \tag{2}$$

$$\tau_B = \text{xcorr}(B, B_{\text{avg}}) \tag{3}$$

where the xcorr() operation represents the time delay τ corresponding to the peak of the cross-correlation. The resulting average waveforms will have an unknown time difference τ_{avg} due to the flow. This time-difference is calculated using zero-crossing detection, to obtain the lowest offset-error possible:

$$\tau_{\text{avg}} = \text{zcross}(A_{\text{avg}}, B_{\text{avg}}) \tag{4}$$

where the zcross() operation represents the time difference between the first zero-crossing of each waveform, after the amplitude of the signal reaches a threshold value (in this work the threshold was set to 10% of the peak amplitude). With this time-difference the flow speed associated with the moving average can be determined. The difference between this average flow speed and the instantaneous flow speed can be determined by the earlier calculated time shifts τ_A and τ_B, assuming that only the flow speed has changed. Thus a low-offset version of the time difference representing the instantaneous flow is obtained:

$$\Delta T = \tau_{\text{avg}} + \tau_A - \tau_B \tag{5}$$

Fig. 4: Pair of transducers made of an air-backed piezo-ceramic disc mounted onto a PVC cylinder.

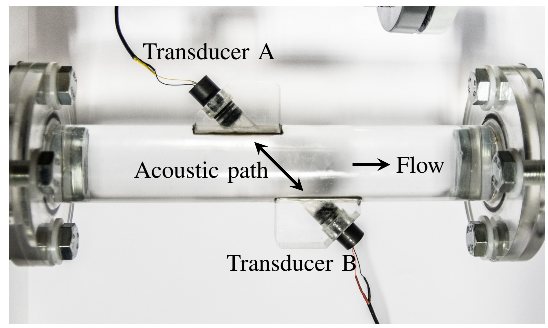

Fig. 5: Transducers placed co-axially at a 45° angle in a 40 mm inner-diameter pipe section of the flow-loop.

The random error on the resulting flow value is comparable to that on the cross-correlation, assuming the noise level on the averaged signals is sufficiently small to be negligible. In addition to reducing the offset error, the algorithm also reduces the random error compared to cross-correlation between the upstream and downstream signal. By calculating the cross-correlation between the two signals and their averages separately, the random error is reduced. The same cross-correlation results can also be used to align the signal and update the average without the flow influencing the averaged waveform.

V. Measurement Setup

A pair of transducers was built with 10 mm diameter Pz27 piezo-ceramic discs (Meggit A/S, Kvistgaard, Denmark), with a thickness of 1 mm and a resonance frequency of 2 MHz. The piezo-discs were glued onto a PVC cylinder to create air-backed transducers, as shown in Figure 4. The transducers were then placed at a 45° angle in a pipe section with an inner diameter of a 40 mm (Figure 5) mounted in a flow-loop filled with water. A reference flow meter (Optosonics 3400, KROHNE, Dordrecht, the Netherlands) with an accuracy of

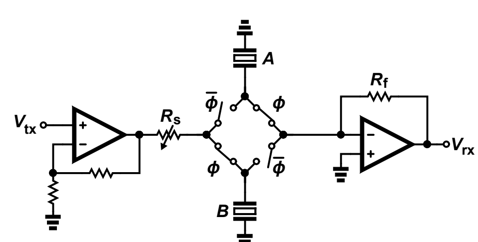

Fig. 6: Circuit used in the measurements.

±0.3 % + 2 mm/s, placed downstream, was used to validate the measured flow rate.

A measurement setup was built to first test several transmit waveform shapes in zero-flow condition and then measure a varying flow using the proposed algorithm. An Agilent 33522A (Agilent, Santa Clara, USA) arbitrary waveform generator was used to create a single square pulse, gaussian apodized sine and chirp signal. A printed circuit board (PCB), schematically shown in Figure 6, was produced. An amplifier (OPA847, Texas Instruments, Dallas, USA) mounted on the PCB was used to buffer the transmit waveform and create a low impedance output to drive the transducers. A trans-impedance amplifier (TIA) constructed using a THS3001 (Texas Instruments, Dallas, USA) amplifier was used to amplify the received acoustic signals with a low input impedance. The upstream (A) and downstream (B) transducer were alternately switched between the transmit and receive circuit using reed relays. Received signals were digitized using a Spectrum M3i.4121 (Spectrum, Grosshansdorf, Germany) acquisition card, with a sampling rate of 250 MS/s.

VI. Experimental Results

In zero-flow conditions, measurements were performed with several transmit waveforms with equal peak-to-peak transmit voltage. In Figure 7 the measurements with three common transmit waveforms are compared; a square pulse, a gaussian apodized sine wave (2 MHz) and a chirp (1.5-2.5 MHz). As can be seen in the second row, the signal amplitude of the received waveform is highly dependent on the energy contained in the transmitted signal. When we plot the zero-crossing time difference (Figure 7, bottom row) we notice that for each type of waveform the first detected zero-crossing has the lowest transit-time difference, confirming that the first zero-crossing is the best estimate of the zero-flow value. The cross-correlation results always show a relatively large offset error as shown in Table II.

Moreover, these examples show the benefit that can be obtained by choosing the right transmit waveform, because they result in very different random errors with the same transmit amplitude. The table also shows that the random

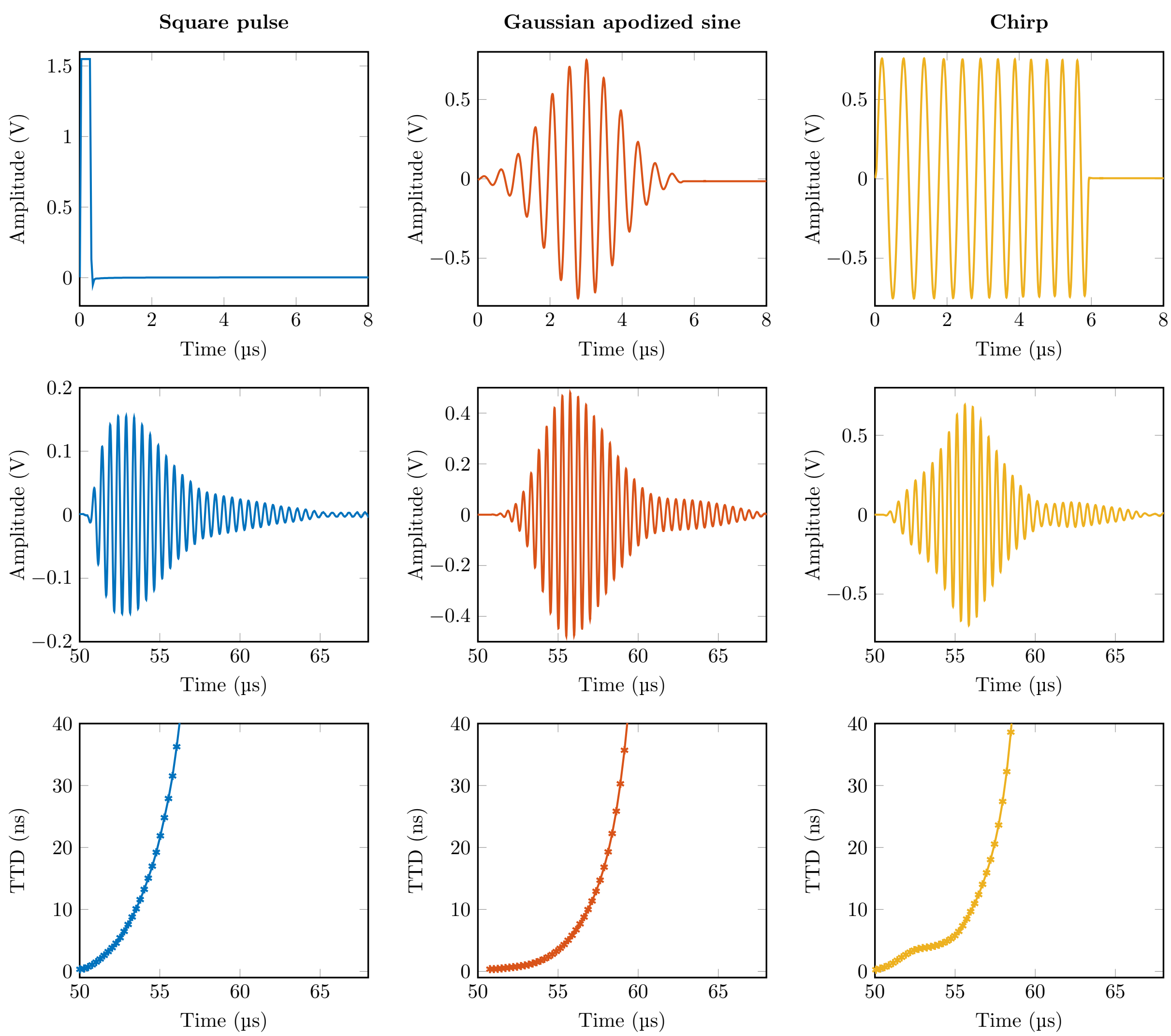

Fig. 7: Measured transmit waveform (top), receive waveform (middle) and zero-crossing transit time-difference (bottom), for 3 different transmit waveforms with similar peak-to-peak amplitude: square pulse (left), gaussian apodized sine (middle) and chirp (right).

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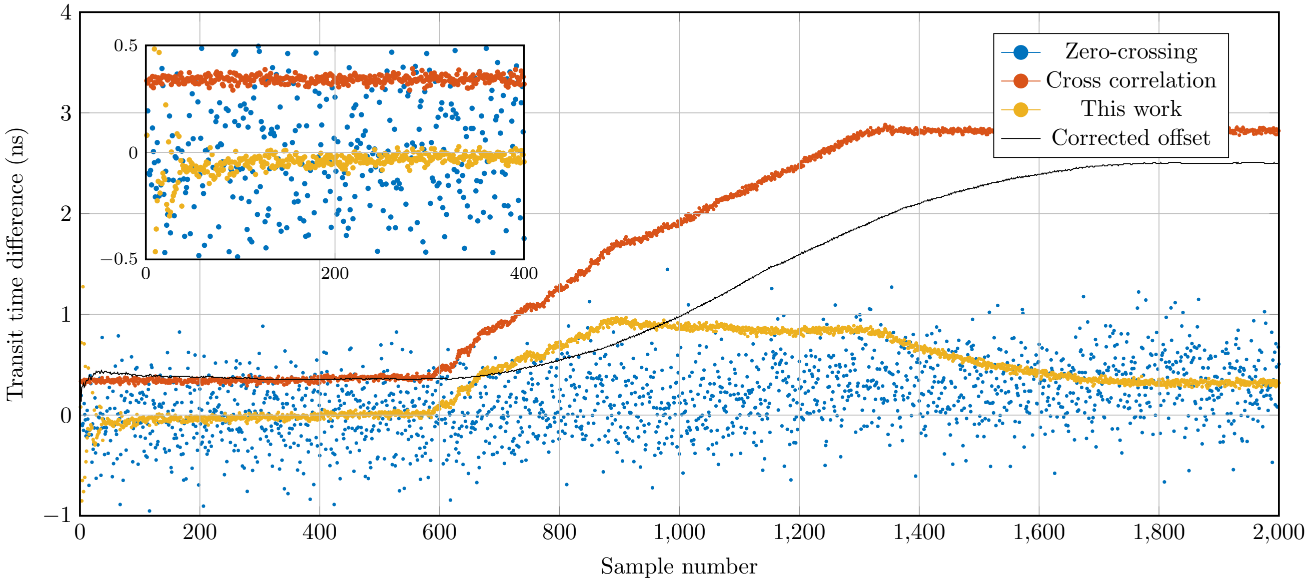

Fig. 8: Zero flow measurement with varying reciprocity, by introducing a mismatch between the transmit and receive circuit impedance. The corrected offset shows the absolute difference between the cross-correlation algorithm and this work.

error is larger for the zero-crossing method than for cross-correlation, as expected.

Another measurement was performed at zero-flow conditions, this time to compare the proposed algorithm with the cross-correlation and zero-crossing method to see its effect on the offset error. The inset in Figure 8 shows the transit-time differences for the first 400 consecutive measurements, calculated using cross-correlation, zero-crossing detection and the algorithm presented in this work with a moving average of 400 samples. In this measurement averaging the signal starts at sample 1, causing the offset error to be poorly estimated for the first few samples, where the average still has a low SNR, converging towards a steadier offset estimate when the SNR of the average signal improves. It is evident from the measurement that the random error significantly improves compared to the zero-crossing detection algorithm. The offset is reduced compared to the cross-correlated data by the correction that the zero-crossing detection on the averaged signals provides. As the average waveform is based on 400 measurements only, it is not yet possible to detect the earliest zero-crossing, resulting in a residual offset. By averaging more this offset can be reduced further, because an earlier zero-crossing can be detected.

After 600 measurement the reciprocity of the circuit was gradually reduced by changing the impedance of the transmit circuit (R_s in Figure 6). This measurement emulates changing environmental conditions. Figure 8 shows how the offset error increases when the mismatch between the impedances of the transmit and receive circuit is larger. The algorithm is still dependent on the reciprocity of the system, but the offset error is significantly lower compared to cross-correlation. In this measurement the offset error is reduced by more than a factor of 7. Moreover, the random error of the algorithm is with a standard deviation of 17 ps a factor of 10 lower than with zero-crossing detection, which has a standard deviation of 182 ps in the measurement. The figure also shows that abrupt changes temporarily cause an increased offset error compared to zero-crossing detection, this is caused by the low-pass behavior of averaging.

TABLE II: Measured offset error and random error (std.) calculated using zero-crossing detection and cross-correlation for three types of transmit waveforms.

	zero-crossing		**cross-correlation**	
Waveform	offset	std.	offset	std.
Square pulse	0.35 ns	2.8 ns	8.7 ns	1.49 ns
Gaussian apodized sine	0.36 ns	1.7 ns	8.6 ns	0.29 ns
Chirp	0.17 ns	1.8 ns	7.2 ns	0.20 ns

A large benefit of the algorithm is that the average signals can be updated in the presence of flow. To show the performance with varying flow velocities, measurements were performed in a flow loop. The flow velocity was varied from 0 m/s to 0.6 m/s. The measurement results shown in Figure 9 confirm that the algorithm is able to calculate the flow velocity with a significantly lower offset error than obtained using cross-correlation. The random error is also significantly lower than it is for the samples based on the zero-crossings (blue markers). At low flow velocities (v<0.2 m/s) the random error of the cross-correlation result is noticeably lower. This difference is likely due to the transition from turbulent to laminar flow condition.

To test the effect of temperature changes on the algorithm, a measurement over a few hours was performed, starting with hot water of 75°C in the setup and allowing it to cool down towards ambient temperature. Figure 10 shows the measurements for the different algorithms. Also here the proposed algorithm is able to reduce the offset significantly. The figure includes, for comparison, a curve representing the cross-correlation results corrected based on a calibration for the offset error at the start of the measurements. This results

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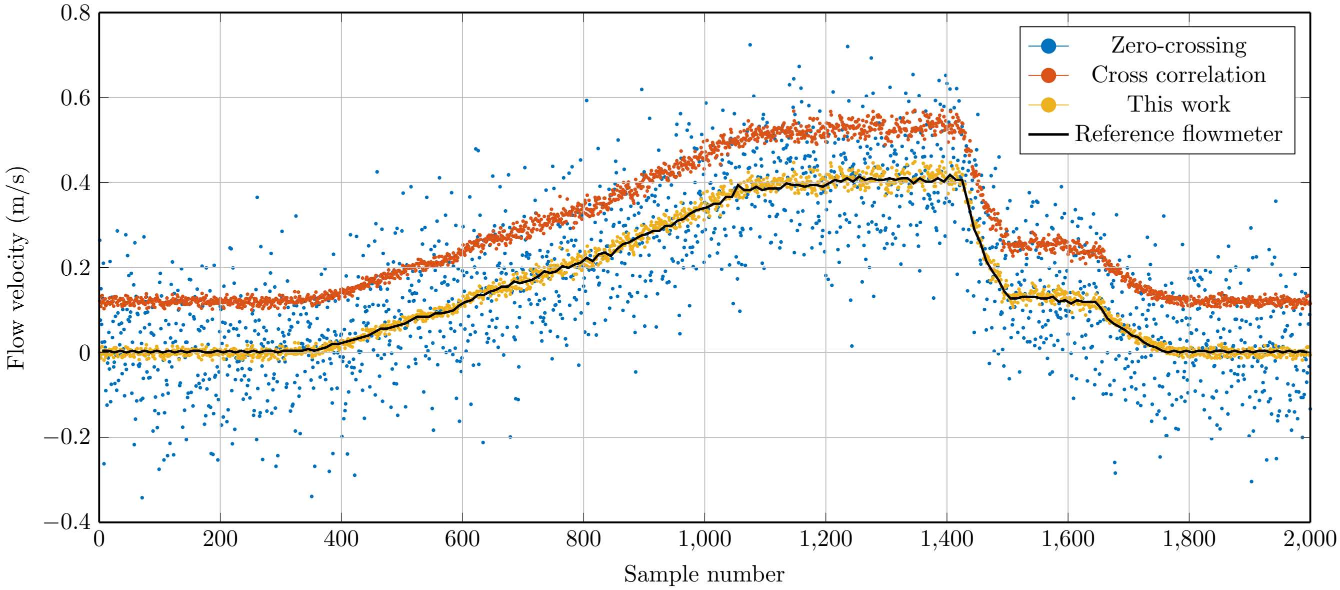

Fig. 9: Measured flow velocity in the flow-loop with varying flow, showing the effectiveness of zero-crossing detection, cross-correlation and the method described in this work.

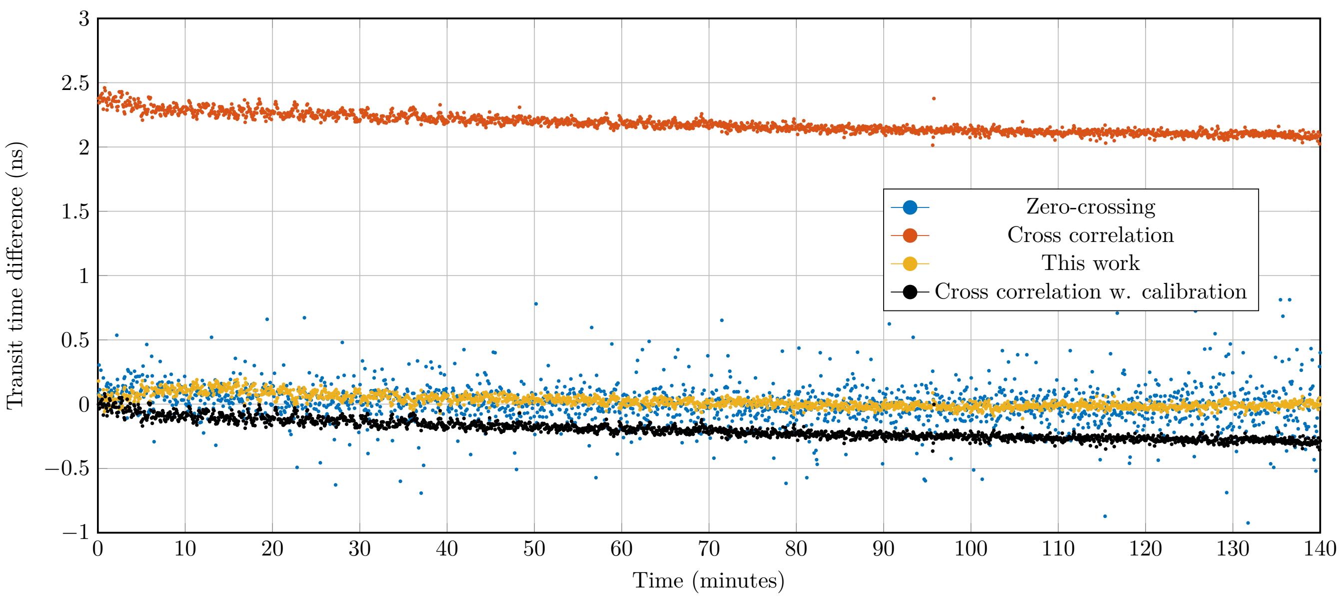

Fig. 10: Measured transit time difference in zero-flow condition with water temperature decreasing from 75°C to 30°C.

in a significant offset error at the end of the measurement, in contrast with our algorithm, that effectively nulls the offset.

VII. Discussion

The algorithm presented in this work is most effective in transit-time flow meters in which the electronics suffer from non-reciprocity. In applications with quickly changing environments, such as fluctuating temperatures, it might not always be optimal because a smaller number of averages must be used, reducing the measurement accuracy. In the more common environments that have slowly changing environmental parameters, for example changing over the course of minutes, a large number of averages in the order of tens of thousands of samples can be used to make the zero-crossing detection used in the algorithm as insensitive as possible to noise on the receive signal and thus making the algorithm very robust. The flow measurements shown in this work (Fig. 9) only use an average of 2000 waveforms, which can be recorded in a few seconds.

Naturally, averaging is only effective at reducing noise. Periodic interference, such as reflections of the acoustic wave, can still interfere with the measurement and alter the phase of the waveform. Moreover, zero-crossing detection inherently results in a residual offset, because physically the received signal cannot start with a zero-crossing, and thus the phase difference developed at a half-period will remain. Improvements can likely be made by predicting the actual start of the signal, or extrapolating the zero-crossing points.

It is important to note the distinct difference in the way averaging is implemented compared to prior work. By time-shifting the samples to align them before averaging, the average is not affected by a change in flow velocity, in fact, even instantaneous flow changes can be tolerated. The algorithm discussed here is, unlike prior work, not limited to specific waveforms with the benefit that the waveform can be optimized for maximum SNR.

In a practical implementation the sample rate can be significantly lower than that of the acquisition card used in this work. Moreover, cross-correlation can take place during the transit-time, which is in the order of 50 µs, relaxing the hardware requirements.

Several implementation variants on the algorithm are conceivable, with differing hardware complexity. For example, cross-correlation with an averaged waveform can be left out when a slight adjustment is made to the algorithm, at the cost of an increase in random error.

VIII. Conclusion

An algorithm for transit-time ultrasonic flow measurements that calculates the flow velocity with a low offset error and with high precision has been designed. It was shown that zero-crossing detection yields the lowest offset error while cross-correlation results in the lowest random error. The algorithm combines those benefits by detecting the zero-crossings of a long-term average. Cross-correlation with the same average was used to achieve the best precision. The described algorithm improved the flow measurements significantly with a 7 times reduction of the offset error compared to cross-correlation. The random error was comparable to cross-correlation and in the measurements 10 times lower compared to zero-crossing detection.

The algorithm was able to adjust to simulated environmental changes, proving it does not require calibration in zero-flow conditions. Moreover, it can be implemented on existing transit-time ultrasonic flow meters that already employ cross-correlation, by updating the software only, potentially improving the specifications with just a firmware update.

Acknowledgment

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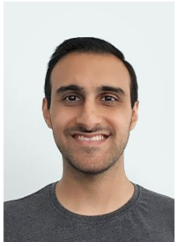

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