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Feasibility of Ultrasonic Flow Measurements via Non-linear Wave Propagation

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***Abstract*—Typically, ultrasonic flow meters assume linear wave propagation. Nevertheless, if the transducers of an ultrasonic flow sensor excite a pressure wave with a high amplitude, nonlinear wave propagation effects become significant. The appearance of higher harmonics increases the bandwidth of the received signal, which may potentially lead to a more precise flow measurement. However, the question arises whether the increased bandwidth can be used in practice, since the intensity of the 2nd harmonic can be 25 dB below the fundamental. One exploit of the increased bandwidth is to filter the received signals and to obtain two components: the fundamental and the 2nd harmonic. Differences between the upstream and downstream transit times are directly related to the flow speed, and these can be computed for each component of the received signals. This paper shows that averaging the transit time differences of the fundamental signals and the 2nd harmonic signals results in a lower standard deviation compared to the standard deviation of the transit time differences of the fundamental or the 2nd harmonic signal alone. This demonstrates the feasibility of using non-linear wave propagation to improve the precision of flow measurements using ultrasound.**

Keywords—flow, non-linearity, ultrasound, precision

I. INTRODUCTION

Ultrasound is one of the methods to measure flow in an industrial setting. The typical in-line scheme consists of two transducers with their faces oriented under a certain angle with respect to the moving fluid (Fig. 1). Two signals are sent and measured: one downstream and another one upstream of the flow. The velocity of the liquid and the propagation speed add or subtract vectorially. Thus, the difference between the up- and downstream transit times is proportional to the flow speed. Usually, in the design and modelling of ultrasonic flow meters, linear wave propagation is assumed. However, acoustic wave propagation is fundamentally nonlinear [1]. During wave propagation, higher harmonics build-up progressively, distorting the propagating wave. The harmonics increase the total bandwidth of the received signal. In general, a larger bandwidth leads to more precise measurements. However, as the amplitudes of these harmonics are always significantly lower (< -20 dB) compared to the level of the fundamental, it is not clear whether and how this can also be exploited here. This question will be addressed in the current work.

II. THEORY

A. Ultrasound Flow Measurements

Ultrasound can be used to measure flow by placing transducers in direct contact with the moving medium (in-line, see Fig. 1.a). By exciting each transducer and recording the received signal on the other end, it is possible to compute the flow speed of the moving medium from the arrival time differences [2]:

$$v_m = \frac{L(t_u - t_d)}{2 t_u t_d \cos\theta} \qquad (1)$$

In (1), L represents the distance between the centers of the transducers, t_u and t_d represent the transit times of the upstream and downstream signals, respectively. The angle θ represents the orientation of the transducers with respect to the flow direction. A different setup for measuring flow speed has both transducers on top of the pipe wall (clamp-on, see Fig. 1.b). The analysis in this paper can easily be adapted to this case.

B. Non-Linear Wave Propagation Considerations

The theory about non-linear wave propagation is well known in literature; [3] provides a description of this phenomenon in an ultrasonic flow measurement setting. The nonlinearity of wave propagation leads to a progressive build-up of harmonics as the wave propagates through a medium. For the purpose of flow measurements, it is important to make sure that the non-linear component of the recorded signals is due to the wave propagation phenomenon only and not due to the electronic circuitry that drives the transducer and amplifies the received signal.

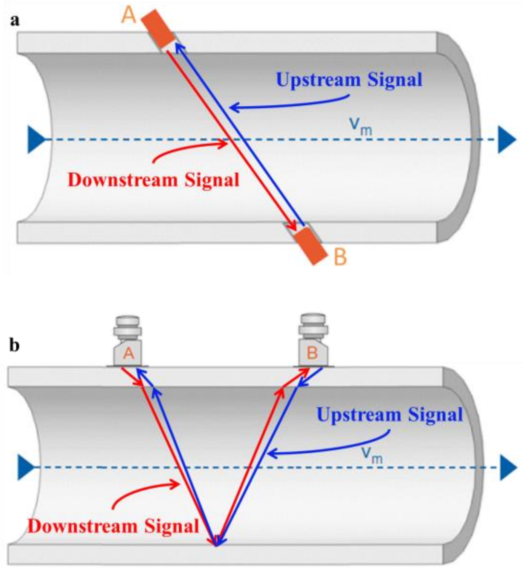

Fig. 1. Sketch of an in-line (a) and a clamp-on (b) ultrasonic flow sensor. Notice that flow is travelling from left to right with a speed equal to v_m. The travel path of the signals has been spatially exaggerated for visualization purposes. Modified image from KROHNE.

III. METHODOLOGY

This section provides a detailed description on how the data was acquired and processed.

A. *Experimental Setup*

A flow sensor was built consisting of two transducers (V382, Olympus, Tokyo, Japan, center frequency of 3.5 MHz, -6 dB bandwidth: 2.24 - 4.42 MHz) mounted inline in an acrylic pipe (inner diameter 40 mm) and oriented at 45° with respect to the direction of the flow. The sensor was tested using a custom-built flow loop. The liquid used was water.

B. *Data Acquisition Scheme*

A 5-cycle Gaussian-apodized sine wave with a center frequency of 2.3 MHz was used as excitation signal. Five different flow speeds, ranging between 0.1 m/s and 0.5 m/s, were measured. A reference ultrasonic flow meter (Optosonics 3400, KROHNE, Dordrecht, Netherlands) was used as benchmark. For each flow speed, three different peak-to-peak input voltages were used: 60 V, 120 V and 180 V. These values were obtained with a 50 dB amplifier (2100L RF Amplifier, Electronic Navigation Industries, Rochester, NY, USA). The flow was kept constant sufficiently long to perform 1000 measurements per flow speed. The acquisition procedure consisted of a signal triggered by an AWG (Agilent 33521A, Keysight Technologies, Santa Rosa, CA, USA) and amplified 50 dB. The amplified signal was sent to a custom-made PCB that contained a 50-ms alternating switch to select one of the two transducers for transmission. The transmitted signal was also sent to an attenuator (Bench Top Attenuator, JFW Industries Inc., IN, USA) before recording it simultaneously with the received signal by an acquisition card (M3i.4142 Spectrum Instrumentation GmbH, Großhansdorf, Germany). Fig. 2 shows a sketch of the electronic acquisition scheme.

C. *Data Processing Scheme*

After data acquisition, the following processing steps were applied to each pair of upstream and downstream signals:

1. Time-window the received signals.

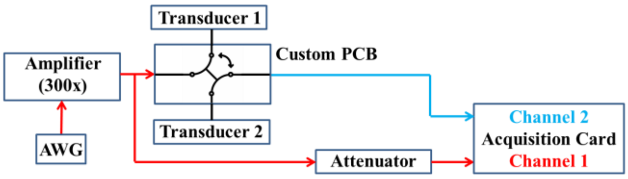

Fig. 2. Electronic acquisition scheme used to record data from a custom-made ultrasonic flow sensor. The red and blue arrows show the path of the transmitted and received signals, respectively. The transmit signal was attenuated 55 dB before being recorded in order to avoid damage of the acquisition card.

2. Apply trigger time interpolation on the upstream and downstream transmitted signals.
3. Apply a Fourier transformation on the received signals.
4. Separate, in the frequency domain, the fundamental and the 2nd harmonic spectra of the received signals.
5. Apply an inverse Fourier transform to obtain the fundamental and 2nd harmonic of the received signals in the time domain.
6. Compute the transit time difference between the upstream and downstream time domain signals via cross-correlation and subsequent interpolation, for the originally received signals, the fundamentals, and the second harmonics.
7. Repeat 1-6 for all 1000 measurements and average the transit time differences for the fundamental (1000 values), 2nd harmonic (1000 values), and the combined fundamental and 2nd harmonics (2000 values) to obtain a value for the respective flow speed.

IV. RESULTS AND DISCUSSION

Fig. 3 shows the frequency content of the transmitted and received signals recorded for each transmitted voltage. It was observed that for peak-to-peak voltages higher than 180 V the transmitted signals started to show harmonic content, so it was concluded that beyond this value the non-linearity of the amplifier started to have a non-negligible influence.

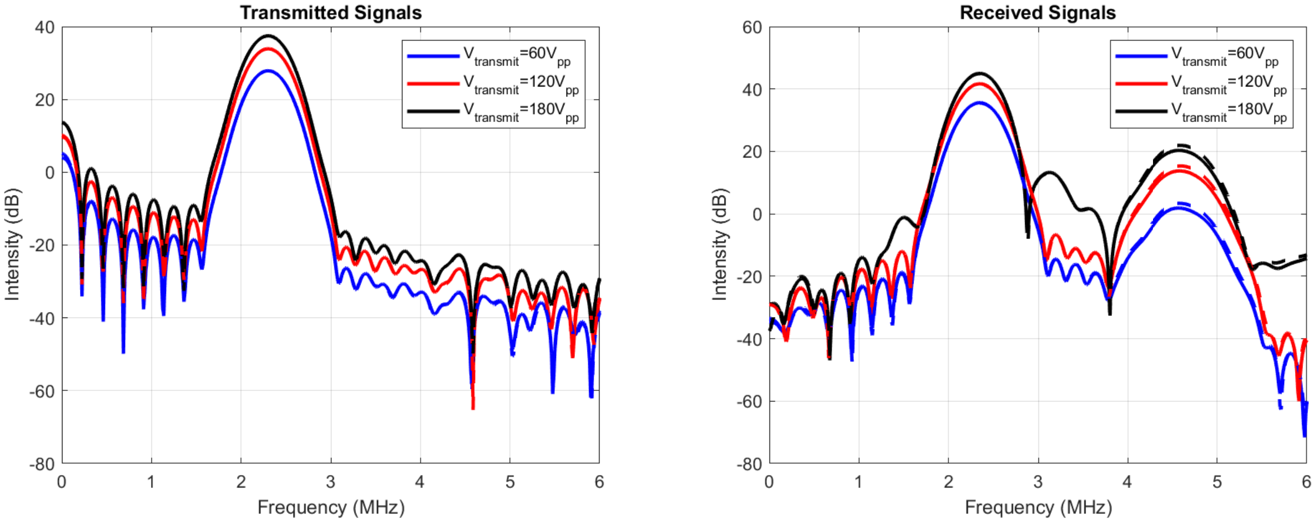

Fig. 3. Frequency spectra of the mean transmitted and received upstream (solid) and downstream (dashed) signals. Due to the attenuator , the transmitted signals shown here have lower levels than the received signals.

Table I shows the flow speeds measured and the transmitted voltages applied on the transducers, and Table II shows the expected transit time differences for each reference flow speed.

A. *Frequency Spectra of Transmitted and Recorded Signals*

In Fig. 3 the peak spectral values of the transmitted signals are below those of the received signals. This effect is due to the 55 dB attenuation applied on the transmitted signals before recording them (Fig. 2). For the received signals in Fig. 3, a clear 2nd harmonic centered around 4.6 MHz is visible.

B. *Time Delays*

For each single upstream-downstream pair of originally received signals, and their fundamentals and 2nd harmonics, a cross-correlation algorithm was used to compute the transit time difference. Fig. 4 contains a histogram for the computed values for the 1000 measurement pairs at a single flow speed in case of a peak-to-peak transmit voltage of 120 V. These values seem to follow a normal distribution.

C. *Individual and Combined Standard Deviations*

Fig. 5 shows the obtained standard deviations of the computed transit time differences for 1000 measurements and peak-to-peak transmit amplitudes of 60 V, 120 V and 180 V, respectively. The standard deviations for the original (not shown) and the fundamental signals were the same. Two details can be observed from Fig. 5. First, there appears to be no trend between the standard deviation of upstream/downstream transit time difference and the flow speed. Second, and most importantly, the standard deviation of the combined fundamental and 2nd harmonic signals is smaller than the standard deviation of the fundamental alone. Thus, for a sufficiently large transmit voltage, the 2nd harmonic part of the received signals could also be used to compute transit time differences.

D. *Flow Speed vs. Time Delay Relation*

Fig. 6 shows the relation between the computed transit time differences and flow speeds. A clear linear relation can be observed for the fundamental as well as for the 2nd harmonic signals. Even though Fig. 6 only shows the trend for the obtained results for a peak-to-peak transmit amplitude of 180 V, the same linearity was observed for the results obtained at 60 V and 120 V. The linearity of the fundamental data was expected from equation (1). Nevertheless, it is observed that the 2nd harmonic data also follows a linear trend. This was not a trivial result to expect since (1) assumes linear wave propagation, and furthermore, the level of the harmonic part of the signal is 25 dB lower than the fundamental. However, these results show the feasibility of using the 2nd harmonic to compute flow speed, and together with the fundamental component, improve the precision of ultrasonic flow measurements.

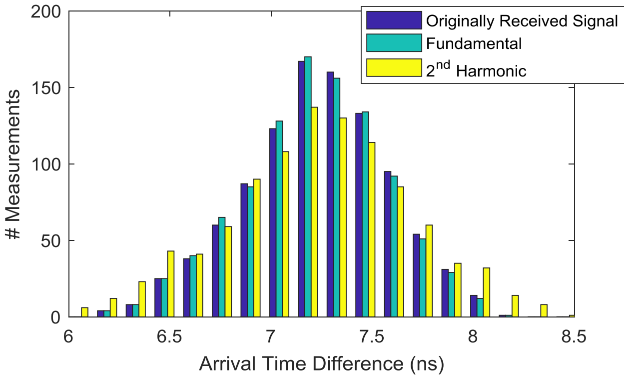

Fig. 4. Histogram of computed transit time differences for a reference flow speed of 0.3 m/s and a peak-to-peak transmit amplitude of 120 V.

Besides its potential advantage in terms of precision, using nonlinear wave propagation could also be of interest for clamp-on flow meters, if the wavelength in the pipe wall is relatively large compared to the pipe wall thickness: it would allow a reduction of the emitted frequency and effectively increase the opening angle in the liquid.

TABLE I. MEASUREMENT SETTINGS

Input Voltages	**Reference Flow Speeds**[a]				
60 V_{pp}	0.1 m/s	0.2 m/s	0.3 m/s	0.4 m/s	0.5 m/s
120 V_{pp}	0.1 m/s	0.2 m/s	0.3 m/s	0.4 m/s	0.5 m/s
180 V_{pp}	0.1 m/s	0.2 m/s	0.3 m/s	0.4 m/s	0.5 m/s

[a] Flow speeds read from the reference flow meter.

TABLE II. TRANSIT TIME DIFFERENCES

Reference Flow Speeds	**Transit Time Difference**
0.1 m/s	2.9 ns
0.2 m/s	5.9 ns
0.3 m/s	8.8 ns
0.4 m/s	11.7 ns
0.5 m/s	14.5 ns

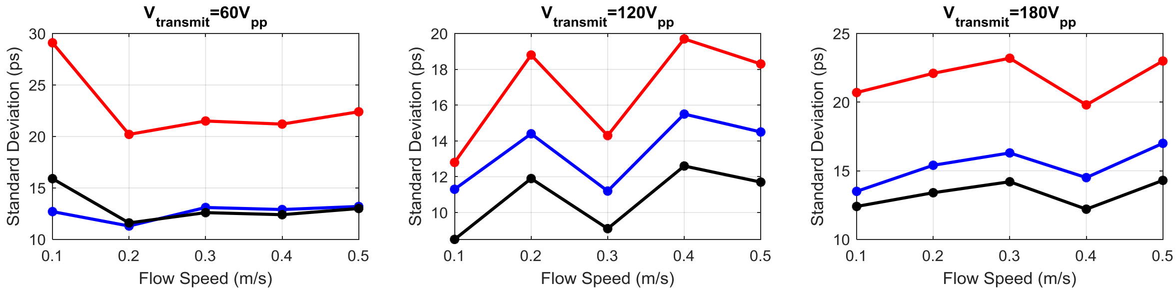

Fig. 5. Standard deviations of the computed transit time differences for the fundamental (blue), 2nd harmonic (red) and the combined fundamental and 2nd harmonic (black) components.

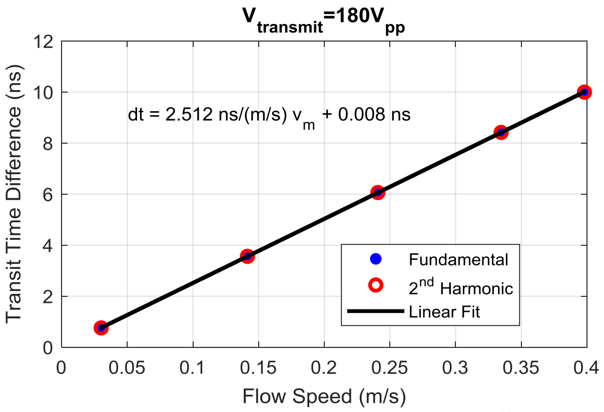

Fig. 6. Linear relation between computed transit time differences and flow speeds. Notice the very good agreement between the flow speeds reported by the fundamental and 2nd harmonic signals.

V. CONCLUSIONS

In this work, the potential of non-linear wave propagation in ultrasonic flow measurements was investigated. By separating the fundamental and 2nd harmonic of upstream and downstream received signals, it was possible to compute the transit time differences for each version. It was found that the standard deviation of the computed transit time differences for the combined fundamental and 2nd harmonic data was lower than for the fundamental data alone. Therefore, it can be concluded that the 2nd harmonic part of the received signals can be used to improve the precision of ultrasonic flow measurements.

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