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Linearity error in Clamp-on ultrasonic flowmeters due to the installation on pipes made of dispersive materials

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***Abstract*—this article analyses and explains the implications that dispersive materials have over the linearity in flow measurement when a Clamp-on ultrasonic flowmeter is used. This is of capital importance because dispersive materials are commonly used in the manufacture of transducer wedges and pipes.**

The evaluation of this phenomenon has been tested by experimental measurement. The used setup consisted of a water flow calibration facility where a commercial Clamp-on ultrasonic flowmeter was installed on it and its flow measurement was compared with a reference flowmeter.

Two experiments have been conducted. A first experiment was performed to evaluate only the effect produced by the fact that the transducer wedge is made of dispersive material. For this reason, an ultrasonic flowmeter was installed on a pipe made of non-dispersive material, in this case, an INOX pipe. Linearity error introduced by the wedge was below 1%. This error complies with the accuracy specification of the ultrasonic flowmeter given by the manufacturer (±1.5%).

Finally, a second experiment consisted of installing the ultrasonic flowmeter on a dispersive pipe (PVC pipe) in order to measure the worst condition (both materials, wedge and pipe, were dispersive). Under this condition, the linearity error was increased until it reaches a value of 6.4%. Moreover, in case of a dispersive material pipe, the bigger the pipe thickness is, the bigger non-linearity error is reached.

***Index Terms*—Clamp-on ultrasonic flowmeters, dispersive materials, linearity error, cross-correlation methods**

I. Introduction

Currently, two methods are mainly used for ultrasonic flow measurement in the industry. The first method is "Doppler Effect" and the second one is "Time of Flight"(TOF). This study will focus on the latter.

The working principle is shown in Fig. 1. Transducer TR1 emits an ultrasonic signal that travels along the path 1 and is received by transducer TR2. Then the process is done the other way round, TR2 emits along path 2 and the signal is received by transducer TR1. When there is flow inside the pipe, the ultrasonic signal travelling with the flow is "faster" than the one against the flow. Thus, the difference in propagation time between path 1 and path 2 is proportional to the fluid velocity inside the pipe (1) [1].

$$v = \frac{C^2 \cdot \Delta t}{4 \cdot d \cdot \tan\theta} \quad (1)$$

The term Δt is the difference in time between both propagation paths. C is the sound speed in the liquid, d is the internal diameter of the pipe and Θ is the refraction angle in the liquid.

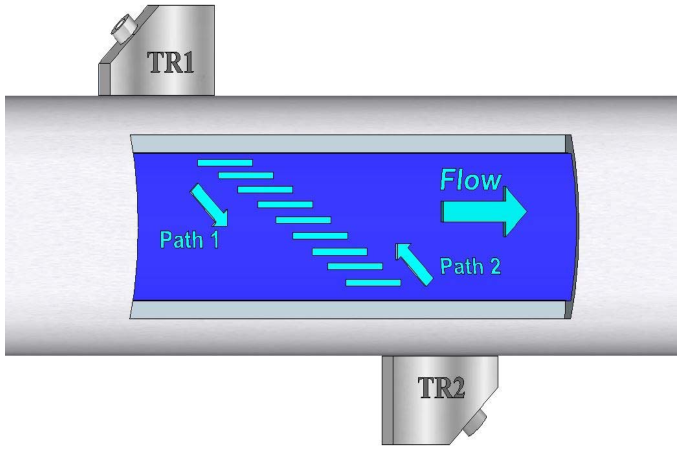

Fig. 1. The working principle of an ultrasonic flowmeter based on the method called "Time of Flight" (ToF)

The problem appears when the pipe, where the transducers are fixed, is made of dispersive material. In this case, as shown below, the ultrasonic flowmeter will have linearity problems in the flow measurement.

The behaviour of dispersive materials is explained in several articles. The parameter of interest associated to dispersion is the variation of the propagation velocity as a function of the frequency [2-5]. The reason is because ultrasonic flowmeters use wedge type transducers. In these transducers, the incident beam angle is not normal to the surface of the pipe [6]. Therefore, when the excitation signal contains several frequency components, each frequency travels with a different velocity. In this circumstance, according to Snell's law, different diffraction angles are produced for each frequency at the boundaries between materials.

As a result the ultrasonic beam widens and the transducer aperture becomes too small to receive all the frequency components contained in the ultrasonic beam. Thus, when the ultrasonic beam is carried by the liquid that flows inside the pipe, the reception transducer receives different frequency contributions, producing a change in its spectral composition. The mixing of these frequencies produces a reception signal modulated in phase and amplitude. This modulation generates nonlinear changes in the signal phase affecting the measurement of the time of flight, producing a non-linear behaviour on the measurement of the Clamp-on ultrasonic flowmeters.

II. MATERIAL AND METHOD

In order to validate the proposal explained above, two experiments have been conducted. The setup used in the experiments is shown in Fig. 2.

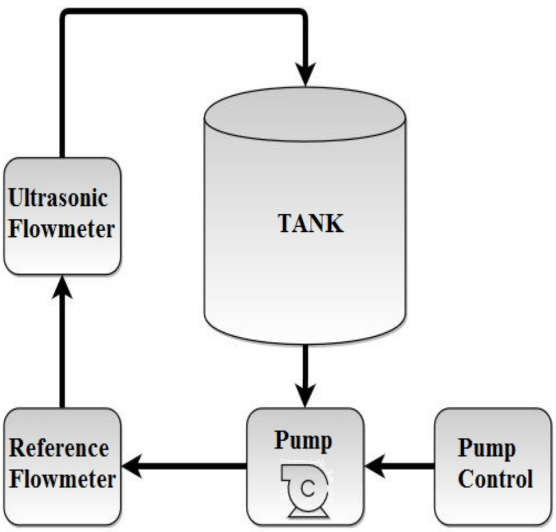

Fig. 2. Setup used in the experiments for measuring the non-linearity produced by dispersive materials

The water flow calibration facility shown in Fig. 2 is composed of a tank with capacity for 4000 litters, a pump with Qmax= 125 m^3/h controlled by a frequency converter and a commercial electromagnetic flowmeter, which is used as a reference flowmeter. The electromagnetic flowmeter's accuracy is ±0.5% reading value. Moreover, in this setup, it is possible to change a pipe section by a standard flange connection. Tubes under test are an INOX pipe AISI 316L DIN 1.4404 and PVC pipe, both with DN125 and 4mm of wall thickness.

Regarding to the ultrasonic flowmeter under test, its accuracy is ±1.5%, the reading value ±0.02m/s and the method used to measure the flow is so called "transit-time correlation method". This method is extensively used in commercial ultrasonic flowmeters in order to measure the difference in time between both propagation paths [7-9]. The working principle of this method is shown in Fig. 3 and explained in [10].

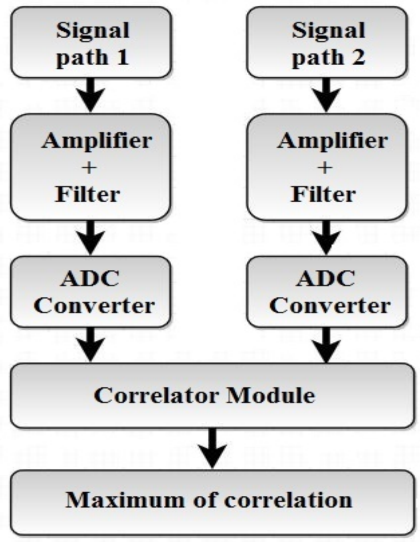

Fig. 3. Block diagram of the transit-time correlation method used to measure the difference in time between both propagation paths

As shown in Fig. 3, signals received from both paths are amplified and filtered to adapt the amplitude and improve the signal to noise ratio (SNR).These signals are sampled by an ADC converter; the sampling frequency is 12.5MS/s. Once both signals are digitized, the cross-correlation is performed between them. The function of the last block is to find the maximum of the cross-correlation. In order to increase the temporal resolution, a parabolic sub-sample interpolation is performed around the maximum. Finally, the measured maximum is directly proportional to the difference in time between both signals.

Once the ultrasonic flowmeter is installed on the pipe a calibration process is performed. This process consist of adjusting the offset under no-flow conditions and the span using flow conditions around 90% of full-scale. Calibration process is done for INOX and PVC pipes.

III. RESULTS

The first experiment consists of installing the ultrasonic flowmeter on the INOX pipe to measure the non-linearity effect produced by transducer wedges. Fig. 4 shows the values measured by the reference instrument and the ultrasonic flowmeter.

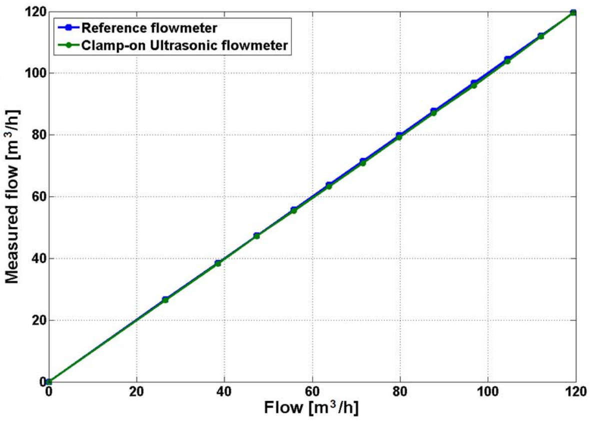

Fig. 4. Flow rate measured by a reference instrument and a Clamp-on ultrasonic flowmeter when the ultrasonic flowmeter is installed on an INOX pipe

Relative and absolute errors between the values measured by the reference instrument (electromagnetic flowmeter) and the ultrasonic flowmeter under test are shown in table 1.

TABLE 1.Relative errors between values measured by the reference instrument and the ultrasonic flowmeter when it is installed on an INOX pipe

Reference $[m^3/h]$	Ultrasonic $[m^3/h]$	Absolute Error $[m^3/h]$	Relative Error [%]
0	0	0	0
26.6	26.4	0.2	0.75188
38.5	38.3	0.2	0.519481
47.3	47.1	0.2	0.422833
55.8	55.4	0.4	0.716846
63.8	63.2	0.6	0.940439
71.5	70.8	0.7	0.979021
79.8	79.1	0.7	0.877193
87.7	87	0.7	0.798176
96.8	96	0.8	0.826446
104.5	103.8	0.7	0.669856
112.1	111.8	0.3	0.267618
119.5	119.6	-0.1	-0.083682

Errors obtained by the first experiment were below 1%. These values comply with the accuracy specification given by the manufacturer (±1.5%). Measured errors include the ultrasonic flowmeter's accuracy and the error caused by the material of the wedge. In this paper, these errors were considered as reference to compare them with the values obtained in the second experiment.

In the second experiment, the pipe was changed by a PVC pipe and the measures were repeated. Fig. 5 shows the values measured by the reference instrument and the ultrasonic flowmeter.

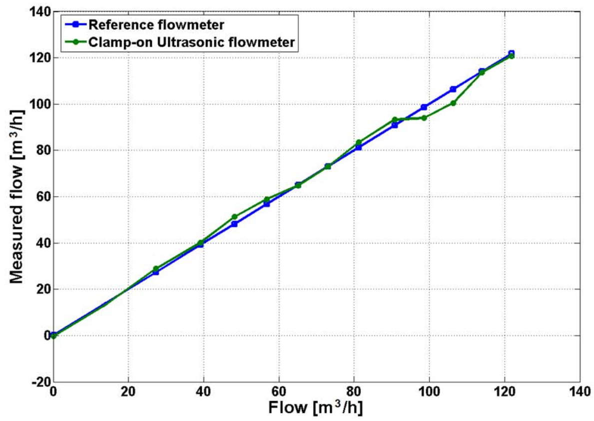

Fig. 5. Flow rate measured by a reference instrument and a Clamp-on ultrasonic flowmeter when the ultrasonic flowmeter is installed on a PVC pipe

Relative and absolute errors between the values measured by the reference instrument and the ultrasonic flowmeter under test are represented in table 2.

TABLE 2.Relative errors between values measured by the reference instrument and the ultrasonic flowmeter when it is installed on a PVC pipe

Reference $[m^3/h]$	Ultrasonic $[m^3/h]$	Absolute Error $[m^3/h]$	Relative Error [%]
0	0	0	0
27.3	28.9	-1.6	-5.860806
39.2	40.2	-1	-2.55102
48.2	51.3	-3.1	-6.431535
56.8	58.9	-2.1	-3.697183
65.1	64.8	0.3	0.460829
73.1	72.9	0.2	0.273598
81.2	83.4	-2.2	-2.70936
90.8	93.3	-2.5	-2.753304
98.6	94	4.6	4.665314
106.3	100.5	5.8	5.456256
114	113.7	0.3	0.263158
121.8	120.8	1	0.821018

Under this condition the linearity error was increased until reach an error of 6.43%.

Fig. 6 shows graphically the relative errors obtained in the table 1 and 2. These errors have been calculated using (2)

$$\delta = \frac{\Delta}{v_{ref}} \cdot 100 \tag{2}$$

Where δ is the relative error (expressed in percentage). Δ is the absolute error and v_{ref} is the value measured by the reference instrument.

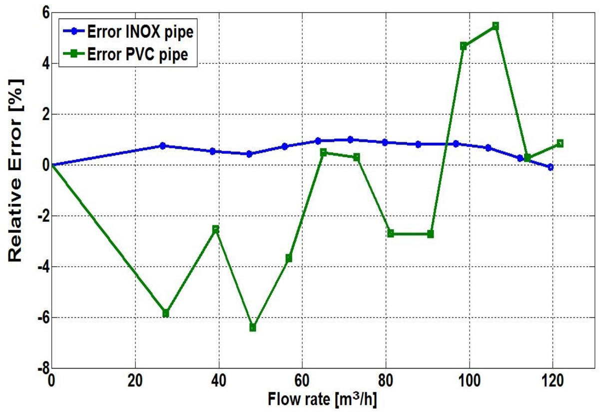

Fig. 6. Relative error between values measured by the reference instrument and the ultrasonic flowmeter for INOX and PVC pipes

As shown in Fig. 6, measurement errors in PVC pipe are higher than in INOX pipe. This is due to the dispersive behaviour of PVC pipe.

IV. Discussion

It is very common in commercial ultrasonic flowmeters to use an excitation signal with high bandwidth. The reason of using this type of signals is to emphasize the maximum in correlation. These signals contain multiple frequencies and each frequency steers with a different angle when it passes through dispersive materials. This effect is shown in Fig. 7.

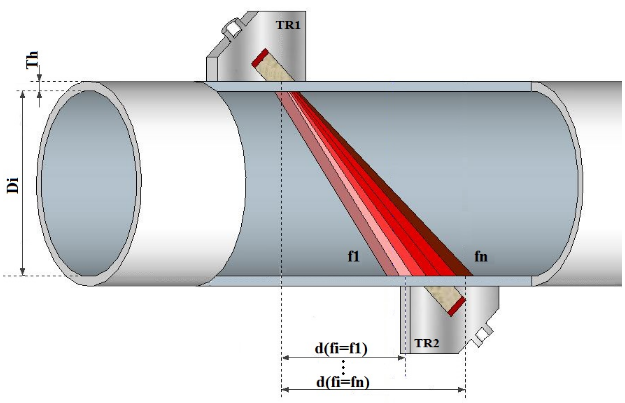

Fig. 7. Effect of splitting the ultrasonic beam path due to the dispersivity of the pipe material. (Each colour is associated to one different frequency)

Considering the case of no flow, in order to know the spatial positions of each frequency component dfi (fig.7) which are contained in the ultrasonic beam (fi= f1 to fn), the equation (3) is applied. This equation is similar to the one used in [11] but applied when the set-up is in "Z-mode" instead of "V-mode".

$$d_{fi} = 2 \cdot Th \cdot \left\{\arcsin\left(\frac{c_p(f)}{c_w(f)} \cdot \sin(\alpha_w)\right)\right\} \; + \quad (3)$$
$$+Di \cdot \left\{\arcsin\left(\frac{c_L}{c_w(f)} \cdot \sin(\alpha_w)\right)\right\}$$

Where Th and Di are the thickness and the interior diameter of the pipe. α_w is the angle of transducer wedge. c_L is the sound propagation speed in liquid (water). cp(fi) and cw(fi) are the sound propagation speeds in the pipe and the wedge of the transducer. In the case that pipe and wedge are made of dispersive materials, their velocities will change as a function of the frequency [2-5].

Equation (7) results from the application of (4), (5) and (6) to the equation (3).

$$\psi = \sin(\alpha_w) \cdot \frac{c_{p(fi)}}{c_{w(fi)}} \quad (4)$$

$$\Upsilon = \sin(\alpha_w) \cdot \frac{c_L}{c_{w(fi)}} \quad (5)$$

$$\tan(\arcsin(x)) = \frac{X}{\sqrt{1-X^2}} \quad (6)$$

$$d_{fi} = \frac{2 \cdot T_h \cdot \psi}{\sqrt{1-\psi^2}} + \frac{D_i \cdot \Upsilon}{\sqrt{1-\Upsilon^2}} \quad (7)$$

In the case where flow exists inside the pipe, the ultrasonic beam is carried by the liquid. The displacement produced by the flow can be calculated by (8).

$$d_L = \frac{c_F \cdot Di}{c_L \cdot \cos(\arcsin(\Upsilon))} \quad (8)$$

Where d_L is the displacement produced by the flow. c_F is the velocity of the liquid inside the pipe. Therefore, to add the effect of flow in (7), equations (8) and (9) are used in order to obtain (10).

$$\cos(\arcsin(x)) = \sqrt{1 - x^2} \quad (9)$$

$$d_{(f)} = \frac{2 \cdot T_h \cdot \psi}{\sqrt{1-\psi^2}} + \frac{D_i \cdot \Upsilon}{\sqrt{1-\Upsilon^2}} + \frac{D_i \cdot c_F}{c_L \cdot \sqrt{1-\Upsilon^2}} \quad (10)$$

Equation 10 describes how the ultrasonic beam is carried by the liquid that flows inside the pipe. This effect it is also shown in Fig. 8.

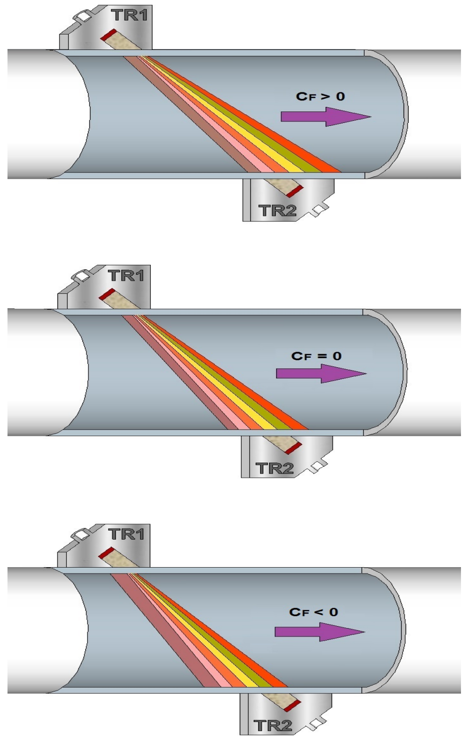

Fig. 8. Displacement of the ultrasonic beam due to the liquid that flows inside the pipe. Liquid velocity >0 (top). Liquid velocity =0 (middle). Liquid velocity <0 (bottom).

As a result that the ultrasonic beam is carried by the liquid, the reception transducer receives different frequency contributions (Fig. 8), producing changes in its spectral composition. The mixing of these frequencies produces a reception signal modulated in phase and amplitude. Moreover, modulation will change as a function of which frequencies are combined in the receptor transducer. This produces a non-linear behaviour on the measurement of the Clamp-on ultrasonic flowmeters.

V. CONCLUSIONS

The effect produced by dispersive materials over the linearity in flow measurement has been proved.

These types of materials are commonly used in the manufacture of transducer wedges and pipes. The effect produced by the transducer wedge is below 1%. These values comply with the accuracy specification given by the manufacturer (±1.5%). Measured errors include the ultrasonic flowmeter's accuracy and the error caused by the material used in the wedge.

The biggest linearity error is produced when the pipe is made of a dispersive material. Linearity error measured increased until reaches an error of 6.4%. Moreover, the bigger the pipe thickness is, the bigger non-linearity error is arises.

Once this phenomenon has been demonstrated by experimental measurement, the authors are developing the analytical model that explains how the spectral composition in the reception transducer changes as a function of the liquid that flows inside the pipe. In this study, it is also studied the error in the measurement of the time of flight using the cross-correlation due to changes in the spectral composition of the received signal.

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