Adaptive Asymmetric Double-Path Ultrasonic Transit-Time Gas Flowmeter

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***Abstract* – In this study we demonstrate that a double-path ultrasonic transit-time gas flowmeter can be extended significantly in its rangeability by shifting the two receiving transducers by the same amount in flow direction, such that the length of one sound path is increased, the other decreased. Such an asymmetric configuration is optimized in terms of signal-to-noise ratio (SNR) for the range of higher flow velocities, because it compensates for the parasitic carry-along (sound drift) effect. Further, this approach enables the realization of an adaptive asymmetric UFM, where the two receiving transducers can be shifted during operation for optimum SNR depending on the gas flow velocity. Our results show that the asymmetric configuration increases UFM rangeability without drawbacks.**

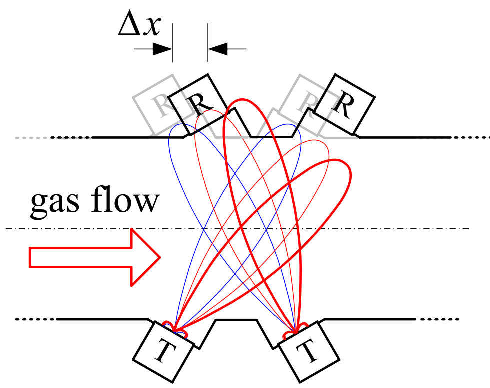

Fig. 1. A double-path UFM extended in its rangeability by shifting both receiving transducers (R) by the same shift distance (Δx) in flow direction to compensate for the carry-along effect (sound drift).

I. Introduction

Ultrasonic gas flowmeters (UFMs) utilizing the transit-time method, which is the most widely used non-intrusive ultrasonic method for flow metering, are advantageous for many applications because of their high accuracy; almost zero pressure drop; and the nonexistence of moving parts. At least one pair of ultrasonic transducers is required to measure the upstream and downstream ultrasonic transit times for the calculation of the gas flow velocity without knowledge of the speed of sound [1].

In many applications, constraints associated with the possible pipe diameter are a limiting factor in terms of the rangeability of the UFM. On the other side, shorter sound path lengths in such smaller UFMs attenuate the ultrasonic waves less, and, therefore, ultrasonic transducers utilizing higher frequencies can be used [2]. The advantage is a better time resolution and the capability to operate outside noise-dominated frequency ranges [3]. Because of their better acoustic impedance match to gases, compared to piezoelectric transducers, capacitive ultrasonic transducers (CUTs) or capacitive micromachined ultrasonic transducers (CMUTs) are excellent candidates. The main drawback of using higher frequencies (300-800 kHz) are narrower ultrasound beams (main lobe), which cause problems in terms of low SNRs at higher gas flow velocities due to the parasitic carry-along (sound drift) effect [4]. In [5] a solution is presented, where the transducers are inclined at an angle to the inter-transducer centerline in order to overcome the carry-along effect. This solution is applicable for both single-path and multi-path measurement cell configurations.

If at least two independent sound paths, *i.e.* one upstream and one downstream oriented path, are available, another solution to compensate for the carry-along effect can be realized. Usually, a double-path UFM has equal distances between receiver and transmitter in both of its sound paths, *i.e.* it is a symmetric configuration in terms of its ideal sound path lengths, which is also the case in the solution described in [5].

In our solution the two receiving transducers are shifted by the same shift distance (Δx) in flow direction, such that one path is increased, the other decreased. The result of this idea is an asymmetric UFM (Fig. 1), with a significant improvement in terms of rangeability. Compared to the solution reported in [5], our solution enables a simple UFM

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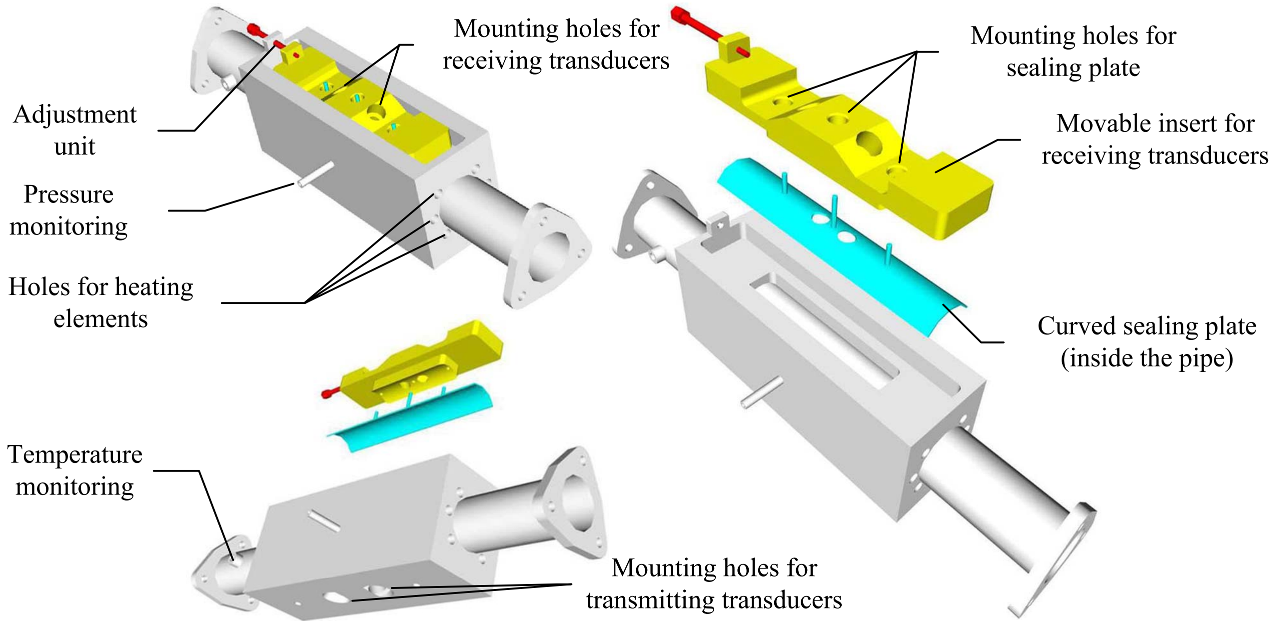

Fig. 2. Design drawings (different views) to illustrate the realization of an adaptive asymmetric UFM. The movable insert enables shifting both receiving transducers with and against the flow direction during UFM operation. The curved sealing plate is mounted inside the pipe. (Drawing by courtesy of AVL List GmbH, Graz, Austria.)

realization where the two receiving transducers can also be shifted during UFM operation. Consequently, this paper introduces an adaptive asymmetric UFM that can adjust itself to the optimum conditions to maximize SNR over a wide measurement range.

II. Realization of an Adaptive Asymmetric UFM

By using a movable insert for the two receiving transducers, an adjustment unit, and a curved sealing plate inside the pipe, the idea of an adaptive asymmetric UFM can be implemented (Fig. 2). The prototype has a pipe diameter of 50 mm and utilizes four identical CUTs, operated at a center frequency of 350 kHz in a wetted configuration, *i.e.* in direct contact to the gas. The four wetted transducers are positioned such that no protrusion into the pipe occurs, achieved with four transducer port cavities (Fig. 3).

III. Derivation of UFM Equations

It is essential to consider the transducer port cavities for the derivation of the UFM equations for the gas flow velocity v and the speed of sound c. Both are the mean values along the sound paths. Details of this derivation are described in [6].

In the case of the asymmetric UFM the derivation needs to be extended such that the shift distance (Δx) is considered. By using the measured temperature

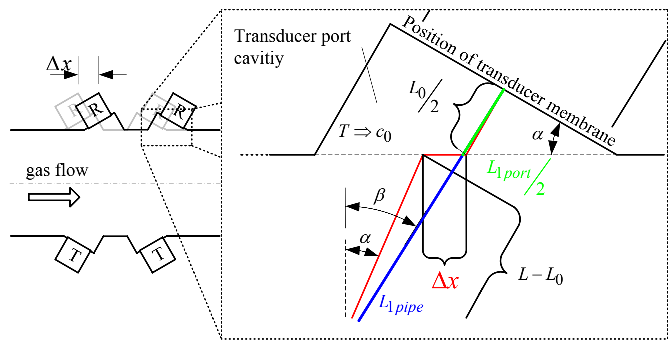

Fig. 3. Schematic of how the shift distance (Δx) and transducer port cavities are considered for the derivation of the UFM equations (v, c) for the asymmetric configuration.

information (T) from inside the transducer port cavity, the speed of sound c_0 can be calculated and the equations for the downstream transit time as a function of (Δx), *i.e.*

$$t_{down}(\Delta x) = \frac{L_{1pipe}(\Delta x)}{c + v\,\sin(\beta(\Delta x))} + \frac{L_{1port}(\Delta x)}{c_0(T)} \qquad (1)$$

and for the upstream transit time

$$t_{up}(\Delta x) = \frac{L_{2pipe}(\Delta x)}{c - v\,\sin(\gamma(\Delta x))} + \frac{L_{2port}(\Delta x)}{c_0(T)} \qquad (2)$$

can be written (Fig. 3), where $L_{1pipe}(\Delta x)$ and $L_{2pipe}(\Delta x)$ are the ideal sound path lengths inside the

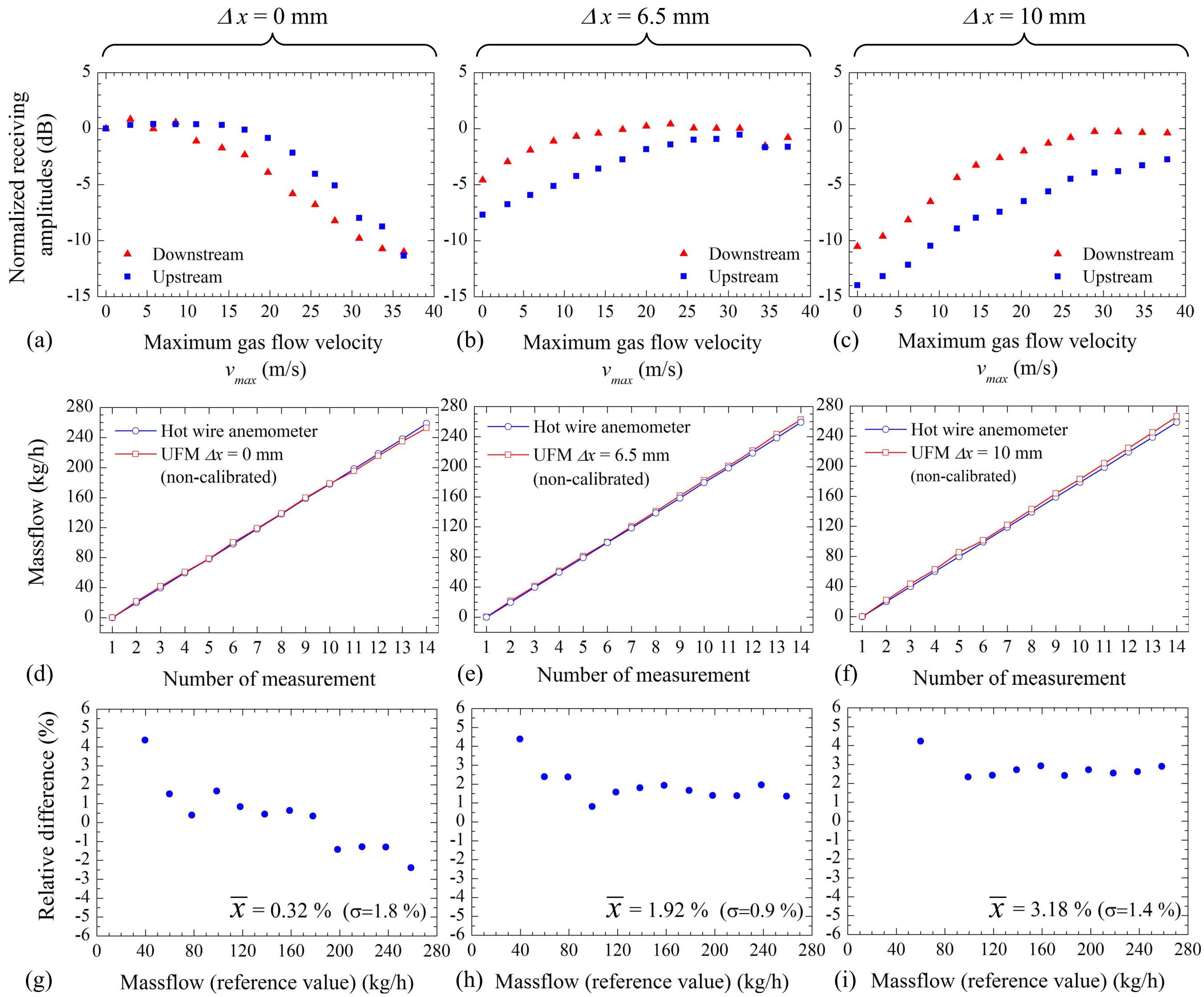

Fig. 4. Best-case-normalized receiving amplitudes depending on the maximum gas flow velocity v_{max} (a, b, c); measured gas mass flow values compared to reference values obtained from a certified hot wire anemometer (d, e, f); relative differences with respect to reference mass flow (g, h, i); all for a symmetric ($\Delta x = 0$ mm) and two asymmetric ($\Delta x = 6.5$ mm, $\Delta x = 10$ mm) UFM configurations.

pipe, $L_{1port}(\Delta x)$ and $L_{2port}(\Delta x)$ are the ideal sound path lengths inside the transducer port cavities, and $\beta(\Delta x)$ and $\gamma(\Delta x)$ are the resulting inclination angles of the ideal sound path lengths, all in downstream and upstream direction, respectively. These two equations can be easily solved for v and c to get the UFM equations for the asymmetric UFM.

IV. Proof of Principle and Results

For the experiments, we installed the UFM in a gas flow loop with a maximum gas flow velocity of 38 m/s (Mach number 0.11). A flow conditioner consisting of a bundle of small pipes (∅5 mm) inside the starting length before the UFM was used to minimize parasitic effects of vortexes. In all experiments we used three different values for the shift distance Δx (0, 6.5 and 10 mm). A determination of transit-times in both channels at 350 kHz and zero gas flow, while increasing the shift distance Δx, revealed that our detection algorithm started to fail when the value of $\Delta x = 14$ mm was reached. Including a safe margin, a shift distance of 10 mm gives an optimum non-adaptive configuration of an asymmetric UFM with the specifications (dimensions, frequency) described above.

In a first experiment we increased the gas flow velocity from 0 m/s to the maximum value of 38 m/s in steps of 2 m/s and measured the amplitudes of the received signals (stationary over 30 s) in both channels (Fig. 4(a), (b) and (c)). The receiving amplitudes are best-case-normalized by dividing all values by the measured amplitudes of the received signals at zero gas flow and zero shift distance. As expected, in the case of the symmetric UFM ($\Delta x = 0$) the normalized amplitudes of the received signals dropped from 0 dB at 0 m/s to -11 dB at 38 m/s (Mach number 0.11). When the receivers were shifted by +10 mm in flow direction, the amplitudes rose from $\sim$-12 dB in average at 0 m/s to -1.5 dB at 38 m/s, implying a significant extension of the rangeability.

In a second experiment, which had the main goal to verify that equations (1) and (2) are suitable for the derivation of the UFM equations, we used the asymmetric UFM in the air flow loop to measure the gas flow velocity v and the speed of sound c and calculated the mass flow rate by using the measured pressure [6]. As reference we used a hot wire anemometer (Sensyflow P DN 80, ABB Automation Products GmbH, Alzenau, Germany), which was certified to have an expanded measurement uncertainty of -0.44% (coverage factor 2) in average over the mass flow range from 30 to 360 kg/h. The mass flow value was increased in steps of $\sim$20 kg/h from 0 kg/h to 260 kg/h and the hot wire anemometer was used to measure the mass flow rate over an integration time of 30 s. The result of the direct comparison to the mass flow rate obtained with the asymmetric UFM, again for the three different shift distances 0, 6.5 and 10 mm, is depicted in Figs. 4(d)-(i). The averaged relative difference to the reference value for the symmetric UFM was 0.32% with a standard deviation of 1.8%.

Only mass flow values larger than 30 kg/h were considered for this calculation, due to the specified lower limit of measurement range of 30 kg/h of the hot wire anemometer used as reference. Further, it should be mentioned that a fully developed turbulent flow profile was assumed for the calculation of the meter factor (0.933).

In the case of 6.5 mm and 10 mm shift distance, the averaged relative difference increases to 1.92% with a standard deviation of 0.9% and 3.18% with a standard deviation of 1.4%, respectively. The reduction of the standard deviation for the cases 6.5 mm and 10 mm shift distance, can be explained by the larger average received amplitudes over the whole gas flow velocity range. Furthermore, this indicates that shifting the two receiving transducers causes only a systematic additional error contribution, which can be reduced by calibration. In this context it should be mentioned that the asymmetric UFM was not calibrated before these measurements.

V. Conclusion

A double-path UFM can be extended in its rangeability by shifting both receiving transducers by the same amount in the flow direction. The extension of the rangeability of such an asymmetric double-path UFM is due to the compensation for the carry-along (sound drift) effect. An analytical solution for the UFM equations (v, c) exists. Because of the simplicity of the approach to shift the two receiving transducers by the same amount in the direction of flow, an adaptive asymmetric double-path UFM can be realized. Such a configuration can adjust itself (control loop), depending on the flow condition, for optimum signal-to-noise ratio over a wide measurement range. The asymmetric configuration increases the UFM rangeability without significant drawbacks.

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