23rd International North Sea Flow Measurement Workshop
Tønsberg, Norway, 18 - 21 October 2005

RECIPROCITY AND ITS UTILIZATION IN ULTRASONIC FLOW METERS

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ABSTRACT

In ultrasonic transit time flow meters for gas and liquid (USMs), the flow direction, the flow velocity and the sound velocity are estimated from the measured up- and downstream transit times. At no-flow conditions, the up- and downstream transit times of such meters should ideally be the same, or the difference should be negligible. This may not be the case unless special precautions are made. In order to reduce the possibility of the meter to detect a false flow at no-flow conditions, USMs are typically "dry calibrated" before being installed in the field. "Dry calibration" (which may be made in different ways), in general involves measurement of (a) the time delays due to electronics, cables and transducers, (b) the socalled "Δt-correction" (for each acoustic path, also denoted "zero flow offset factor"), and (c) geometrical parameters. Various Δt-correction approaches may be used by different manufacturers, but these are basically similar and have the same purpose: to reduce the false flow detection and improve the accuracy at low and no-flow conditions ("zero flow adjustment"), without significantly affecting the accuracy at the high velocity measurements. The AGA-9 report and the API MPMS Ch. 5.8 standard both prescribe need for "zero flow verification test (zero test)" or "zeroing the meter", for gas and liquid USMs, respectively.

Advances in USM technology based on the electroacoustic reciprocity principle have provided methods for reduction or even neglection of the need for "Δt-correction" of USMs. That means, if the USM measurement system is reciprocal, and operated in a "sufficiently reciprocal" way, the "Δt-correction" may be negligibly small over the operational range of pressure and temperature, and irrespective of whether the transducers are equal or not. Thus, "dry calibration" may be simplified, since reciprocal operation may provide possibilities for "auto-zeroing" of the USM.

However, reciprocal operation is not an "obvious" property of an USM. Even though the USM measurement system consisting of two transducers, electronics, etc. (e.g. an acoustic path), may be reciprocal, it may not necessarily be reciprocally *operated*. Control and careful design is essential to realize reciprocal operation at no-flow conditions in an acoustical measurement system such as a USM.

In the present paper, reciprocal operation of USMs is discussed on basis of general electroacoustical principles, and related to utilization in ultrasonic flow metering of gas and liquid. Criteria for "sufficient reciprocal operation" of a USM are developed. It extends earlier works by (a) taking into account finite-valued electrical impedances of the electronics and the transducers employed in the meter, (b) deriving specific design criteria for "sufficient reciprocal operation" of a USM, in terms of requirements for the electrical impedances of the electronics and transducers, and (c) giving criteria for transducer manufacturing reproducibility, in terms of bounds for variations of the phase of the transducer impedances. In addition, use of the transducer input signal as the reference for the transit time measurements is discussed in this respect, which is shown to provide reduced requirements for achieving "sufficient reciprocal operation". Laboratory measurements and USM "dry calibration" measurements made over a range of pressures, temperatures and signal levels ("firing voltages"), in combination with theoretical calculations, are used to demonstrate reciprocal operation and validity of the theoretical results, also for transducers not being equal in performance (due to production variations). Violation of reciprocity by e.g. "nonlinear driving" of the transducers is demonstrated. Consequences for USMs are addressed, such as e.g. (a) simplified "dry calibration" and cost reduction, (b) improved linearity at low flow velocities, and (c) improved accuracy at low flow velocities (in relation to temperature, pressure, ageing drift, etc.). The paper provides insight into the significance and potentials of utilizing reciprocity in USM technology, as well as the improvements already achieved by realizing "sufficient reciprocal operation" in high precision flow meters for gas and liquid.

1. INTRODUCTION

Ultrasonic transit time flow meters for gas and liquid (USMs) are gaining increased popularity for custody transfer and allocation metering of gas and oil. AGA recommendations on gas USMs were issued in 1998 [1] (this document is presently under revision), a handbook on uncertainty evaluation of gas USM metering stations was prepared in 2001 [2,3], an API standard on liquid ultrasonic meters was issued in February 2005 [4], an ISO standard on gas USMs is under development [5], etc.

In such meters the flow direction, the flow velocity and the sound velocity of the fluid are estimated from the measured up- and downstream transit times. These transit times are obtained by transmitting and detecting acoustic pulses up- and downstream with respect to the direction of the flow, using ultrasonic transducers and dedicated electronics. One or several acoustic paths may be used, depending on the accuracy required. For further details, cf. e.g. [1-6]. Fig. 1 shows a cross-section of such a meter, schematically.

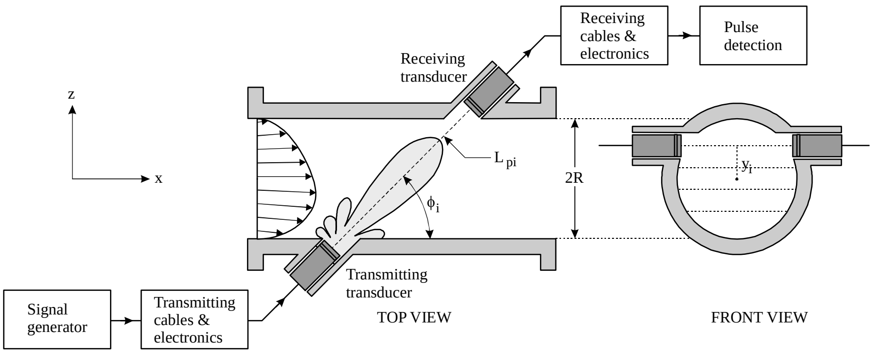

Fig. 1. Schematic illustration of a single path in a multipath ultrasonic transit time flow meter with non-reflecting paths (for downstream sound propagation). (Left: centre path example (y_i = 0); Right: path at lateral chord position y_i.)

In ultrasonic transit time flow meters with reflecting or non-reflecting paths, the volumetric flow rate (at line conditions) is given as [1-6]

$$q_{USM} = \pi R^2 \bar{v}_A , \qquad \bar{v}_A = \sum_{i=1}^{N} w_i \bar{v}_i , \qquad \bar{v}_i = (N_{refl,i} + 1) \frac{2\sqrt{R^2 - y_i^2}\,(t_{1i} - t_{2i})}{t_{1i} t_{2i} \left|\sin 2\phi_i\right|} , \tag{1}$$

where (cf. Fig. 1), R is the inner radius of the USM meter body; $\bar{v}_A$ is the axial volume flow velocity (at line conditions); N *is* the number of acoustic paths; i is the path number; w_i is the integration weight factor for path no. i; $\bar{v}_i$ is the average axial flow velocity along path no. i (i.e. the line integral along the path); y_i is the lateral distance from the pipe center (lateral chord position) for path no. i; L_i is the interrogation length for path no. i; ϕ_i is the inclination angle (relative to the pipe axis) of path no. i; t_{1i} and t_{2i} are the measured transit times for upstream and downstream sound propagation of path no. i; and $N_{refl,i}$ is the number of wall reflections for path no. i ($N_{refl,i}$ = 0, 1 or 2 in current USMs), $i = 1, \ldots, N$.

For convenience in the discussion, define

$$\Delta t_i \equiv t_{1i} - t_{2i} \tag{2}$$

as the transit time difference for path no. i, $i = 1, \ldots, N$. At no-flow conditions, the measured up- and downstream transit times of such meters should ideally be the same, i.e. Δt_i should be zero. Alternatively, the difference should be negligible. This may not be the case unless special precautions are made. It is by no means obvious that the upstream and downstream transit times of a single path in a USM are equal in a no-flow situation.

In order to reduce the possibility of the meter to detect a false flow at no-flow conditions, USMs are typically "dry calibrated" before being installed in the field. "Dry calibration" (which may be made in various ways), in general involves measurement of (a) the time delays due to electronics, cables and transducers, (b) the socalled "Δt-correction"[1] (for each acoustic path), and (c) geometrical parameters. Various Δt-correction approaches may be used by different manufacturers, but these are basically similar and have the same purpose: to reduce the false flow detection and improve the accuracy at low and no-flow conditions ("zero flow adjustment"), without significantly affecting the accuracy at the high velocity measurements [1,4][2]. For typical ultrasound transducers, the Δt-correction may vary with pressure (*P)* and temperature (*T)*. Whether the Δt-correction is measured at a single *P-T* point, or at a multitude of *P-T* points, common practice varies between the USM manufacturers.

For several reasons, it would be highly advantageous to avoid use of any Δt-correction in the USM. Use of Δt-correction may contribute to increase the cost of "dry calibrating" the meter, since this adds another parameter to be measured, possibly over a range of pressures and temperatures. More important, the use of Δt-correction may impose possible uncertainties connected to drift of Δt_i, related to pressure, temperature and ageing characteristics of the transducers. Use of Δt-correction may also complicate the zero-flow validation of the meter in case of transducer exchange, since the "old" Δt-correction value is not necessarily valid after a transducer replacement. Such factors may influence on the USM measurement at low flow velocities, such as false flow detection.

Various authors (e.g. [9-19]) have therefore discussed methods to automatically remove (or reduce) the false flow detection at low- and no-flow conditions in USMs, i.e. to ensure that Δt_i is sufficiently close to zero. These methods have been based on electroacoustical reciprocity, and various approaches to achieve reciprocal operation of the USM.

Reciprocal operation is by no means an "obvious" property of a USM. One has to distinguish between the two concepts "electroacoustical reciprocity" and "reciprocal operation" of an electroacoustic system. Although the electroacoustic system may be *reciprocal*, it does not need to be *reciprocally operated*. By "electroacoustical reciprocity" it is referred to the condition given by Eq. (7) below. Reciprocal operation, on the other hand, means that when the system is (a) driven from one side (I) and a measurement signal is received at the other side (II), and (b) driven in the same way from the other side (II) and a measurement signal is received at side (I), the two measurement signals obtained in the two different driving cases are identical (both with respect to magnitude and phase).

By employing a relationship derived in [7,8] (Eq. (30) of ref. [8], cf. also Eq. (8) below), Hemp [9] indicated a technique by which zero-flow time differences and associated zero drift in an ultrasonic flowmeter can be reduced or even eliminated. Basically it was proposed to drive the transmitter with a voltage pulse and detect the current pulse at the receiver, or *vice versa*. This technique which has been elaborated in more detail in Refs. [10-13], was proposed to achieve reciprocal operation of the electroacoustic system. However, no condition (or design criteria) for "*sufficient* reciprocal operation"

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1 By AGA-9 (Section 6.3) [1] the "Δt-correction" is denoted "zero flow offset factor".

2 By AGA-9 (Section 6.3) [1] and API MPMS Ch. 5.8 (Section 12.7) [4] this procedure is referred to as "zero flow verification test (zero test)" and "zeroing the meter", respectively, and involves checking the meter at "zero flow" conditions, e.g. using blind flanges, at stabilized pressure and temperature conditions.

By AGA-9 (Section 6.3) [1] it is stated that: (1) "To verify the transit time measurement system of each meter, the manufacturer shall perform a Zero Flow Verification Test", and (2) "The manufacturer may also implement a zero flow offset factor, in engineering units of positive or negative feet per second or meters per second. This zero flow offset factor would be applied to the meter's flow-rate output. Use of this factor is intended to improve the accuracy of the low gas velocity measurements, while not significantly affecting the accuracy of the higher velocity measurements. This zero-flow offset factor, if used, shall be documented by the manufacturer".

By API MPMS Ch. 5.8 (Section 12.7) [4] it is stated that: "Zeroing an UFM is a procedure that involves checking the output while the meter is blocked-in. Under these conditions, and if the output of the meter does not indicate zero flow, then the manufacturer's (re-)zeroing procedure shall be followed. Whenever the meter is re-zeroed, it shall be reproved. Normally, a UFM does not require manual zeroing. However changes or replacement of transducers, electronics or transducer cables shall require that the meter zero be checked and if necessary (re-)zeroing procedures shall be followed. In any case, changes or replacement of transducers, electronics or transducer cables shall require the UFM to be reproved".

was discussed, for a set of given transducers and electronics. That is, the effects of finite impedances of the transducers and the transmitting and receiving electronics were not accounted for.

By Sanderson and Torley [14] the technique of reciprocal operation proposed by Hemp [9-11] to reduce zero drifts in USMs was tried out experimentally in an ultrasonic transit time clamp-on flow meter for liquid, using voltage transducer driving and current detection of the received signal.

In connection with ultrasonic gas flow meters for household application, von Jena et al. [15,16] also demonstrated high degree of reciprocal operation (at low firing voltages), as well as violation of reciprocal operation by non-linearity (at high firing voltages). The "zero offset" (i.e. Δt_i) was measured as a function of firing voltage of the transmitting transducer, for different terminating electronics (for reciprocal as well as non-reciprocal set-ups). They concluded that zero-point stability can be achieved if (i) the response of the active components, i.e. the transducers, is linear, and (ii) "if the electrical termination of the input and output is made symmetrical" ("electrical symmetry").

Also by Martin et al. [17] a specific realization of electrical symmetry was proposed to achieve reciprocal operation of a liquid flow meter. Experimental data obtained for a USM given in Ref. [18] further demonstrate the importance of reciprocal operation of USMs.

On a general basis (i.e., from the theoretical principle of electroacoustic reciprocity, cf. e.g. Section 2), it is well known that if reciprocal operation of the measurement system holds, the transducers are allowed to be different in their characteristic parameters (as also pointed out in refs. [9-13] and [15,18], in connection with application to USMs). On the other hand, in a recent simulation study of the effects of non-identical ultrasonic transducers on reciprocity and "dry calibration" in transit time flow meters, van Deventer and Delsing [19] claimed that reciprocal operation holds only when the transmitting and receiving transducers are identical. They concluded that since it is only possible to manufacture identical transducers within a certain tolerance range, "dry calibration" of Δt_i is necessary, to establish a Δt-correction in the USM. These results are not in agreement with the conclusions of the present work.

In the present paper, reciprocal operation of USMs for gas and liquid is discussed on basis of a relatively general theory for linear, reversible and passive electroacoustic systems where the USM is represented in terms of a two-port electroacoustic system[3]. It extends earlier works by (a) taking into account finite-valued electrical impedances of the electronics and the transducers employed in the meter, (b) deriving specific design criteria for "sufficient reciprocal operation" of a USM, in terms of requirements for the electrical impedances of the electronics and transducers, and (c) giving criteria for transducer manufacturing reproducibility, in terms of bounds for variations of the phase of the transducer impedances (Section 2). In addition, use of the transducer input signal as the reference for the transit time measurements is discussed in this respect, which is shown to provide reduced requirements for achieving "sufficient reciprocal operation". Control and careful design is essential to realize reciprocal operation at no-flow conditions in an acoustical measurement system such as an USM. Laboratory measurements and USM "dry calibration" measurements made over a range of pressures, temperatures and signal levels ("firing voltages"), in combination with theoretical calculations, are used to demonstrate reciprocal operation and validity of the theoretical results, also for transducers not being equal in performance (due to production variations) (Section 3). Violation of reciprocity by e.g. "nonlinear driving" of the transducers is demonstrated. Consequences for USMs are addressed, such as e.g. (a) simplified "dry calibration" and cost reduction, (b) improved linearity at low flow velocities, and (c) improved accuracy at low flow velocities (in relation to temperature, pressure, ageing drift, etc.) (Section 4). The paper is intended to provide insight into the significance and potentials of utilizing reciprocity in USM

[3] Alternatively, and with the same results, the present analysis could have been based on the much more general theory of passive, linear electroacoustic systems due to Primakoff and Foldy [7,8]. This is so because Eq. (8) derived and used here is the same as Eq. (30) in [8], which was shown to be more generally valid than the two-port system model used here.

technology, as well as the improvements already achieved by realizing "sufficient reciprocal operation" in high precision flow meters for gas and liquid.

2. THEORY

In the present section the USM measurement system is represented in terms of a two-port electroacoustic system, and the theory of such systems is used to derive specific criteria for "sufficient reciprocal operation" of a USM.

2.1 Conditions for electroacoustic reciprocity in USMs

Consider a single path in a USM as shown in Fig. 1, at a no-flow situation. It is assumed that this electroacoustic system is (a) linear (i.e., that the signal levels are sufficiently low), (b) reversible (i.e., that the transducers can be used as both transmitter and receiver of sound), and (c) passive (i.e., that the power delivered by the transducer to the electrical or acoustical systems to which it is connected is derived from power absorbed by the transducer from these systems).

Denote the transducers at the left and right hand sides of the USM path shown in Fig. 1 by I and II, respectively. The portion of the path between the transmitting and receiving electronics (i.e. the two transducers I and II, and the fluid medium) can be described as shown in Fig. 2a. Here, V_I and I_I are the voltage and current at the electrical terminals of Transducer I, respectively, and V_{II} and I_{II} are the voltage and current at the electrical terminals of Transducer II, respectively. The directions chosen here for positive voltage and current are defined in the figure. All quantities are complex-valued, accounting for magnitude and phase.

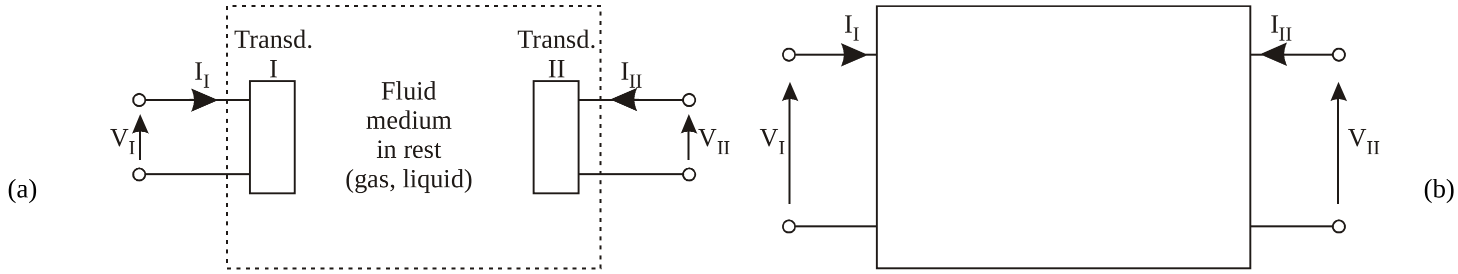

Fig. 2. (a) Schematic illustration of the "mid" part of the single USM path shown in Fig. 1, including the two transducers and the fluid medium. (b) Two-port ("black box") representation of the electroacoustic system shown in Fig. 2a.

The system shown in Fig. 2a can be represented by the two-port ("black box") electroacoustic system shown in Fig. 2b, where the "black box" includes the two transducers and the fluid medium inbetween. This two-port electroacoustic system is described by the two equations

$$\begin{aligned} V_I &= Z_{11} I_I + Z_{12} I_{II} \\ V_{II} &= Z_{21} I_I + Z_{22} I_{II} \end{aligned} \qquad (3)$$

where Z_{11}, Z_{22}, Z_{12} and Z_{21} are the Z-parameters (impedance parameters) of the system. Note that the system is completely described by Z_{11}, Z_{22}, Z_{12} and Z_{21}. That means, if these four parameters are known, the properties of the electroacoustic system (the "black box") is also known. The two impedance parameters Z_{12} and Z_{21} (which are also referred to as transfer impedances) are defined as

$$Z_{12} = \left.\frac{V_I}{I_{II}}\right|_{I_I=0}, \qquad Z_{21} = \left.\frac{V_{II}}{I_I}\right|_{I_{II}=0}, \tag{4}$$

respectively.

Next, consider two-way operation of path no. *i* of the USM shown in Fig. 1, i.e. upstream and downstream electroacoustic signal propagation (still at no-flow conditions). Two-port electroacoustic representation of this situation is shown in Fig. 3, where parts (a) and (b) of the figure apply to up- and downstream propagation in path no. *i*, respectively. In part (a), $V_I^{(1)}$ and $I_I^{(1)}$ are the voltage and current at the input terminals of transducer I, which acts as transmitter of an acoustic signal to transducer *II*, acting as the receiver. At the output terminals of transducer II the voltage is $V_{II}^{(1)}$ and the current is $I_{II}^{(1)}$. In part (b) of the figure, the situation is *vice versa.* That is, transducer II is now the transmitter and transducer I is the receiver. The notation is also the same, except that superscript (1) is replaced by (2), reflecting downstream propagation[4].

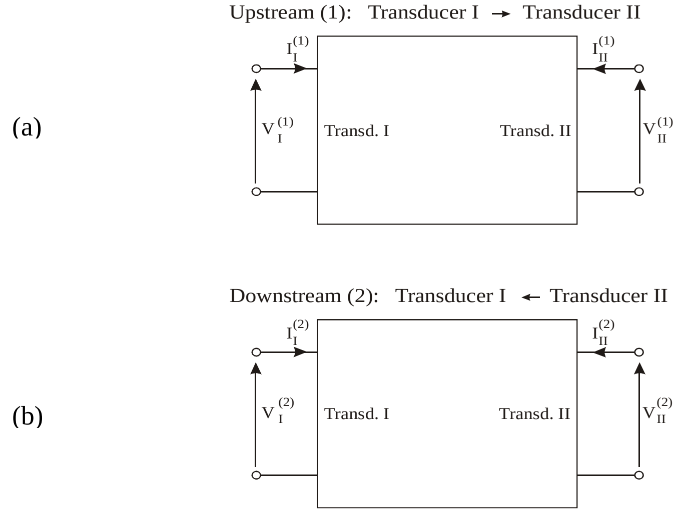

Fig. 3. Two-port ("black box") electroacoustic system representation of (a) upstream and (b) downstream signal propagation in the "mid part" of the single USM path shown in Fig. 1 (i.e. transducers and fluid medium), at no-flow conditions.

From Eqs. (3), the two-port equations for this situation become

$$\begin{aligned} V_I^{(1)} &= Z_{11} I_I^{(1)} + Z_{12} I_{II}^{(1)} \\ V_{II}^{(1)} &= Z_{21} I_I^{(1)} + Z_{22} I_{II}^{(1)} \\ V_I^{(2)} &= Z_{11} I_I^{(2)} + Z_{12} I_{II}^{(2)} \\ V_{II}^{(2)} &= Z_{21} I_I^{(2)} + Z_{22} I_{II}^{(2)} \end{aligned} \tag{5}$$

From Eqs. (5) it follows that

$$\left[V_I^{(1)} I_I^{(2)} - V_I^{(2)} I_I^{(1)}\right] \pm \left[V_{II}^{(1)} I_{II}^{(2)} - V_{II}^{(2)} I_{II}^{(1)}\right] = \left(Z_{12} \mp Z_{21}\right)\left[I_{II}^{(1)} I_I^{(2)} - I_{II}^{(2)} I_I^{(1)}\right] . \tag{6}$$

Eqs. (6) - which in fact are two equations (by applying the upper sign or the lower sign, respectively) - represent two general relations (properties) for a two-port electroacoustic system being operated in two directions. So far nothing has been assumed about reciprocity. If one of the conditions

4 The notation of Primakoff and Foldy [8] is used here, as also used by Hemp [9-13].

$$Z_{12} = Z_{21} \qquad \text{or} \qquad Z_{12} = -Z_{21} \tag{7}$$

is fulfilled, the electroacoustic system is reciprocal or anti-reciprocal, respectively. In such cases Eqs. (6) reduce to

$$\left[V_I^{(1)} I_I^{(2)} - V_I^{(2)} I_I^{(1)}\right] \pm \left[V_{II}^{(1)} I_{II}^{(2)} - V_{II}^{(2)} I_{II}^{(1)}\right] = 0 \ , \tag{8}$$

where the plus and minus signs apply to reciprocal and anti-reciprocal systems, respectively. That is, in Eqs. (7) and (8) the plus sign is to be taken if the two transducers have electroacoustic coupling of the "same type" (e.g., if one is piezoelectric and the other piezoelectric or electrostatic, etc.), in which case the system displays electroacoustic reciprocity. The minus sign is to be taken if the two transducers have electroacoustic coupling of the "opposite type" (e.g., if one is piezoelectric and the other magnetostrictive or electromagnetic, etc.), in which case the system displays electroacoustic antireciprocity [8][5,6].

The first and second of Eqs. (7) are the conditions of electroacoustic reciprocity and electroacoustic anti-reciprocity, respectively. Eqs. (8) are general relations (properties) of reciprocal or anti-reciprocal two-port electroacoustic systems being operated in two directions. We shall here refer to Eqs. (7) and (8) as the "electroacoustic reciprocity conditions" and the "electroacoustic reciprocity relations", respectively[7].

Eqs. (7) are inherent properties of the electroacoustic system, which is represented by a two-port network. Whether Eqs. (7) are fulfilled or not, - i.e. whether the system is reciprocal or anti-reciprocal or not, for the electroacoustic system at hand, has to be checked by measurements (doing a "reciprocity check").

In the following, reciprocity of the electroacostic system will be assumed, i.e. that the condition $Z_{12} = Z_{21}$ is fulfilled, cf. Eq. (7). The + sign then applies in Eq. (8). Moreover, since the majority of transit time ultrasonic flow meters used today employ piezoelectric transducers, it is in the following assumed that the transducers are piezoelectric.

In general the quantities involved in the electroacoustic system addressed above will vary with time. In the derivation of Eq. (8) a steady state single frequency case was assumed, in which all of the quantities vary harmonically with time, with the same frequency, *f*. In Eq. (8) and in the following, the harmonic

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[5] It is worth noting that in a rigorous analysis, Primakoff and Foldy [7,8] have shown that Eqs. (8) (cf. Eq. (30) of Ref. [8]) are relations of very general validity for electroacoustic systems (far more general than the two-port systems considered here), provided certain sufficient conditions are met. These conditions are:

(a) the transducers are acoustically coupled via stationary bodies (fluid or solid media in contact, at no-flow conditions),
(b) the transducers and the cables, electronics and acoustic media to which they are connected behave perfectly linearly (i.e., the signal levels are assumed to be sufficiently low in amplitude),
(c) the transducers are passive (i.e., that the power delivered by the transducer to the electrical or acoustical systems to which it is connected is derived from power absorbed by the transducer from these systems),
(d) the coefficients in the constitutive relations governing the electroacoustic system satisfy certain "symmetry conditions",
(e) no magnetostrictive media and no static magnetic field are present in the transducers (that is, that the coupling is purely electrostatic or piezoelectric or both), or that no piezoelectric media and no static charge density are present in the transducer (that is, that the coupling is purely electromagnetic or magnetostrictive or both), and
(f) the transducers do not radiate electromagnetic waves from their surfaces.

[6] Note that the generality of the relation given by Eq. (8) means that it may be applied e.g. to different types of flowmeters, such as for example ultrasonic flowmeters (various types), electromagnetic flowmeters and Coriolis mass flowmeters [12].

[7] A comment on this terminology may be useful. In Refs. [9-13] the relationship given by Eq. (8) (Eq. (30) of ref. [8]) is referred to as the "electroacoustic reciprocity theorem". By other authors (e.g. [7,8]) another relationship (between the source and receiving sensitivities of a transducer) is referred to as the "electroacoustic reciprocity theorem" (Eq. (51) of ref. [7]). These two relationships are not necessarily equivalent. Eq. (8) is a relationship derived by Primakoff and Foldy and used by them in the proof of the source/receiving sensitivity relationship. It thus represents a sufficient condition for that source/receiving sensitivity relationship to be valid, but it has not been shown to be a necessary condition for that source/receiving sensitivity relationship. To avoid confusion, the terminology "electroacoustic reciprocity theorem" is thus not used here.

time variation factor $e^{i\omega t}$ has been omitted, where $\omega = 2\pi f$ is the angular frequency, t is the time, and $i = \sqrt{-1}$. Cases in which the time variation is not harmonic (such as pulsed operation) can be treated with the usual method of Fourier analysis by decomposition into harmonic components, since the equations are all linear and hence the principle of superposition can be used [8]. The results obtained in the following on basis of Eq. (8) will thus apply also for pulsed operation.

2.2 Conditions for reciprocal operation of USMs

Eq. (7) is the condition for *reciprocity* of the electroacoustic system given by Figs. 1-3, but is not sufficient for *reciprocal operation* of this system. Whether a reciprocal system (i.e. fulfilling Eq. (7)) is reciprocally operated or not, will in addition depend on the electrical termination conditions for the system, at the transmitting and receiving sides. In the following the "electroacoustic reciprocity relation" Eq. (8) will be used to derive conditions which are sufficient for reciprocal operation of the system, taking into account the electrical impedances seen by the two transducers I and II towards the transmitting and receiving electronics.

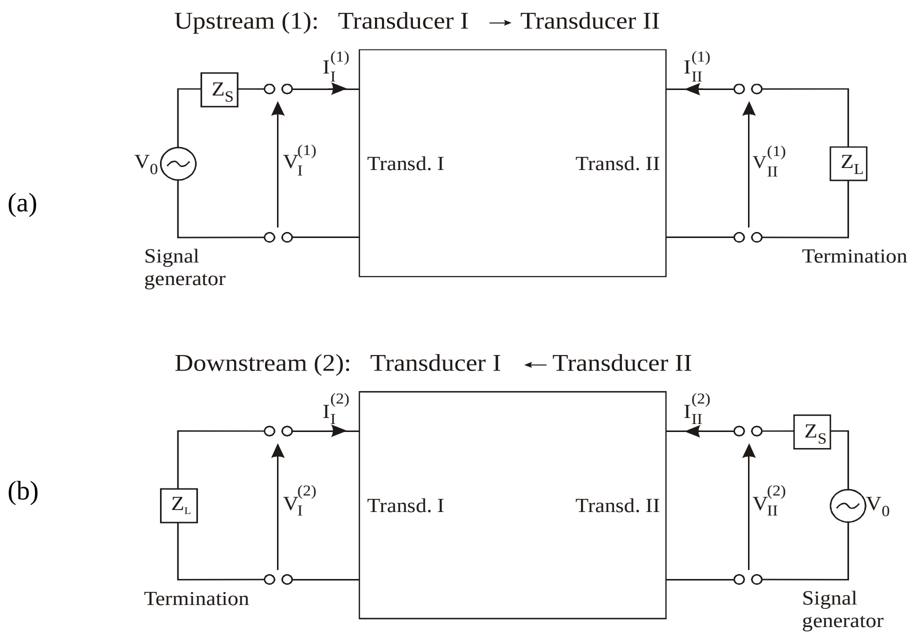

Fig. 4. Two-port ("black box") electroacoustic system representation of (a) upstream and (b) downstream signal propagation in the single USM path shown in Fig. 1, including signal generator and electrical termination, at no-flow conditions.

Consider the situation illustrated in Fig. 4, where parts (a) and (b) of the figure apply to up- and downstream propagation in path no. i, respectively. Fig. 4 represents a direct extension of Fig. 3, by including a description of the signal generator / transmitting electronics and the electrical termination at the receiver side. In part (a), a signal generator (including the transmitting electronics and the transducer cable) with voltage V_0 and output electrical impedance Z_S delivers a voltage $V_I^{(1)}$ and a current $I_I^{(1)}$ to the input terminals of transducer I, which acts as transmitter of an acoustic signal to transducer *II*, acting as the receiver. At the output terminals of transducer II the voltage is $V_{II}^{(1)}$ and the current is $I_{II}^{(1)}$. The network is terminated with an electrical impedance Z_L, which represents the input impedance of the transducer cable / receiving electronics. In part (b) of the figure, the situation is *vice versa*. That is, transducer II is now the transmitter and transducer I is the receiver, and the generator (V_0, Z_S) and electrical load (Z_L) are the same[8]. The input electrical impedances of transducers I and II are defined as

$$Z_I \equiv \frac{V_I^{(1)}}{I_I^{(1)}}, \qquad Z_{II} \equiv \frac{V_{II}^{(2)}}{I_{II}^{(2)}}, \tag{9}$$

respectively.

In the USM, the transit time measurements can be done on the output signals from the receivers[9]. That is, on the voltage $V_{II}^{(1)}$ or the current $I_{II}^{(1)}$ for upstream propagation, and the voltage $V_I^{(2)}$ or the current $I_I^{(2)}$ for downstream propagation. However, a transit time measurement has to be done relative to a "reference signal"[10]. Two different cases are discussed in the following: (a) use of the generator signal (voltage or current) as the reference signal, and (b) use of the transducer input signal (voltage or current) as the reference signal. Both cases are relevant for description of USMs.

2.2.1 Use of the generator signal as the reference signal

In the case where the generator signal is used as the reference signal for the transit time measurement (i.e., the voltage V_0 in the case of voltage generator, or the current V_0/Z_S in the case of current generator), two ratios are of interest: the ratio of the voltage signals $V_{II}^{(1)}$ and $V_I^{(2)}$, and the ratio of the current signals $I_{II}^{(1)}$ and $I_I^{(2)}$. By employing Eq. (9) and the relations (cf. Fig. 4)

$$\frac{V_{II}^{(1)}}{I_{II}^{(1)}} = -Z_L, \qquad \frac{V_I^{(2)}}{I_I^{(2)}} = -Z_L, \tag{10}$$

$$V_0 = (Z_S + Z_I) I_I^{(1)}, \qquad V_0 = (Z_S + Z_{II}) I_{II}^{(2)}, \tag{11}$$

it follows from the "electroacoustic reciprocity relation", Eq. (8) (by employing the + sign), that

$$\frac{V_I^{(2)}}{V_{II}^{(1)}} = \frac{I_I^{(2)}}{I_{II}^{(1)}} = \frac{(Z_S + Z_I)}{(Z_S + Z_{II})} \frac{(Z_L + Z_{II})}{(Z_L + Z_I)} . \tag{12}$$

In theory, perfect reciprocal operation of the USM is obtained when the generally complex-valued ratio at the right hand side of Eq. (12) is real and equal to 1, so that the magnitude and phase differences between the two measurement signals completely vanish. As outlined in Section 2.1, it follows from the method of Fourier analysis that Δt_i is then equal to zero (also for pulsed signals, irrespective of whether time detection is made in the transient or the stationary part of the signal).

In practice, "sufficient reciprocal operation" of the USM can be obtained when the right hand side of Eq. (12) is "sufficiently close to 1", so that the magnitude and phase differences between the two

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[8] This assumption, that the generator (V_0, Z_S) and electrical load (Z_L) are the same in Figs. 4a and 4b is a special case, used here since that is relevant for USM applications. Note that Eq. (8) governs also more general cases, where the generator and the electrical load may be different in the two cases of operation, (a) and (b). If so, the present theory can be modified to cover this more general case, and that has to be taken into account if deriving conditions for "sufficient reciprocal operation".

[9] In practice, the transit time measurement is not made on the signal appearing directly at the output terminals of the transducer, but after that signal has propagated through the transducer cable and into the electronics. The latter case can be treated with a slight modification of the present theory. Thus, for simplicity and without loss of generality, the former case is considered here.

[10] For instance, the transit time can be measured as the time difference between corresponding zero crossings in the "measurement signal" and the "reference signal".

measurement signals are sufficiently small, i.e. within the limits determined for the USM (cf. Section 2.3 and Eqs. (24) and (31)).

Four different cases are of particular interest to analyze in this respect, for which the relevant measurement signal ratios are given approximately (from Eq. (12)) as

$$\frac{V_I^{(2)}}{V_{II}^{(1)}} \approx \frac{Z_I}{Z_{II}}\left(1+\left(\frac{Z_{II}}{Z_L}+\frac{Z_S}{Z_I}\right)\left(1-\frac{Z_I}{Z_{II}}\right)\right), \quad \text{for } \textit{voltage generator and voltage receiver,} \tag{13}$$

$$\frac{V_I^{(2)}}{V_{II}^{(1)}} \approx 1+Z_{II}\left(\frac{1}{Z_L}-\frac{1}{Z_S}\right)\left(1-\frac{Z_I}{Z_{II}}\right), \quad \text{for } \textit{current generator and voltage receiver,} \tag{14}$$

$$\frac{I_I^{(2)}}{I_{II}^{(1)}} \approx 1+\frac{Z_S-Z_L}{Z_I}\left(1-\frac{Z_I}{Z_{II}}\right), \quad \text{for } \textit{voltage generator and current receiver,} \tag{15}$$

$$\frac{I_I^{(2)}}{I_{II}^{(1)}} \approx \frac{Z_{II}}{Z_I}\left(1-\left(\frac{Z_{II}}{Z_S}+\frac{Z_L}{Z_I}\right)\left(1-\frac{Z_I}{Z_{II}}\right)\right), \quad \text{for } \textit{current generator and current receiver,} \tag{16}$$

respectively. The approximate expressions given in each of Eqs. (13)-(16) are based on series expansions, where the four cases are characterized by

- Voltage generator and voltage receiver: $|Z_S| << |Z_I| \text{ and } |Z_{II}|$, $|Z_L| >> |Z_I| \text{ and } |Z_{II}|$,
- Current generator and voltage receiver: $|Z_S| >> |Z_I| \text{ and } |Z_{II}|$, $|Z_L| >> |Z_I| \text{ and } |Z_{II}|$,
- Voltage generator and current receiver: $|Z_S| << |Z_I| \text{ and } |Z_{II}|$, $|Z_L| << |Z_I| \text{ and } |Z_{II}|$,
- Current generator and current receiver: $|Z_S| >> |Z_I| \text{ and } |Z_{II}|$, $|Z_L| << |Z_I| \text{ and } |Z_{II}|$,

respectively. The asymptotic approximate expressions for the measurement signal ratios given by Eqs. (13)-(16) are given in Fig. 5, in the limits as $|Z_S/Z_I| \to 0$, $|Z_L/Z_I| \to \infty$, etc. As indicated in the figure, the results fall into two categories. The first category is simply denoted "No"; the other is denoted "OK".

For the category denoted "No" (i.e. by operating the USM either using the combination of voltage generator / voltage receiver, or using the combination of current generator / current receiver), perfect reciprocal operation of the USM is obtained only when the transducers I and II are identical. The ratio of the measurements signals depends heavily on the input electrical impedances of the transducers, Z_I and Z_{II}, and is identically equal to 1 only when these impedances are identical. The phase difference and thus Δt_i vanish only when the transducers I and II are identical. In practice, this will rarely be the case, since transducers - although being of the same design - can hardly be made perfectly identical, and since transducers may have different temperature, pressure and ageing characteristics. Δt_i may thus depend on temperature, pressure, ageing, etc., and a false flow detection may be experienced even at zero flow conditions. In case of non-identical transducers, a "dry calibration" of Δt_i will then be necessary to compensate for the non-negligible Δt_i. Such type of operation of the USM may therefore not be an optimal strategy.

In practice, since there is a specified lower flow velocity limit of the USM, perfect reciprocal operation of the USM is not necessary, and criteria for "sufficient reciprocal operation" of the USM could be determined also for the category "No" (similar to the analysis made in Section 2.3 for category "OK"). However, for the reasons explained above, these criteria would be much more dependent on "equalness" of the two transducers than for category "OK", which is therefore the category of primary interest here.

For the category denoted "OK" (i.e. by operating the USM either using the combination of current generator / voltage receiver, or using the combination of voltage generator / current receiver), reciprocal operation of the USM is obtained automatically in the asymptotic cases indicated in the Fig. 5, irrespective of the properties of the transducers I and II (in fact, irrespective of design of these transducers). By proper design of the electrical impedances of the transmitting and receiving electronics, Z_S and Z_L, in relation to the transducer impedances Z_I and Z_{II} (cf. Section 2.3 for more specific design criteria), the phase difference between the measurement signals (and thus Δt_i) can be made sufficiently small over the whole temperature and pressure range of the USM, and with respect to ageing. Consequently, for such type of operation of the USM no "dry calibration" of Δt_i will be necessary.

	Voltage generator	**Current generator**
Voltage receiver	$\lvert Z_S\rvert \ll \lvert Z_I\rvert$ & $\lvert Z_{II}\rvert$ $\lvert Z_L\rvert \gg \lvert Z_I\rvert$ & $\lvert Z_{II}\rvert$ => $\frac{V_I^{(2)}}{V_{II}^{(1)}} \to \frac{Z_I}{Z_{II}}$ *"No"*	$\lvert Z_S\rvert \gg \lvert Z_I\rvert$ & $\lvert Z_{II}\rvert$ $\lvert Z_L\rvert \gg \lvert Z_I\rvert$ & $\lvert Z_{II}\rvert$ => $\frac{V_I^{(2)}}{V_{II}^{(1)}} \to 1$ ***"OK"***
Current receiver	$\lvert Z_S\rvert \ll \lvert Z_I\rvert$ & $\lvert Z_{II}\rvert$ $\lvert Z_L\rvert \ll \lvert Z_I\rvert$ & $\lvert Z_{II}\rvert$ => $\frac{I_I^{(2)}}{I_{II}^{(1)}} \to 1$ ***"OK"***	$\lvert Z_S\rvert \gg \lvert Z_I\rvert$ & $\lvert Z_{II}\rvert$ $\lvert Z_L\rvert \ll \lvert Z_I\rvert$ & $\lvert Z_{II}\rvert$ => $\frac{I_I^{(2)}}{I_{II}^{(1)}} \to \frac{Z_{II}}{Z_I}$ *"No"*

Fig. 5. Four asymptotic special cases of Eqs. (13)-(16), for operation of the USM in which the generator signal is used as the reference signal for the transit time measurement. For interpretation of the categories "No" and "OK", see the text.

Finally, note that in the case of *"electrical symmetry"* (i.e. $Z_S = Z_L$), Eq. (12) reduces exactly to

$$\frac{V_I^{(2)}}{V_{II}^{(1)}} = \frac{I_I^{(2)}}{I_{II}^{(1)}} = 1 , \tag{17}$$

which means that this case also falls into category "OK", discussed above[11]. This case was also discussed in ref. [11].

2.2.2 Use of the transducer input signal as the reference signal

In the case where the transducer input signal (voltage or current) is used as the reference signal for the transit time measurement, four different ratios are of interest, dependent on whether the reference signal is voltage or current, and whether the received (measured) signal is voltage or current (cf. Fig. 4).

[11] From ref. [16] it appears that this may be the same type of "electrical symmetry" as referred to by von Jena et al. [15] (cf. Section 1). Also Martin et al. [17] used this type of "electrical symmetry", realized in a slightly different way. Both approaches were based on voltage generation and voltage reception.

For instance, consider one of these cases, e.g. voltage reference and voltage receiver. For upstream propagation, the reference and measurement signals are $V_I^{(1)}$ and $V_{II}^{(1)}$, respectively, so that the phase difference between these is given by the ratio $V_{II}^{(1)}/V_I^{(1)}$. The corresponding ratio for downstream propagation is $V_I^{(2)}/V_{II}^{(2)}$. The other three cases are treated similarly.

Consequently, by employing Eqs. (9) and (10), it follows from the electroacoustic reciprocity relation, Eq. (8) (by employing the + sign), that for the four different cases, the relevant measurement signal ratios are given as

$$\frac{V_{II}^{(1)}/V_I^{(1)}}{V_I^{(2)}/V_{II}^{(2)}} \approx \frac{Z_{II}}{Z_I}\left(1-\frac{Z_{II}}{Z_L}\left(1-\frac{Z_I}{Z_{II}}\right)\right), \qquad \text{for } \textit{voltage reference and voltage receiver,} \tag{18}$$

$$\frac{V_{II}^{(1)}/I_I^{(1)}}{V_I^{(2)}/I_{II}^{(2)}} \approx 1-\frac{Z_{II}}{Z_L}\left(1-\frac{Z_I}{Z_{II}}\right), \qquad \text{for } \textit{current reference and voltage receiver,} \tag{19}$$

$$\frac{I_{II}^{(1)}/V_I^{(1)}}{I_I^{(2)}/V_{II}^{(2)}} \approx 1+\frac{Z_L}{Z_I}\left(1-\frac{Z_I}{Z_{II}}\right), \qquad \text{for } \textit{voltage reference and current receiver,} \tag{20}$$

$$\frac{I_{II}^{(1)}/I_I^{(1)}}{I_I^{(2)}/I_{II}^{(2)}} \approx \frac{Z_I}{Z_{II}}\left(1+\frac{Z_L}{Z_I}\left(1-\frac{Z_I}{Z_{II}}\right)\right), \qquad \text{for } \textit{current reference and current receiver,} \tag{21}$$

respectively. The approximate expressions given in each of Eqs. (18)-(21) are based on series expansions, where the condition $|Z_L| >> |Z_I| \; and \, |Z_{II}|$ has been used for voltage reception, and $|Z_L| << |Z_I| \; and \, |Z_{II}|$ has been used for current reception.

Analogous to the situation discussed in Section 2.1, reciprocal operation of the USM is obtained when the generally complex-valued ratio at the right hand side of each of Eqs. (18)-(21) is real and equal to 1, so that the magnitude and phase differences between the two measurement signals completely vanish. In that case Δt_i becomes equal to zero.

The asymptotic approximate expressions for the measurement signal ratios given by Eqs. (18)-(21) are given in Fig. 6, in the limits as $|Z_L/Z_I| \to \infty$, $|Z_L/Z_I| \to 0$, etc. As indicated in the figure, the results fall into two categories "No" and "OK", similarly to the situation discussed in Section 2.1. The meaning of "No" and "OK" and the consequences for the two categories are the same as in Section 2.1.

Hence, for the category denoted "No" (i.e. by operating the USM either using the combination of voltage reference / voltage reception, or using the combination of current reference / current reception), reciprocal operation of the USM is obtained only when the transducers I and II are identical. For further discussion of consequences in category "No" it is referred to Section 2.1.

Since the achievement of "sufficient reciprocal operation" puts significantly higher requirements to "equalness" of the two transducers for category "No" than for category "OK", the four cases classified under category "No" are not considered further here. This concerns Eq. (13) (voltage generator and voltage receiver), Eq. (16) (current generator and current receiver), Eq. (18) (voltage reference and voltage receiver), and Eq. (21) (current reference and current receiver).

On the other hand, for the category denoted "OK" (i.e. by operating the USM either using the combination of current reference / voltage reception, or using the combination of voltage reference / current reception), reciprocal operation of the USM is obtained automatically, irrespective of the properties or "equalness" of the transducers I and II, by proper design of the output electrical impedance of the receiving electronics, Z_L, in relation to the transducer impedances Z_I and Z_{II} (cf. Section 2.3 for more specific design criteria). For further discussion of consequences in category "OK" it is referred to Section 2.1.

Note also that whereas in Section 2.1 both of the electronics impedances Z_S and Z_L had to be subject to "proper design" in relation to the transducer impedances Z_I and Z_{II}, only the receiving electronics impedance Z_L has to be subject to "proper design" if the USM is operated as in Section 2.2.

The question is thus: what is meant by "proper design" of these impedances. This is the topic addressed in the next section.

	Voltage reference	**Current reference**
Voltage receiver	$\lvert Z_L \rvert >> \lvert Z_I \rvert$ & $\lvert Z_{II} \rvert$ => $\dfrac{(\frac{V_{II}^{(1)}}{V_I^{(1)}})}{(\frac{V_I^{(2)}}{V_{II}^{(2)}})} \to \dfrac{Z_{II}}{Z_I}$ *"No"*	$\lvert Z_L \rvert >> \lvert Z_I \rvert$ & $\lvert Z_{II} \rvert$ => $\dfrac{(\frac{V_{II}^{(1)}}{I_I^{(1)}})}{(\frac{V_I^{(2)}}{I_{II}^{(2)}})} \to 1$ ***"OK"***
Current receiver	$\lvert Z_L \rvert << \lvert Z_I \rvert$ & $\lvert Z_{II} \rvert$ => $\dfrac{(\frac{I_{II}^{(1)}}{V_I^{(1)}})}{(\frac{I_I^{(2)}}{V_{II}^{(2)}})} \to 1$ ***"OK"***	$\lvert Z_L \rvert << \lvert Z_I \rvert$ & $\lvert Z_{II} \rvert$ => $\dfrac{(\frac{I_{II}^{(1)}}{I_I^{(1)}})}{(\frac{I_I^{(2)}}{I_{II}^{(2)}})} \to \dfrac{Z_I}{Z_{II}}$ *"No"*

Fig. 6. The four asymptotic special cases of Eqs. (18)-(21), for operation of the USM by employing the transducer input signal as the reference signal for the transit time measurement. For interpretation of the categories "No" and "OK", see the text.

2.3 Design criteria for "sufficient reciprocal operation" and transducer manufacturing

The asymptotic results shown in Figs. 5 and 6 reflect idealized situations, theoretically valid in the limits such as $|Z_S/Z_I| \to 0$, $|Z_S/Z_I| \to \infty$, $|Z_L/Z_I| \to 0$ or $|Z_L/Z_I| \to \infty$, etc. In practice they do not reflect the real situation, that the impedances of the transmitting and receiving electronics have finite values. From Eqs. (14), (15), (19) and (20), it follows that not even for the four cases classified under category "OK", where reciprocal operation of the USM can be achieved irrespective of the values of the transducer impedances Z_I and Z_{II}, the ratio of the measurement signals can be perfectly real and equal to 1. Due to the finite impedances, there will always be a finite phase difference between the measurement signals. It follows that perfect reciprocal operation will never be achieved, and that Δt_i will never be perfectly zero, - not even for category "OK" in a perfectly no-flow situation.

The question is then: how small can we - for category "OK" - make the phase difference, and thus Δt_i, in a no-flow situation? Or formulated in another way, - what are the requirements to Z_S and Z_L, given the transducer impedances Z_I and Z_{II}? That is, what are the requirements to "sufficient reciprocal operation".

To answer that question, we will first need a typical number for the maximum value of Δt_i that can be tolerated in the USM at the specified minimum flow velocity of the USM, say e.g. 0.5 m/s, and still avoid detecting false flow. Such a number can be established using Eqs. (1)-(2). For simplicity, and without much loss of generality[12], consider a path passing through the pipe centerline (y_i = 0), at an inclination angle $\theta_i = 45^o$, and assume that the flow has a uniform (constant) profile. The flow velocity of this path is then given approximately as $v_i \approx c^2 \Delta t_i / 2D$, so that

$$\Delta t_i \approx \frac{2D\bar{v}_i}{c^2}, \tag{22}$$

where $D = 2R$ is the inner diameter of the pipe, c is the sound velocity of the fluid in the pipe, and in the nominator of Eq. (1) the upstream and downstream transit times t_{1i} and t_{2i} have been approximated by $\sqrt{2}D/c$, which is sufficient for the present purpose. In a simplified uncertainty "analysis", neglecting all other uncertainty contributions than the uncertainty of Δt_i, the standard uncertainty of Δt_i is then given approximately From Eq. (22) as

$$u(\Delta t_i) \approx \frac{2D}{c^2} u(\bar{v}_i) = \frac{2D|\bar{v}_i|}{c^2} \left| \frac{u(\bar{v}_i)}{\bar{v}_i} \right| = \frac{2D|\bar{v}_i|}{c^2} E_{\bar{v}_i}, \tag{23}$$

where $u(\bar{v}_i)$ and $E_{\bar{v}_i} \equiv |u(\bar{v}_i)/\bar{v}_i|$ are the standard and relative standard uncertainties of the average flow velocity, $\bar{v}_i$. In order to establish some tentative figures to use in an example to illustrate the method of achieving "sufficient reciprocal operation", consider two USMs, - one operating in natural gas and the other in oil. In the gas example, the sound velocity of the gas is taken as c = 500 m/s (as a tentative upper bound), and the upper limit for the contribution of the standard uncertainty of Δt_i to the standard uncertainty of the USM (as an isolated uncertainty contribution), is taken as $E_{\bar{v}_i}^{max}$ = 0.4 % at $\bar{v}_i$ = 0.5 m/s[13]. In the oil example, the sound velocity of the oil is taken as c = 1500 m/s (as a tentative upper bound), and the upper limit for the contribution of the standard uncertainty of Δt_i to the standard uncertainty of the

[12] A more rigorous treatment of this topic would require e.g. use of a more complete uncertainty model for USMs than the simplified analysis used here, such as the *GARUSO* model [20, 6]. However, analyses which have been made on this subject using *GARUSO*, where all paths in multipath USMs are considered, and where the simplifying approximations involved here are not used, have shown that the results found using the simplified analysis leading to Eqs. (22)-(23) and Table 1, are sufficiently representative.

[13] From the AGA-9 report [1], the recommended maximum relative deviation (error) of gas USMs from the flow calibration reference measurement is 1.4 % at the low-end of the flow velocity range. By assuming a Type B uncertainty, at a 100 % confidence level and a rectangular probability distribution (with coverage factor $k = \sqrt{3}$) [24], the corresponding relative expanded uncertainty is, according to the "GUM" [24], equal to $2(1.4/\sqrt{3})$ % ≈ 1.6 % (at a 95 % confidence level, with coverage factor k = 2). This corresponds to a relative standard uncertainty of 0.8 %. Taking into account that only one source of uncertainty is considered in the text, namely the uncertainty of Δt_i, and that all other uncertainty contributions are neglected, a "safety factor" of 2 is used here relative to the value 0.8 %. That means, the number $E_{\bar{v}_i}^{max}$ = 0.4 % used in the example of the text corresponds to saying that the standard uncertainty of Δt_i should not contribute more to the standard uncertainty of the USM than 0.4 %, as an isolated uncertainty contribution.

USM (as an isolated uncertainty contribution), is taken as $E_{\bar{v}_i}^{\max}$ = 0.05 % at $\bar{v}_i$ = 0.5 m/s[14]. (Note that these are tentative example figures only, - another low flow velocity limit for the USM than 0.5 m/s would give other numbers.)

Table 1 gives typical upper limit figures for $u(\Delta t_i)$, i.e. $u(\Delta t_i)_{\max}$, calculated from Eq. (23) and these example figures, for the gas and the liquid USMs, and for some pipe diameters in the range 6" to 20" (15 to 50 cm inner diameter).

Table 1. Tentative and typical upper limit figures for the standard uncertainty of Δt_i in a gas USM and a liquid USM, $u(\Delta t_i)_{\max}$, for some inner diameters of the pipe, *D*. (Note that these are example figures only, for an assumed specified lower flow velocity limit of the USM taken to be 0.5 m/s.)

	Inner diameter, D		
	6"	12"	20"
Gas USM:	$2.4 \cdot 10^{-9}$ s	$4.8 \cdot 10^{-9}$ s	$8.0 \cdot 10^{-9}$ s
Liquid USM:	$33 \cdot 10^{-12}$ s	$67 \cdot 10^{-12}$ s	$111 \cdot 10^{-12}$ s

To avoid any Δt-correction in the USM, a possible Δt-correction of the USM, Δt^{corr}, should not be larger than $u(\Delta t_i)_{\max}$. Consequently, from these examples,

$$\Delta t^{corr} < \Delta t_{\max}^{corr} = u(\Delta t_i)_{\max} = \begin{cases} 2.4\ ns & (\mathit{for\ gas\ USMs}) \\ 33\ ps & (\mathit{for\ liquid\ USMs}) \end{cases} \tag{24}$$

are used as tentative example requirement values for Δt^{corr} in the following, applying only to an assumed specified minimum flow velocity of the USM equal to 0.5 m/s. Consequently, if Eq. (24) is fulfilled for all operating conditions of the USM (with respect to pressure, temperature, ageing, etc.), Δt^{corr} is negligible, and active Δt-correction is not needed in the USM, for flow velocities higher than the min. flow velocity specified for the USM (in the present case 0.5 m/s).

Note that from Eq. (23) and Table 1, the requirements to Δt^{corr} given by Eq. (24) represent "worst case" figures for the diameters considered here (6" and upwards). For USMs larger than 6" diam., the requirements are less severe, and decrease proportionally to the diameter *D*.

Now, having established Eq. (24), we return to the requirements to be imposed on the impedances Z_S and Z_L to automatically fulfil Eq. (24), leading to conditions for "sufficient reciprocal operation" (defined in Section 2.1.1).

First, to cover all four cases of category "OK" in a single analysis, note that Eqs. (14), (15), (19) and (20) can all be expressed on the form

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[14] The API standard on liquid ultrasonic flow meters [4] does not prescribe any linearity requirements for such meters. From the NPD regulations [25], which are used here as an example, the maximum relative expanded uncertainty of liquid USMs is 0.2 % in the working flow velocity range (linearity, at a 95 % conf. level, with coverage factor k = 2). The corresponding relative standard uncertainty is 0.1 % [24]. Taking into account that only one source of uncertainty is considered in the text, namely the uncertainty of Δt_i, and that all other uncertainty contributions are neglected, a "safety factor" of 2 is used here relative to the value 0.1 %. That means, the number $E_{\bar{v}_i}^{\max}$ = 0.05 % used in the example of the text corresponds to saying that the standard uncertainty of Δt_i should not contribute more to the standard uncertainty of the USM than 0.05 %, as an isolated uncertainty contribution.

$$Ae^{i\Delta\phi} \approx 1 + K(1 - Be^{i\Delta\psi}) \,, \tag{25}$$

where *A* is the magnitude and $\Delta\phi$ the phase of the measurement signal ratio, i.e.

$$A \equiv \left| \frac{V_I^{(2)}}{V_{II}^{(1)}} \right|, \qquad A \equiv \left| \frac{I_I^{(2)}}{I_{II}^{(1)}} \right|, \qquad A \equiv \left| \frac{V_{II}^{(1)} / I_I^{(1)}}{V_I^{(2)} / I_{II}^{(2)}} \right|, \qquad A \equiv \left| \frac{I_{II}^{(1)} / V_I^{(1)}}{I_I^{(2)} / V_{II}^{(2)}} \right|, \tag{26a}$$

$$\Delta\phi \equiv \angle\left(\frac{V_I^{(2)}}{V_{II}^{(1)}} \right), \; \Delta\phi \equiv \angle\left(\frac{I_I^{(2)}}{I_{II}^{(1)}} \right), \; \Delta\phi \equiv \angle\left(\frac{V_{II}^{(1)} / I_I^{(1)}}{V_I^{(2)} / I_{II}^{(2)}} \right), \qquad \Delta\phi \equiv \angle\left(\frac{I_{II}^{(1)} / V_I^{(1)}}{I_I^{(2)} / V_{II}^{(2)}} \right), \tag{26b}$$

for the four cases described by Eqs. (14), (15), (19) and (20), respectively, *K* is a quantity dependent on the impedances Z_S , Z_L, Z_I and Z_{II}, i.e.

$$K \equiv Z_{II}\left(\frac{1}{Z_L} - \frac{1}{Z_S} \right), \qquad K \equiv \frac{Z_S - Z_L}{Z_I}, \qquad K \equiv -\frac{Z_{II}}{Z_L}, \qquad K \equiv \frac{Z_L}{Z_I}, \tag{27}$$

for the same four cases, respectively, and *B* is the magnitude and $\Delta\psi$ the phase of the transducer impedance ratio, defined as

$$B \equiv \left| \frac{Z_I}{Z_{II}} \right|, \qquad \Delta\psi \equiv \angle\left(\frac{Z_I}{Z_{II}} \right), \tag{28}$$

respectively. Note that due to the assumptions made for the impedances Z_S and Z_L for the respective four cases (cf. Section 2.2), one has $A \approx 1$ and $\Delta\phi << \pi/2$ in every case. For transducers which are approximately equal (but not identical[15]) (that is, $Z_I \approx Z_{II}$, i.e. $B \approx 1$ and $\Delta\psi << \pi/2$), Eq. (25) then yields

$$|K| \approx \frac{\Delta\phi}{\Delta\psi} = \frac{\omega \Delta t_i}{\Delta\psi} \,, \tag{29}$$

since we have $\Delta\phi = \omega \Delta t_i$. "Sufficient reciprocal operation" is thus obtained if the requirement

$$|K| < \frac{2\pi f \cdot \Delta t_{\max}^{corr}}{\Delta\psi} \tag{30}$$

is fulfilled, where $\Delta t_{\max}^{corr}$ is given by Eq. (24). Consequently, "sufficient reciprocal operation" is definitely obtained if the even stronger requirement

$$|K| < \frac{2\pi f \cdot \Delta t_{\max}^{corr}}{\Delta\psi_{\max}} \tag{31}$$

is imposed, where $\Delta\psi_{\max}$ (given in radians) is a representative figure for the maximum phase deviation of the transducers' input electrical impedances, at the frequency *f* in question, for accepted transducers in a complete transducer production series. $\Delta\psi_{\max}$ may typically be established empirically, from inspection of transducer production over time.

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[15] The case of identical transducers is theoretically trivial and also of minor practical interest, and is not addressed further here.

Eq. (31) is here the condition used for "sufficient reciprocal operation" of the USM. If Eq. (31) is fulfilled for all operating conditions of the USM (with respect to pressure, temperature, ageing, etc.), "sufficient reciprocal operation" is automatically achieved. That means, Δt^{corr} is negligible, and active *Δt*-correction is not needed in the USM, for flow velocities higher than the min. flow velocity specified for the USM (0.5 m/s used in Table 1 and Eq. (24)).

The specific consequences of Eq. (31) for the four cases classified under category "OK" (cf. Eq. (27)) are discussed separately in the following, cf. the cases (a)-(d) below.

(a) **Current generator and voltage receiver**, governed by Eq. (14). From Eq. (27) we have $K \equiv Z_{II}\left(1/Z_L - 1/Z_S\right)$ for this case, so that the requirement given by Eq. (31) leads to the two equivalent requirements

$$\left|\frac{1}{Z_L} - \frac{1}{Z_S}\right| < \frac{2\pi f \cdot \Delta t_{\max}^{corr}}{\Delta \psi_{\max} |Z_{II}|}, \tag{32a}$$

$$\Delta \psi_{\max} < \frac{2\pi f \cdot \Delta t_{\max}^{corr}}{|Z_{II}| \left|\frac{1}{Z_L} - \frac{1}{Z_S}\right|}, \tag{32b}$$

for the electronics impedances and the transducer impedances, respectively.

Eq. (31a) represents a "sufficient reciprocal operation" requirement for design and manufacturing of the electrical impedances of the transmitting and receiving electronics, given that typical values for (i) the magnitude and (ii) the variation in phase angle of the transducer impedance are known (for the complete transducer production). Similarly, Eq. (31b) represents a "sufficient reciprocal operation" requirement for reproducibility in manufacturing of the transducers, given that a typical value for (i) the magnitude of the transducer impedance and (ii) the electrical impedances of the transmitting and receiving electronics are known.

(b) **Voltage generator and current receiver**, governed by Eq. (15). From Eq. (27) we have $K \equiv \left(Z_S - Z_L\right)/Z_I$ for this case, so that the requirement given by Eq. (31) leads to the two equivalent "sufficient reciprocal operation" requirements

$$|Z_S - Z_L| < \frac{2\pi f \cdot \Delta t_{\max}^{corr}}{\Delta \psi_{\max}} |Z_I|, \tag{33a}$$

$$\Delta \psi_{\max} < 2\pi f \cdot \Delta t_{\max}^{corr} \left|\frac{Z_I}{Z_S - Z_L}\right|, \tag{33b}$$

for the electronics impedances and the transducer impedance reproducibility, respectively (for interpretation, cf. (a)).

(c) **Current reference and voltage receiver**, governed by Eq. (19). From Eq. (27) we have $K \equiv -Z_{II}/Z_L$ for this case, so that the requirement given by Eq. (31) leads to the two equivalent "sufficient reciprocal operation" requirements

$$\frac{1}{|Z_L|} < \frac{2\pi f \cdot \Delta t_{\max}^{corr}}{\Delta \psi_{\max} |Z_{II}|}, \tag{34a}$$

$$\Delta\psi_{\max} < 2\pi f \cdot \Delta t_{\max}^{corr} \left| \frac{Z_L}{Z_{II}} \right| , \tag{34b}$$

for the electronics impedances and the transducer impedance reproducibility, respectively (for interpretation, cf. (a)).

(d) **Voltage reference and current receiver**, governed by Eq. (20). From Eq. (27) we have $K \equiv Z_L / Z_I$ for this case, so that the requirement given by Eq. (31) leads to the two equivalent "sufficient reciprocal operation" requirements

$$|Z_L| < \frac{2\pi f \cdot \Delta t_{\max}^{corr}}{\Delta\psi_{\max}} |Z_I| , \tag{35a}$$

$$\Delta\psi_{\max} < 2\pi f \cdot \Delta t_{\max}^{corr} \left| \frac{Z_I}{Z_L} \right| , \tag{35b}$$

for the electronics impedances and the transducer impedance reproducibility, respectively (for interpretation, cf. (a)).

An example can be useful to illustrate typical figures resulting from e.g. Eq. (33a). Consider a gas USM and a liquid USM operating at, say, 150 kHz and 1 MHz, respectively. Assume that in average (for a production series), the magnitude of the transducer impedance $|Z_I|$ is 50 and 500 Ω at the operating frequency, for the gas and the liquid transducers, respectively (for simplicity, as relevant examples). Furthermore, as an example, assume that the maximum phase deviation of the transducer's input electrical impedances, $\Delta\psi_{\max}$, is (say) 10^o (for a production series). From Eqs. (33a) and (24), the "sufficient reciprocal operation" requirement becomes $|Z_S - Z_L|$ < 0.6 Ω for the gas and liquid USMs, in the case when the generator signal V_0 is used as the reference signal for the time detection. Similar calculations can be made for Eq. (33b), as well as for the other three cases governed by Eqs. (32), (34) and (35).

3. MEASUREMENT RESULTS

In the present section, results from experimental laboratory measurements of Δt_i at approximate "zero flow" conditions are used to verify and demonstrate practical realisation of the theory described in Section 2, and illustrate the potentials of utilizing the theory.

Two experimental measurement setups have been used for this purpose. At CMR a 6" test spoolpiece setup was used in measurements at room temperature and low pressure, addressing e.g. the question of nonlinearity in relation to reciprocal operation (cf. Sections 3.2 and 3.3). At FMC Kongsberg Metering a dedicated pressure chamber was used to investigate reciprocal operation over wide pressure and temperature ranges (cf. Section 3.3). The key components of these measurement systems (the standard MPU 1200, 600 and 200 electronics boards and transducers [22]) were equal in the two setups, cf. Section 3.1 (different production units, though).

3.1 Measurement system

A principle sketch of the measurement system is shown in Fig. 7a, designed to achieve "sufficient reciprocal operation" according to the theory outlined in Section 2, cf. Eqs. (24) and (31). The design criterion used for the gas USM is Δt^{corr} < 2.4 ns, in accordance with Eq. (24). Voltage generation and current reception are used to achieve reciprocal operation. Electronic switches are used to realize the multiplexing between upstream and downstream measurements. The switches are shown for transducer I as transmitter and transducer II as receiver; - they toggle on/off for up- and downstream transmission. The impedances of the electronics components involved are matched so that $|Z_S - Z_L|$ < 0.55 Ω, which is within the example requirement $|Z_S - Z_L|$ < 0.6 Ω for "sufficient reciprocal operation" of gas and liquid USMs discussed in Section 2.3, cf. Eq. (33a). This figure is based on component specifications, so in reality $|Z_S - Z_L|$ is likely to be much smaller than 0.55 Ω.

The transducers and electronics boards (analog and digital) used in these measurements are shown in Figs. 7b and c. These are the transducers and boards used in the FMC Kongsberg Metering MPU 200, 600 and 1200 ultrasonic gas flow meters [22].

(a) (b) (c)

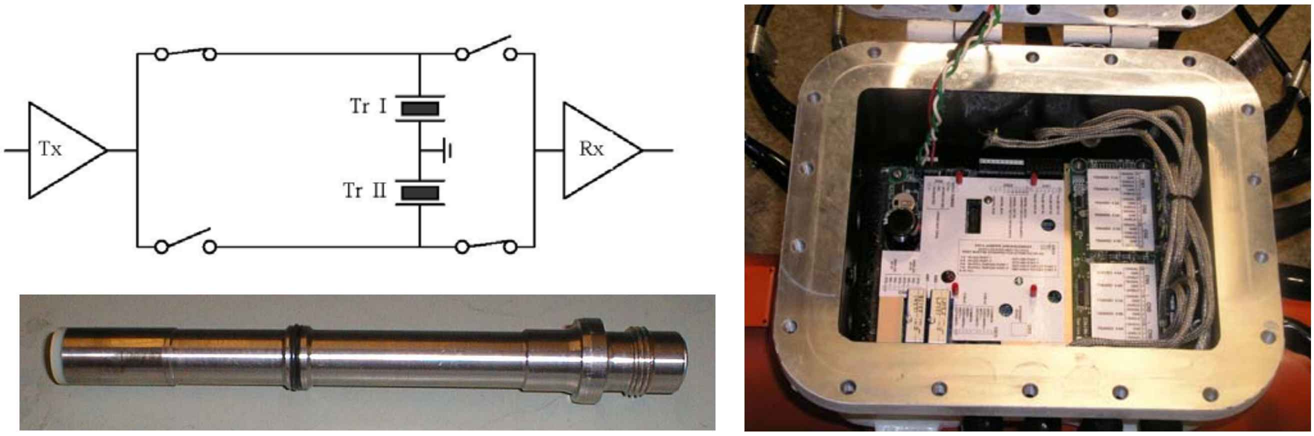


Fig. 7. (a) Principle sketch of the measurement system, (b) ultrasonic transducers and (c) electronics board used in the test measurements of Δt_i .

3.2 Effects of nonlinearity (high "firing voltages")

Measurements of Δt_i at approximate "zero flow" conditions have been made at CMR in a 6" test spoolpiece (with a single path), in air at 8.5 barA and about 21 ^{o}C. The spoolpiece was put in a water bath for temperature stabilization, to minimize temperature induced convection flow. Since the present measurements aim to measure Δt_i well below 2.4 ns (cf. Eq. (24)), preferably better than 1 ns, even extremely small convection flows can destroy the measurements. An example may illustrate the zero-flow stability requirements: From Eq. (22), Δt_i = 1 ns corresponds to an air flow velocity of about 0.4 mm/s, i.e. 2.4 cm/min. Thus, if the flow is of the order of 2-3 cm/min, it becomes difficult to verify the theory of Section 2. In the measurements presented in Figs. 8 and 9, a sufficient "zero-flow" stability has been achieved[16].

Fig. 8 shows Δt_i measurements for five transducer pairs, for transmitter (Tx) gain setting 1 (the lowest setting available for the "firing voltage" of the transmitting transducer), in air at 21 ^{o}C / 9.5 barA. A selection of transducers were used here, consisting of transducers which *had* passed the transducer production QA, as well as transducers which had *not* passed the QA.

[16] This was demonstrated e.g. by interchanging the transducer cables in the pair (at all TX gain settings), and observing that the sign of Δt_i did not change, for the lowest TX gain setting (= 1), cf. Fig. 8. If convection flow was a dominating effect, the sign of Δt_i should change by this cable interchange.

In Fig. 8, Δt_i is shown to be less than about 0.7 ns in 20 out of 23 measurements (the remaining three are about 1.1 and 1.6 ns), and all measurements are well below the "sufficient reciprocal operation" design criterion of 2.4 ns used for the gas USM, cf. Eq. (24). This is so also for the transducer pair no. 4, with relatively high phase difference, 33.5°. The reason for that is probably that $|Z_S - Z_L|$ in practice may be much less than 0.55 Ω. Such results strongly support and strengthen the present realization of "sufficient reciprocal operation", cf. Eq. (24). They also confirm that the transducers do not have to be equal to realize reciprocity.

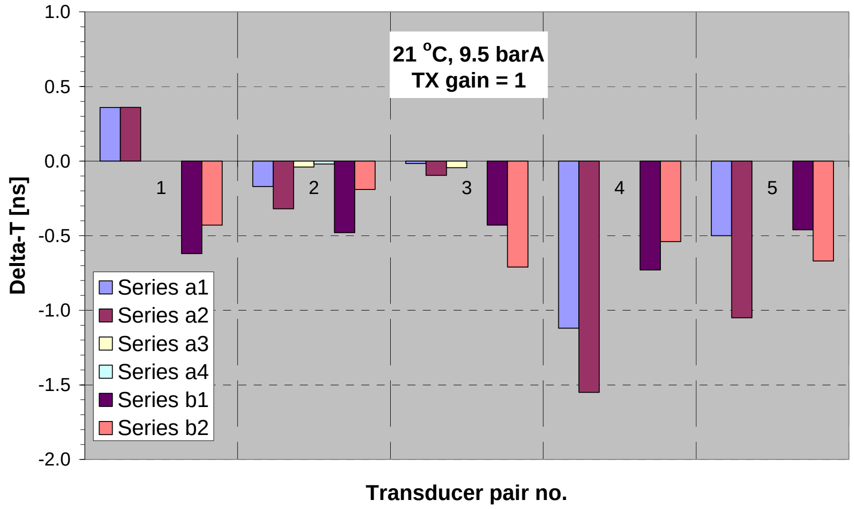


Fig. 8. Δt_i measurements made in the test spoolpiece, at approximate "zero flow conditions", for five different pairs of MPU 1200 ultrasonic transducers, for transmitter (Tx) gain setting 1 (lowest gain available), in air at 21 °C / 9.5 barA.

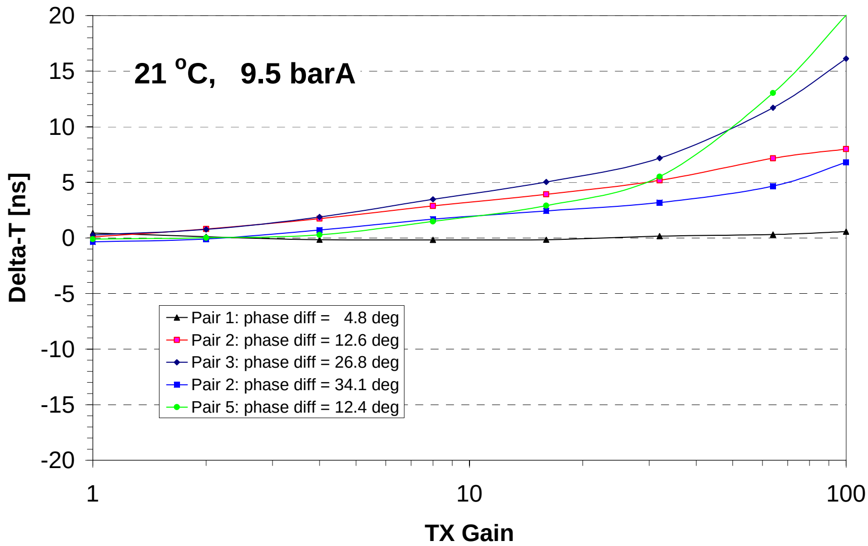


Fig. 9. Δt_i measurements made in the test spoolpiece, at approximate "zero flow conditions", for five different pairs of MPU 1200 ultrasonic transducers, as a function of transmitter (Tx) gain setting (in the range 1-100), in air at 21 °C / 9.5 barA. All pairs are fulfilling "sufficient reciprocal operation" at the lower TX gain settings, cf. Fig. 8.

Fig. 8 demonstrates that "sufficient reciprocal operation" is definitely realized at sufficiently low TX gain settings ("firing voltages"), at low pressure and room temperature, when the system is driven linearly. There is then the question of how higher "firing voltages" will influence on reciprocity.

Fig. 9 shows measurement results for the same five transducer pairs, this time shown as a function of transmitter (Tx) gain setting (i.e. "firing voltage" settings of the transmitting transducer, in the range 1-100, where 1 is the minimum and 100 the maximum setting available for the MPU software and electronics boards used here). Up to TX gain equal to about 70, this setting is proportional to the excitation voltage of the transmitting transducer[17]. Each curve is an average of 4-6 different measurements, taken over a time period of about 6-8 hours. For all pairs, the individual 4-6 measurements have been very repeatable, so that the (averaged) curves in Fig. 9 are highly representative for the individual curves. This reflects stable conditions in the spoolpiece.

A systematic trend of increasing Δt_i with increasing TX gain setting is observed in these results, which is assumed to be caused by increasing nonlinearity in the system (in the transducers or the gas medium), and which probably demonstrates violation of reciprocal operation by non-linear effects (as pointed out and demonstrated also in ref. [15]). Using the tentative example criterion of 2.4 ns given by Eq. (24), "sufficient reciprocal operation" is demonstrated up to about TX gain = 6, for these five transducer pairs.

3.3 Effects of pressure and temperature

In addition to the measurements made at CMR in air at low pressure and room temperature, described in Section 3.2, supplementary measurements of Δt_i at approximate "zero flow" conditions have been made over a range of pressures and temperatures, in a dedicated high-pressure gas transducer measurement chamber belonging to FMC Kongsberg Metering.

Fig. 10 gives an overview of the high-pressure transducer measurement chamber system, and some details, with transducer mounting, etc. In this chamber, 12 transducers of a MPU 1200 ultrasonic gas flow meter [22] can be measured simultaneously, in terms of 6 transducer pairs. The chamber consists of an inner pressure chamber submerged in a temperature controlled water bath. It has entry ports for 12 transducers, and is designed for gas pressures up to 215 barA, using nitrogen. The temperature-controlled water provides even temperature around the pressure chamber, to minimize temperature-induced gas movement (convection flow) in the pressure chamber (approximate "zero flow" conditions). The transducers pairs are all mounted as horizontal centre paths (about 181 mm transducer distance), to further minimize the effect of possible convection flow on the measurements. Measurements are made under the assumption of no flow in the chamber. The transducers are characterized for different operating conditions by changing the gas pressure and temperature by means of a pressure regulator and a water temperature controller. The temperature can be adjusted between 0 and 70 °C. The transducers are mounted in the chamber and connected with transducer cables to a MPU electronics unit. A personal computer (PC) with dedicated software communicates with the MPU electronics through an Ethernet connection. The transducer measurement is done automatically by the computer program after the initial operator set-up.

The chamber is normally used for factory measurement of transducer delay ("dry calibration"), and a quality check of the transducers, before shipment of a meter. "Dry calibration" of Δt_i is normally not made for the gas and liquid USMs considered here [22,23], due to the "sufficient reciprocal operation" design utilized in these meters, according to the theory presented in Section 2 (cf. Fig. 7a), so that no zero flow adjustment or active Δt-correction is used in these meters.

In the present study, however, Δt_i measurements have been made in the chamber in order to test and demonstrate realization of the theory presented in Section 2, over a range of pressures and temperatures. Results of these Δt_i measurements are given in Figs. 11-12. Fig. 11 shows Δt_i measurements for six

[17] Note that for Tx gain equal to about 70 or larger, the input amplifier is driven into saturation. As a consequence, the excitation signal starts to "clip", and at Tx gain = 100, the signal sent through the transmit - receive system is highly distorted.

transducer pairs (representing an arbitrary[18] selection of transducers, and an arbitrary pairing), for transmitter (Tx) gain setting 1 (the lowest setting available), for some combinations of temperature and pressure: 10 °C / 55 barA, 10 °C / 165 barA, 25 °C / 55 barA, 25 °C / 165 barA and 65 °C / 55 barA. In these results, Δt_i is shown to be less than about 1.6 ns in all measurements, except for two values, which are about 1.8 and 2.3 ns. All values are below the "sufficient reciprocal operation" design criterion of 2.4 ns used for the gas USM, cf. Eq. (24). That is, false flow *is* detected, but at a sufficiently low level to be negligible.

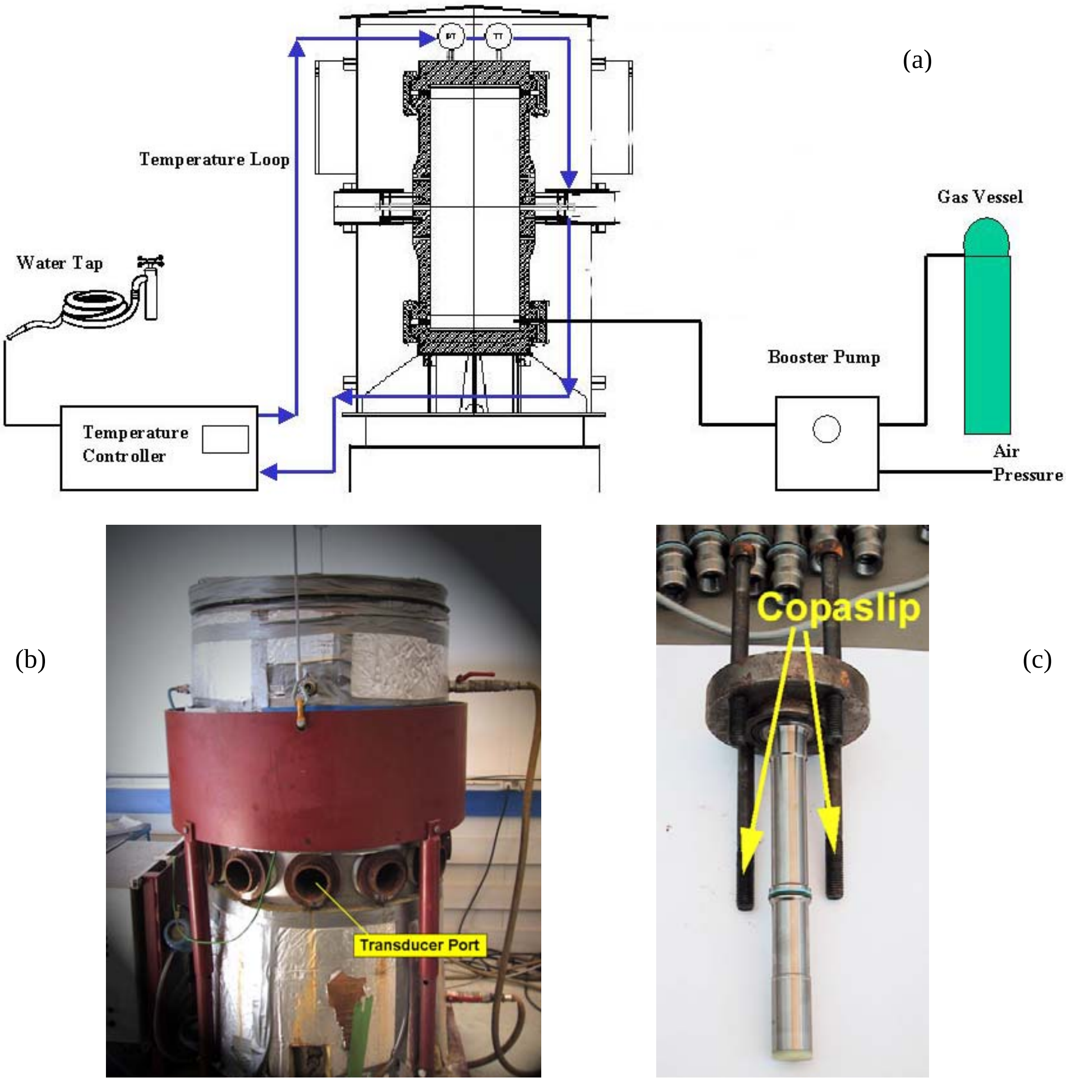


Fig. 10. The high-pressure transducer measurement chamber system used for Δt_i measurements (in nitrogen at "zero flow" conditions, as a function of pressure and temperature), for experimental "verification" of the theory in Section 2. (a) schematic overview, (b) photograph of chamber, and (c) transducer mounting arrangement.

In Fig. 11 (as in Fig. 12 below), each value of Δt_i is an average of 20-30 individual Δt_i measurements (single two-way "shots"), typically. In the data material underlaying Fig. 11, no individual Δt_i measurement was above 6.25 ns in magnitude, and typically the individual Δt_i measurements were below

[18] Only transducers having passed the transducer production QA were used in these pressure chamber measurements.

2.2 ns in magnitude. Such results further supports and strengthens the present realization of "sufficient reciprocal operation", cf. Eq. (24).

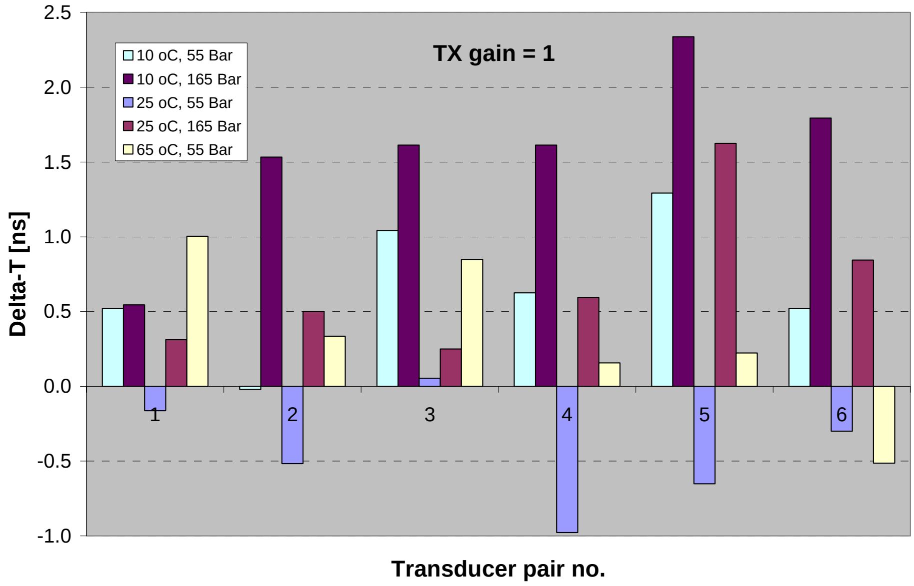


Fig. 11. Δt_i measurements made in the high-pressure chamber, at approximate "zero flow conditions", for six pairs of MPU 1200 ultrasonic transducers (arbitrary paired), for transmitter (Tx) gain setting 1 (lowest gain available), for some combinations of temperature and pressure: 10 ^{o}C / 55 barA, 10 ^{o}C / 165 barA, 25 ^{o}C / 55 barA, 25 ^{o}C / 165 barA and 65 ^{o}C / 55 barA.

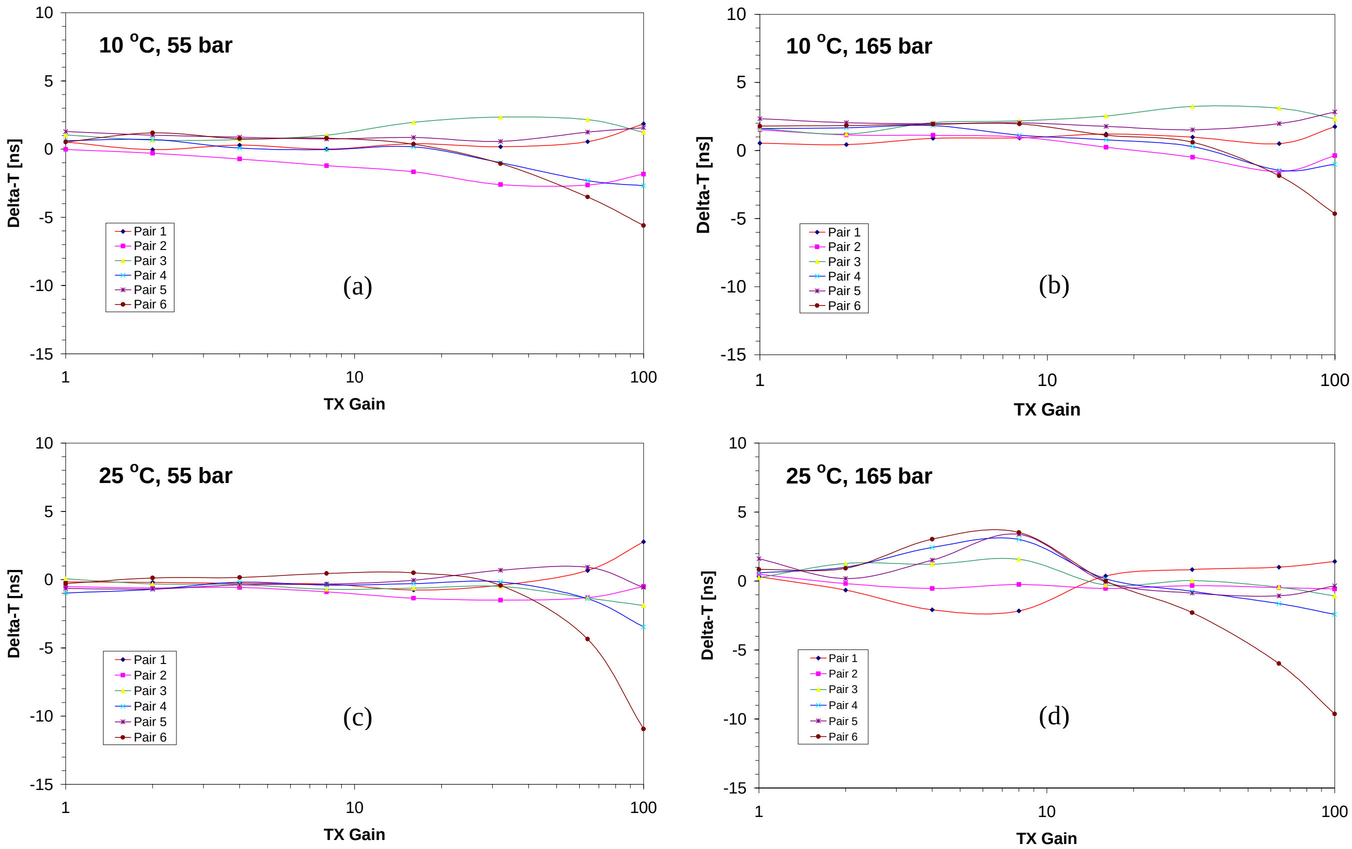
Some additional observations can also be made from Fig. 11, at a more detailed level than actually needed here for the discussion of reciprocal operation or not, but which anyway may be of interest for better understanding the USM technology in relation to reciprocity.

From Fig. 11 it is noted that for a given transducer pair, the measured Δt_i may be positive at one *P-T* condition, and negative at another. This could be caused by small convection flows in the chamber, changing by changing *P-T* conditions, regulation system, etc. This could also possibly be explained by Eq. (29), which predicts that a sign change for $\Delta\psi$ leads to a sign change for Δt_i. That is, if the phase difference between the electrical impedances of transducers I and II ($\Delta\psi$, cf. Eq. (28)) changes sign from one *P-T* condition to another, so will also Δt_i.

For the same reason, the measured Δt_i may be positive at one pair, and negative at another (in Fig. 11 this is rarely the case, but Fig. 12 below demonstrates this effect clearly). That is, if the phase difference between the electrical impedances of transducers I and II changes sign from one USM path to another, at no-flow conditions, so will also Δt_i. In a flow meter this comes out as an advantage, since at no-flow conditions, one path may detect *positive* false flow, while another may detect *negative* false flow, depending on which transducer that is fired first in each pair, and the phase difference between the transducers (which may come out as a kind of "quasi-random" effect). So if the false flow detection at each path corresponds to a Δt_i of about (say) 1.6 ns (which according to Eq. (24) is already well below the limit of acceptable false flow detection!), the effective false flow detection of the USM (the integrated effect of all paths) will be even smaller. Such results further supports and strengthens the present realization of "sufficient reciprocal operation".

In Fig. 12, the measured Δt_i is shown as a function of transmitter (Tx) gain setting (in the range 1-100), for the same combinations of temperature and pressure. A tendency of increased Δt_i with increasing Tx gain may be observed in the results. However, the trend is not as clear as the results given in Fig. 9, which may indicate that other effects may possibly also be influent on the results shown in Fig. 12, possibly masking the effect of nonlinearity. It is also noted that the increase in Δt_i with increasing Tx gain is larger for pair no. 6 than for the other pairs, for most of the *P*-*T* conditions investigated here. The reason for that has not yet been clarified.

Thus, using the tentative example criterion of 2.4 ns given by Eq. (24), "sufficient reciprocal operation" has been demonstrated for the gas USM system at the lower TX gain settings, for number of transducer pairs, at all pressure-temperature points investigated here, covering points in the range 10 - 65 ^{o}C, 10 - 165 barA.



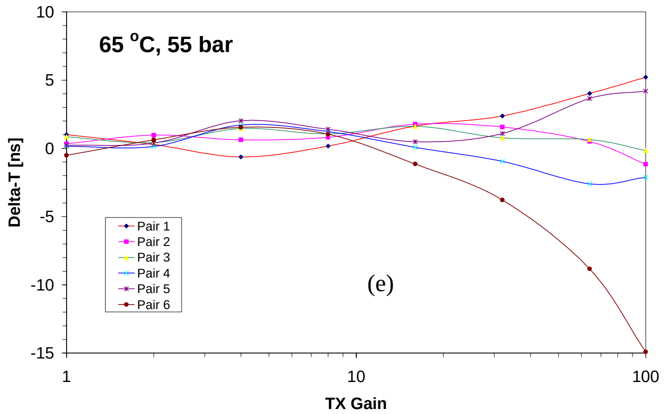


Fig. 12. Δt_i measurements made in the high-pressure chamber, at approximate "zero flow conditions", for six pairs of MPU 1200 ultrasonic transducers (arbitrary paired), as a function of transmitter (Tx) gain setting (in the range 1-100), for some combinations of temperature and pressure: (a) 10 ^{o}C / 55 barA, (b) 10 ^{o}C / 165 barA, (c) 25 ^{o}C / 55 barA, (d) 25 ^{o}C / 165 barA and (e) 65 ^{o}C / 55 barA.

4. CONSEQUENCES FOR ULTRASONIC FLOW METERS

A key question is of course, - "what can *sufficient reciprocal operation* do for the flow meter, if successfully exploited and implemented"? In fact it can do a lot:

- The need for measuring the Δt-correction as part of the "dry calibration" procedure ("zero flow verification") may be eliminated (or reduced), to the advantage of the manufacturer and the customer, such as simplified and reduced "dry calibration" procedures, reduced cost, and improved accuracy.

- By such methods the USM manufacturer can - by design - eliminate (or reduce) the need for active Δt-correction in the USM under field operation, independently of pressure, temperature, transducer ageing, drift, etc. Changes of transducer properties with T (or P) can be made less influent, so that these do not cause significant zero flow timing errors.

  For example, by using sufficiently low "firing voltage", so that the system is driven in a linear manner, it is demonstrated here that the transducers can be very different in characteristics, and "sufficient reciprocal operation" is still achieved. This means that if the transducers for some reason may be subject to significant drift over time (changing characteristics), the reciprocity of the USM system may not be significantly affected by that, as long as the system is driven linearly.

- This contributes to improve accuracy, linearity and reliability of the USM, in flow calibration as well as in field operation of the USM, at low flow velocities, without significantly affecting the accuracy at the high velocity measurements. That means, it can eliminate (or reduce) false flow reading in the range above the minimum flow velocity specified for the USM.

- It provides requirements for reproducibility in transducer production, in terms of the input electrical impedance of the transducer, which may simplify transducer QA, and contribute to cost reduction.

- The transducers are allowed to be different in their characteristic parameters, such as static capacitance, electrical impedance, resonance frequency, source and receiver sensitivities, directivity, etc. This will apply to all conditions of P, T, gas compositions and acoustic path length, as long as the "sufficient reciprocal operation" condition is met. In this connection it is worth noting that Eqs. (13)-(16) and (18)-(21) are derived without *any* assumption of "equalness" of the transducers[19]. Eq. (31) (and thus Eqs. (32)-(35)), on the other hand, i.e. the condition of "sufficient reciprocal operation", has been derived under a relatively weak assumption for the electrical impedances of the transducer production series, namely that the magnitudes are "about equal", and that the phase difference is much less than 90^o, i.e. $\Delta\psi_{\max} << \pi/2$.

  There is another interesting point in relation to "equalness" of the transducers. In ref. [19] it was claimed (on basis of simulation results) that reciprocal operation of the measurement system holds only when the transmitting and receiving transducers are identical (cf. Section 1). From the paper it seems as the authors have used voltage firing of the transmitting transducer and voltage reception at the receiver for simulating the transit time difference, Δt_i. If so, that may explain their findings, since in that case it has been shown above (Section 2) that perfect reciprocal operation of the USM relies on either (1) the transducers I and II being identical ($Z_I = Z_{II}$), or (2) "electrical symmetry" ($Z_S = Z_L$). The authors may possibly have overseen the latter possibility of "electrical symmetry" to achieve reciprocal operation, as well as the possibility of using one of the other cases classified under category "OK" above (e.g. current generator and voltage receiver, voltage generator and current receiver, etc.), for which reciprocal operation can be achieved much more independent of the transducers and their properties, cf. Section 2.

[19] "Sufficient reciprocal operation" can thus be achieved without using Eq. (31). Eq. (31), however, gives a specific *criterion* for that.

Possible *disadvantages* of using reciprocity may include factors such as:

- More careful design of the electronics circuitry is necessary, e.g. according to the conditions of "sufficient reciprocal operation" derived in Section 2, cf. Eq. (31).

- The USM system should be driven linearly, with maximum limits for the signal used for transducer excitation. That is, you cannot drive the transducer as "hard" as you like, which could otherwise be an attractive approach to achieve a high signal-to-noise ratio (SNR), required for accurate time detection [23]. When high excitation pulses are applied to the piezoelectric transducers the linear regime may be transcended, in which case there may be little advantage in reciprocal operation. Linearity of the transducers and the measurement system is an underlying assumption for the theory used in Section 2 to achieve "sufficient reciprocal operation". Investigations have shown that for firing voltages used in some USMs today, linearity may be violated to some extent [21,6]. A high firing voltage may cause a larger Δt-correction (a larger systematic timing error, and a larger false flow detection at low flow velocities, if not corrected for) than a low firing voltage [15].

  On the other hand, reciprocal operation is important only at the lower flow velocities. Noise may be more of a problem at the higher flow velocities (e.g. flow noise), for which reciprocal operation is not important, and higher "firing voltage" can be used to achieve a sufficient SNR.

  Moreover, there is an unsolved question whether a high degree of "equalness" of the transducers can possibly reduce the destroying effect of non-linearity on reciprocity. If so, this could possibly be exploited to use higher signal levels to increase the SNR at low flow velocities under difficult conditions (highly attenuating media) [23]. This interesting question has not been addressed in great detail here, and will require further effort to investigate in full depth.

5. CONCLUSIONS

With fluid flow approching zero, the USM method becomes increasingly dependent upon the reciprocity of the electro-acoustic measurement system. If reciprocity is not fulfilled, the measured transit times of upstream and downstream propagation will not be equal at zero flow, resulting in a zero flow timing offset, which becomes highly important in the low-velocity flow range, and provides false flow detection and degraded accuracy and linearity of the USM in this range. The AGA-9 report [1] and the API MPMS Ch. 5.8 standard [4] both prescribe need for "zero flow verification test (zero test)" or "zeroing the meter", for gas and liquid USMs, respectively.

In the present work, criteria have been established for "sufficient reciprocal operation" of the USM. By such methods the USM manufacturer can - by design - eliminate (or reduce) the need for active Δt-correction, and achieve "auto-zeroing" of the USM. Possible changes of transducer properties with temperature, pressure, and time (ageing, drift) can be made less influent, so that these do not cause significant zero flow timing errors. This contributes to improve the accuracy and reliability of the USM. Moreover, the need for measuring the Δt-correction as part of the “dry calibration” may be eliminated (or reduced), which may reduce costs and in several ways is advantage both for the manufacturer and the user of the flow meter. In addition, criteria have been derived to establish requirements for the reproducibility of the transducer production, which can be used in transducer production QA.

Disadvantages of using reciprocity may include factors such as (a) more careful electrical design is required, and (b) at low flow velocities, the USM system should be driven linearly, with maximum limits for the signal used for transducer excitation. Thus at such low flow velocities it may be more difficult to achieve the signal-to-noise ratio (SNR) which is required for accurate time measurement. For higher flow velocities, however, where high levels of flow noise may force a need for higher signal level to achieve a sufficient SNR, reciprocity is not an important concern.

The techniques to achieve "sufficient reciprocal operation" derived here have been implemented in ultrasonic flow meters for gas [22] and liquid [23]. In the present paper "sufficient reciprocal operation" has been demonstrated for the gas USM [22], with measured Δt_i of the order of 2 ns or less at approximate "zero flow" conditions and low-to-moderate signal excitation levels, over the pressure and temperature ranges 10-65 ^{o}C / 55-165 barA. At presumably more stable measurement conditions, using air at 21 ^{o}C and 9.5 barA, "sufficient reciprocal operation" has been demonstrated to within 0.7 ns, typically.

Similarly, "sufficient reciprocal operation" has been demonstrated for the liquid USM [23] (not shown here), with measured Δt_i of the order of 10-20 ps, using basically the same spoolpiece, electronics units (analog and digital) and software, for the gas and the liquid USMs.

Both results (for the gas and the liquid USMs) are well within the tentative requirements of 2.4 ns and 33 ps used here, respectively, cf. Eq. (24). As a result, auto-zeroing is achieved, and active Δt-correction is not used in these meters.

The methods derived and demonstrated here for "sufficient reciprocal operation" may be of general interest also to other electroacoustic measurement systems than the USM considered here, i.e. to all systems falling into the scheme of Fig. 4, and also to the more general case for which the signal generator (V_0, Z_S) and the electrical load (Z_L) may not be equal in (a) and (b) of Fig. 4.

ACKNOWLEDGEMENTS

Useful discussions with Kjell-Eivind Frøysa, Christian Michelsen Research AS (CMR), are highly appreciated. The work has evolved from and been inspired by project cooperation over a number of years, related to USM fiscal metering of gas and oil (custody transfer, sales and allocation metering), involving several partners: Fluenta AS (now Roxar Flow Measurement), Statoil, FMC Kongsberg Metering, FMC Smith Meter (USA), The Research Council of Norway (NFR), The Norwegian Society for Oil and Gas Measurement (NFOGM), the Norwegian Petroleum Directorate (NPD), GERG (Groupe Européen de Reserches Gazières), Norsk Hydro, ConocoPhillips and Gassco AS. In particular, the work has been supported by The Research Council of Norway (NFR), Statoil ASA and Gassco AS, under CMR's 4-year strategic institute programme “Ultrasonic technology for improved exploitation of petroleum resources” (2003-06).

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