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AN ULTRASONIC GAS FLOWMETER USING HIGH FREQUENCY TRANSDUCERS AND CORRELATION TECHNIQUE

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Abstract: The research activities carried out in the past years showed that in gas networks some constraints exist on the ultrasonic working frequency of flowmeters. The study of the transmission and the attenuation of the signal, and noise mechanisms gives us a defined suitable frequency range [1]. Thereby, a working frequency of 500 kHz proves to be the most suitable to avoid noise effects. This frequency is above the noise level detected in gas pipelines. Moreover, the signal lost due to attenuation of ultrasound in gas is still negligible. In parallel, the use of this frequency allows the application of efficient numerical techniques of signal processing such as the correlation method. An initialisation process based on this method is developed for gas flowmeters. It provides low uncertainty on parameters involved in the flow measurement process.
A single path flowmeter equipped with this system has been tested on the Gaz de France test facilities. Its accuracy is better than 1.5% from 250 to 1000 m^3/h without initial adjustment. The auto-calibration process also forms part of the system, using a systematic comparison between ultrasonic measurement of sound velocity and a theoretical approach. The signal to noise ratio remains large enough to perform correctly the measurements even with a control valve installed close to the flowmeter.

Keywords: Ultrasonic gas flowmeter, ultrasound attenuation, valve noise, cross correlation, self calibration.

1 INTRODUCTION

With an increased interest in natural energy resources, an extensive requirement concerns the accurate measurement of large volumes of natural gas in transportation network. The ultrasonic gas flowmeter technology includes many advantages over classical technologies (orifice, turbine or vortex meters). This system contains no moving parts and does not create pressure drop. It remains insensitive to gas composition fluctuations and allows bi-directional measurements. It provides redundant information to easily perform checks of the meter performance during operation. Its fast response allows measurement in transient or pulsating flows. Finally, this system could highly reduce installation and maintenance costs.

The transit-time (or "contrapropagating") method is the most used technique in the flow metering technology. The principle is based on the modification of the time of flight of ultrasound by the fluid velocity along the line of the flight path between two transducers. The transit times and the differential time of flight are functions of the fluid velocity. Therefore this method implies measurement of very short time delays of about few nanoseconds.

This paper presents the constraints inherent to gas networks. In parallel, a new technology used to avoid these influences is described. Some results of measurements conducted in the "Laboratoire de Mécanique Physique" of Bordeaux University and on the test facilities of Gaz de France using a flowmeter equipped with this technology are presented. Another objective of the development is to validate the method with a simple configuration and without initial adjustment of the meter.

2 THE FLUID AND THE NETWORK LIMITS

The acoustic and thermodynamic properties of natural gas limit the choice of suitable transducer resonance frequencies for natural gas flow metering applications. The abrupt change of acoustic impedance between transducer and natural gas and the attenuation of ultrasound due to fluid viscosity, heat exchanges and relaxation phenomena provide a guide on the choice of the frequency required to preserve a correct waveform.

The theoretical study described below shows that the ultrasonic disturbances met in gas networks deteriorate the performance of ultrasonic flowmeters. This study is completed by an experimental investigation of the noise generated by a control valve which demonstrates that the generated perturbations lie in the range of frequencies used by the meter transducers.

2.1 Attenuation of ultrasonic waves in natural gas

The equation used to calculate the total attenuation of a plane wave in a thermo-viscous fluid can be broken down into two phenomena:

- "standard" attenuation that is the sum of attenuation due to fluid viscosity and due to the effects of thermal conduction,
- attenuation due to a relaxation phenomenon. The dispersive aspect of molecular relaxation modifies the speed of sound as well as attenuation.

Hence, the total attenuation (in Np/m) can be written in the form [2, 3]:

$$\alpha_{total} = \alpha_{standard} + \alpha_{relaxation}, \qquad (1)$$

where

$$\alpha_{standard} = \frac{\omega^2}{2\rho C_0^3}\left[(\lambda + 2\mu) + \frac{(\gamma - 1)K}{C_p}\right] \quad \text{and} \quad \alpha_{relaxation} = \frac{\pi}{2C_0}\left[\frac{(\gamma - 1)^2}{\gamma} F_v \frac{\frac{f^2}{f_c}}{1 + \left(\frac{f}{f_c}\right)^2}\right], \qquad (2)$$

where: ω: pulse = $2\pi f$,
ρ: density,
λ: volumetric viscosity,
μ: shear viscosity,
K: thermal conductivity,
C_p: specific heat at constant pressure,
C_0: speed of sound in the gas,
γ: ratio of specific heats,
f_c: relaxation frequency of the gas,
f: frequency of the emitted signal,
F_v: corrective term revealing C_p and C_v variations with pressure and temperature.

As seen in the formula above, this model involves the wave frequency and several thermodynamic coefficients related to the gas characteristics.

The mathematical model developed was validated with air, at atmospheric conditions, using a pair of capacitive transducers [4] installed on a special bench. The signals amplitudes were recorded for several distances between the two transducers. The values of the wave attenuation obtained from the general theoretical model [2] were compared with the measurements carried out on the bench and H. E. Bass's theoretical approach [5]. The results are presented in Figure 1 for two distances between the two transducers.

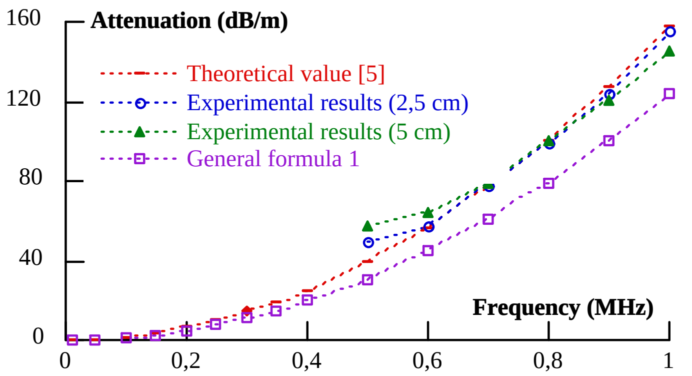

Figure 1: Validation of the theoretical model by application of the general formula in air.

The values were close enough to validate the mathematical model developed above.

The application of this model to real natural gas revealed that the total attenuation remains very low for wave frequencies below 150 kHz, and becomes very high for frequencies higher than 500 kHz. So the high limit of the working frequency was considered around 0.5 to 1 MHz, limit beyond which the ultrasonic signal becomes unusable to perform the measure.
At this stage in the study, the working frequency of the meter should result from a compromise decision. On the one hand, attenuation mechanisms may allow reducing the ultrasonic disruptive sound in gas transmission pipes which is inducing high frequency choice. On the other hand, the transducers dynamic has to be relatively broad to always provide a good signal to noise ratio whatever the frequency and remain insensitive to attenuation losses. According to the nowadays available technologies, this is made easier by reducing frequency.

2.2 Sources of ultrasonic noise in gas transmission pipes

Very few references were found in literature to predict ultrasonic noise amplitudes and frequencies generated by pressure reducers. Whereas the frequency of the noise due to mechanical vibrations of the pressure governor remains at a frequency lower than 3 kHz, the noise may become ultrasonic mainly owing to gas turbulence and gas expansion.
To illustrate this phenomenon, an experimental set up was developed to measure the relative value of the ultrasonic noise produced by gas flowing around an obstacle such a control valve in the gaseous stream.

The transducers used were the capacitive transducers constructed in the laboratory [4]. Their relatively wide bandwidth allows measuring the value of the ultrasonic noise relatively to sound pressure of the transducer from 70 kHz to 0.8 MHz. The emitter was fed with a short pulse of 200 Volts and the signal was acquired without frequency filter. The measurements of the generated noise by a valve have revealed that the frequency spectrum of this noise was contained within a domain the boundary of which is located at about 200-250 kHz (Figure 2).

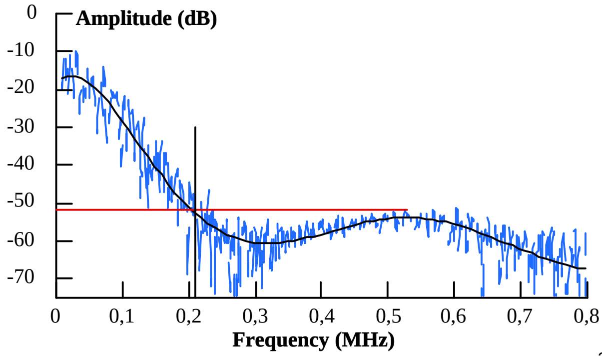

Figure 2: Analysis of noise relating to the ultrasonic signal (Flow: 300 m^3/h; P=4 bar) (frequency-dependent shape).

The ultrasonic noise level depends on upstream and downstream conditions of pressure, P, and density, ρ, on the flow rate, Q_m, and on the acoustic intensity produced by the type of the regulator.
Table 1 gives the maximum amplitude of the noise in volts as well as the root mean square for two flow rates and three values of pressure P (1, 4 and 8 bar). The expansion is defined as follow:

$$\text{Expansion} = \frac{P_{upstream}}{P_{downstream}} \quad (3)$$

where $P_{upstream}$=10 bar and $P_{downstream}$=1, 4 and 8 bar.
The noise level increases with the flow rate and decreases as expansion decreases.

Table 1: Noise level (Volts) for two flow rates and three expansions.

Flow rate	Expansion rates	10 ($P_{downstream}$ = 1 bar)	2.5 ($P_{downstream}$ =4 bar)	1.25 ($P_{downstream}$ =8 bar)
200 m^3/h	Max	1.40	0.50	0.21
	RMS	0.56	0.16	0.059
300 m^3/h	Max	1.70	0.52	0.22
	RMS	0.73	0.19	0.078

This noise is likely to severely disturb the operation of ultrasonic flowmeters that do not use higher frequencies. The ultrasonic signal can be completely drowned out by the noise. By frequency, digital and high-pass (> 0.2 MHz) filtering and a time window, the ultrasonic signal can be restored provided that the working frequency is above the valve noise frequency.

The frequency content of this noise is independent of pressure, expansion, gas velocity.
This leads to think that a characteristic frequency of the valve can be defined regardless of flux values.

3 THE TECHNOLOGY

The ultrasonic transducer constitutes the heart of flowmeter and it seems essential to rightly adapt this main device. As a general rule, manufacturers use piezoelectric transducers typically operating in the frequency range from 40 to 200 kHz. Despite the coupling material they employ to adapt at best impedance of transducers to the impedance of gas, the resulting signals remain resonant and prevent the use of efficient signal processing techniques such as correlation. Furthermore, the frequencies used proved to be inadequate. In some cases, the received signal is buried in the surrounding noise making it impossible to complete the measure.

To solve these problems, we chose some commercial available piezoelectric transducers that present excellent acoustic properties in air [6]. Their broad dynamic allows operating at relatively high frequencies without too large signal energy losses. These high frequencies allow to work above the noise level detected in gas pipes. The relatively wide bandwidth ensures rapid signal build-up and so improves the signal detection with the aid of a suitable and efficient signal processing.

The ULTRAN transducers (model NCT-105 Non-Contact Transducer) [6] chosen have a peak frequency at around 500kHz, an active diameter of 25mm, a bandwidth of around 30% at -6dB and provide a signal to noise ratio of about 44dB. They have a relatively high directivity (emission angle of 3°).

The coupling disk that acts as a matching layer and improves coupling with gaseous medium is the most important part of these transducers since this is the parameter governing the way the transducer will adapt to the ambient fluid. It is made out of porous or non-porous polymers.

The behaviour of these transducers in pressurised air is described in Figure 3. The experimental evolution of these amplitudes is compared to a theoretical expression including absorption [5] and impedance phenomena:

$$\frac{U}{U_0} = \frac{Z_2}{Z_{2\,0}} \exp\left(\alpha_0 - \alpha\right)d \qquad (4)$$

where U: amplitude of the received signal at pressure P,
U_0: amplitude of the received signal at atmospheric pressure,
Z_2: fluid acoustic impedance at pressure P,
$Z_{2\,0}$: fluid acoustic impedance at atmospheric pressure,
α: attenuation of the ultrasonic wave given in the reference 5 at pressure P,
α_0: attenuation of the ultrasonic wave given in the reference 5 at atmospheric pressure,
d: distance between the two transducers.

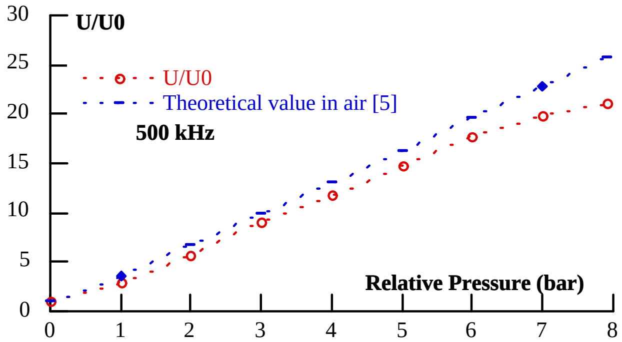

Figure 3: Transducers ULTRAN behaviour in pressurised air

These transducers have been tested in the gas network conditions and they demonstrate good behaviour in natural gas. However, their robustness might still be examined for an extended period of time with fast pressure variations, at high pressures and wetness conditions.

4 THE METHOD

According to the well-known formula determining the mean fluid velocity on the acoustic path from the transit-time method,

$$V = \frac{L^2 \,\mathrm{tg}\,\varphi}{2D}\left(\frac{\Delta t}{t_1 t_2}\right), \qquad (5)$$

where L: distance between the two transducers,

φ: angle between the pipe axis and the line of the flight path,
D: pipe diameter,
t_1 and t_2: times of flight upstream and downstream the flow,
Δt: differential time of flight,

several parameters have to be evaluated. The precision obtained for the diameter D and the angle φ ensues from the meter construction. The distance between the two transducers L is achieved with an auto-calibration process described in §4.5. Formula 5 imposes a good precision on the propagation times and especially on the differential time of flight Δt. For the low flow rates, Δt of few nanoseconds have to be measured. The volumetric flow rate Q is obtained by applying the famous correction factor K depending on Reynolds number Re according to:

$$Q = AK(\mathrm{Re})V \ , \qquad (6)$$

where A is the cross sectional area of the pipe.

4.1 The path configuration

The purpose of this paper is to present the method and the technology used with a straightforward configuration. Obviously, all these choices can be applied to every kinds of configuration: single or multi-path, chord, diametrical or reflective path. The configuration type we used is shown in Figure 4.

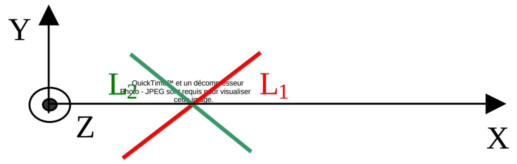

Figure 4: Two paths configuration flowmeter

It operates as a double single-path i.e. it provides two measures on two different single-path. A comparison between the two paths results may make possible an automated correction by eliminating error due to non-axial component of flow such as swirl or radial velocity.

4.2 Simultaneous emission - reception

The oppositely directed interrogations should generally utilise the same path as nearly simultaneously as possible. Similarly to this approach, the technique we use allows signals being emitted and also received simultaneously by the two transducers. This way of concurrently emitting and receiving ultrasonic waves eliminates the switch time inherent in the single-path flowmeter.

Both transducers are simultaneously excited by the signal generator. Then, after few microseconds, two analog switches connect the transducers to two perfectly identical receiving electronic circuits. They are based on a low noise operational amplifier. The associated filter is band pass from 350 kHz to 650 kHz and a gain of around 36 dB is used too. There is no out of phase problem du to difference in the filter nature.

This acquisition system presented in Figure 5 can improve the measures stability and warrant a good signal to noise ratio by filtering and amplifying the signal around the working frequency.

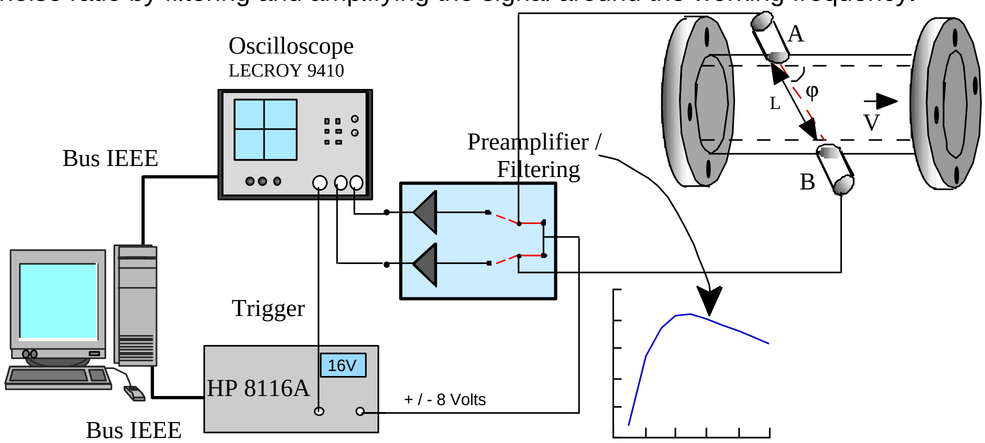

Figure 5: Acquisition system associated with simultaneous emission - reception

4.3 Times of flight measurement

Ultrasonic flowmeters using transit-time method require an accurate and reliable technique to measure the propagation times. Two kinds of time have to be evaluated:

- the differential time of flight Δt that can be of few nanoseconds for low flow rates,
- two absolute transit times that depend on pipe diameter (for our application, they are around 600 to 700 µs).

These two values having very different size, it seems difficult to obtain the same precision on these two parameters.

Contrary to classical techniques where the differential time of flight Δt is *calculated* from the two propagation times measured, here Δt is *measured* simultaneously with the two propagation times using the same method.

Combined with the suitable transducers technology, a technique of cross-correlation is used to evaluate the absolute propagation times and the differential time of flight.

The cross-correlation between two signals $s_1(t)$ and $s_2(t)$ is defined as follow:

$$c_{s_1s_2}(t) = \int_{-\infty}^{+\infty} s_1(\tau)s_2(t-\tau)d\tau = s_1(t) * s_2(t). \tag{7}$$

The FOURIER transform of the cross-correlation function is done by:

$$C_{s_1s_2}(\nu) = F(c_{s_1s_2}(t)) = \int_{-\infty}^{+\infty}\left[\int_{-\infty}^{+\infty} s_1(\tau)s_2(t-\tau)d\tau\right]\exp(-2i\pi\nu t)dt. \tag{8}$$

We can write:

$$C_{s_1s_2}(\nu) = F(s_1(t))F^*(s_2(t)) \text{ and } c_{s_1s_2}(t) = F^{-1}\left[F(s_1(t))F^*(s_2(t))\right]. \tag{9}$$

If we consider a signal $s_1(t)$ and a signal $s_2(t)$ shifted of τ from $s_1(t)$ i. e. as $s_2(t)=s_1(t+\tau)$, then the cross-correlation function between these two signals reaches its maximum for $t = -\tau$.

Thus the delay between two signals of the same kind is done by the t value for which the cross-correlation function is maximum. To increase the method accuracy, the cross-correlation derivative in the FOURIER space is calculated according to the following formula:

$$C'_{s_1s_2}(\nu) = 2i\pi\nu C_{s_1s_2}(\nu). \tag{10}$$

Besides, we have:

$$c'_{s_1s_2}(t) = F^{-1}\left[C'_{s_1s_2}(\nu)\right]. \tag{11}$$

When $c_{s_1s_2}(t)$ is maximal, $c'_{s_1s_2}(t)$ cancel out. The maximum position is known with a ±p precision, p being the range of samples step. A linear interpolation allows to evaluate τ with a better precision than p. The cross-correlation calculation is very little sensitive to noise.

For the differential time of flight evaluation, the two signals propagating in opposite directions (downstream and upstream the flow) are cross-correlated. The peak of the cross-correlation function identifies an accurate measurement of the differential time of flight Δt.

Moreover, the absolute propagation times t_1 and t_2 are evaluated with the same method. In this case, the cross-correlation function has to be calculated between the received pulse and a waveform restoring the emitted signal that, theoretically, is beginning at zero. Unfortunately, such a signal can not be acquired and the zero beginning of a waveform is a definitely subjective idea. Nevertheless, it is possible to define a real reference used in the flow measurement process thanks to a technique we have called the "second echo method". Thereby, as this reference is a real waveform, the cross-correlation function will give good result.

4.4 The "second echo-method"

The simultaneous emission - reception method allows acquisition of every signal a transducer can receive (Figure 6). The first signal S_1 arriving corresponds to the transmission of a wave from transducer 1 to transducer 2 corresponding to a distance L. The second signal S_2 is the signal that is emitted and received by a same transducer and corresponding to a distance 2L. This signal has been reflected on the opposite transducer. Hence, the difference between these two signals corresponds to a distance L and therefore to a propagation time between the two transducers equal to t_0. t_0 is the propagation time in the gas at rest.

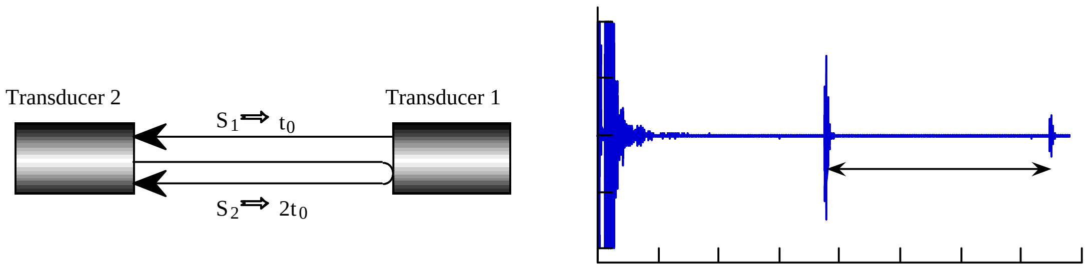

Figure 6: The" second echo method"

Carried out in air or in a known gas at rest, the method observes the following process (Figure 7).

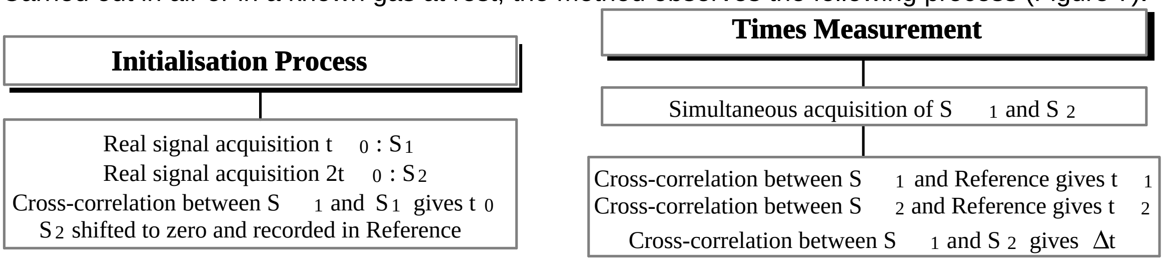

Figure 7: Initialisation process and time measurement

The signals S_1 and S_2 are acquired with large average to obtain a good signal to noise ratio. Hence, these two signals S_1 and S_2 are cross-correlated resulting in a t_0 value. Then, signal S_1 is shifted in time of a t_0 value to obtain a signal used as reference in the flow measurement process. Finally, the absolute propagation times t_1 and t_2 are obtained by cross-correlation between this reference and signals received in flow.

Remark: A time delay due to electronics ε is superimposed to every times measured with this process (as well at the emission as at the reception). The emission delays are negligible since the pulse excitation of both transducers is really simultaneous. Hence, we have:

$$S_1 \Rightarrow (t_0 + \varepsilon)$$
$$S_2 \text{ ¼ } (2t_0 + e) \qquad (12)$$

S_2 is not translated by 2ε since at the second transducer location, there is a simple reflection that does not involve the electronics associated with transducers. This delay is cancelled out when the first and second echoes are cross-correlated.

Hence, this method allows defining a real reference used for the absolute transit time measurement. Moreover, this method uses very similar signals ensuring very good precision in cross-correlation technique. Indeed, it proved to be very effective and accurate for the measurement of inter transducers distance and propagation times.

4.5 Auto-calibration technique

The distance L between the two transducers is the only parameter that is not measured and that is involved in flow measurement. The initialisation process of the flowmeter consists in achieving an accurate measure of this value before using it. For an industrial application, it seems very important to make this process automatic. The "second echo-method" allows to develop an auto-calibration technique applicable with the flowmeter installed on line. This initialisation process follows a main algorithm that is as follow:

- prepare the flowmeter by choosing the initialisation process,
- evaluate temperature and eventually pressure in accordance with the chosen initialisation process,
- theoretical calculation of the sound velocity in the gas conditions,
- measurement of the times of flight t_1 and t_2 by cross-correlation between respectively the received signals s_1 and s_2 with the reference waveform obtained with the method presented in §4.4,
- evaluate the mean value by $t_0 = \frac{t_1 + t_2}{2}$,
- calculate the distance L by $L = C_{0Gas} t_0$.

This method supplies a very small uncertainty on the distance measurement. It only requires a fluid at rest, stable and with a known composition. Moreover, it allows different adaptations to installation conditions of the flowmeter. For instance, an auto-calibration on line will be more convenient for large diameter pipes for which maintenance is heavier. In this case, two valves have to be used on the network to stop the flow at the meter location. Then a chromatographic analysis may supply the required information to determine the theoretical sound velocity. On the contrary, for pipes of smaller diameter that can be easily dismantled, the auto-calibration out of line could be more suitable. In this case, the initialisation process is carried out in air or in well-known gas in order to perform easily the velocity of sound calculation. The initialisation process completed at atmospheric conditions in air can be easily performed and does not require additional fittings on networks.

5 THE RESULTS

A flowmeter equipped with this system and using these methods has been developed. A test program has been carried out on the test facilities of Gaz de France in Alfortville. The geometry of the flowmeter under tests is described in §4.1. The housing diameter D was 156.3 mm. A chromatographic analysis was performed during the tests and a densitometer installed on the test line.

5.1 Tests on baseline configuration

The first tests performed under ideal flow conditions evaluate the meter stability. The meter was installed with long lengths of straight pipe upstream (34 D) and downstream (40 D).
The relative error was calculated between the ultrasonic measurement and the standard value provided by the bench.
For the flow range from 100 to 1000 m^3/h at 5 bar, Figure 8 shows the relative error on the volumetric flow rate.

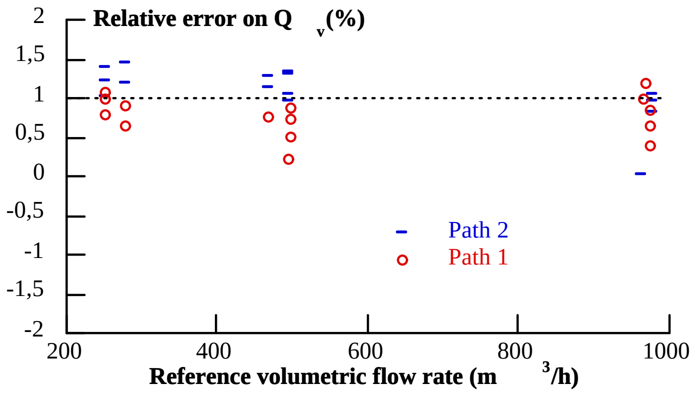

Figure 8: Relative error on volumetric flow for the baseline test configuration

The uncertainty on the Δt measurement ensuing from electronics delay has more influence at low flow rates. At the same time, a comparison of the theoretical speed of sound with the ultrasonic measurement was carried out. The gas composition, pressure and temperature are known and thereby the sound velocity can be computed from the gas equation of state [7]:

$$C_0 = \sqrt{\frac{\kappa P}{\rho}} \quad (13)$$

where κ: isentropic coefficient,
P: pressure,
ρ: density.

As an accurate sound velocity measurement requires a good precision on path length and correct measurement of propagation times [8], the results presented in Figure 9 allow to validate the initial calibration method and the propagation times measurement method.

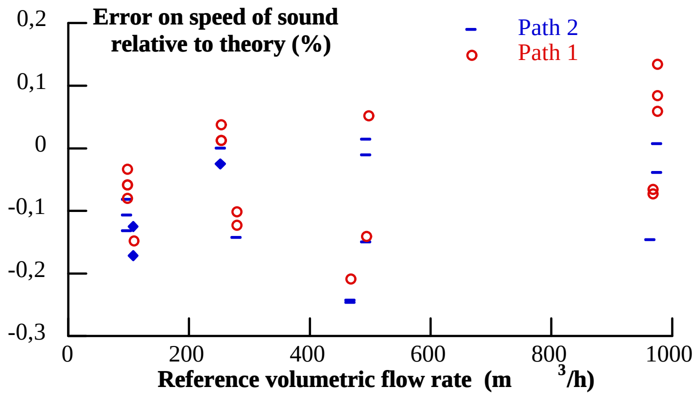

Figure 9: Relative error on speed of sound for the baseline configuration

From this comparison, we can conclude that the distance between the two transducers is undervalued by the initialisation process or that the transit times are over estimated during flow measurement process.

The stability of the measurements is worked out according to the standard deviation formula and is presented in Figure 10:

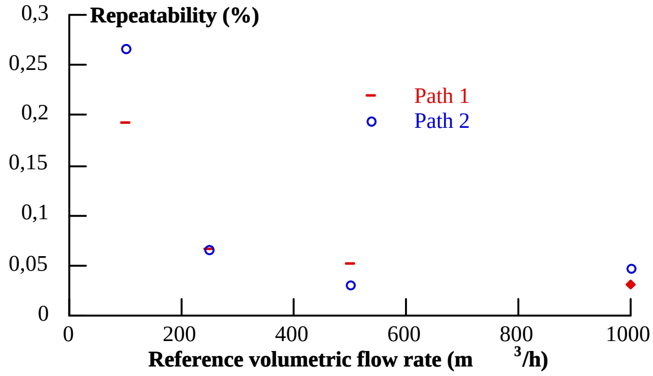

Figure 10: Measurements stability for the baseline configuration

Our ultrasonic meter supplies a stability from 0.05 to 0.2 % for the path 1.

5.2 Tests with control valve downstream of the flowmeter

The use of a control valve together with the flowmeter is a very severe test. Many ultrasonic gas flowmeters have already been tested in a similar way [9, 10, 11]. In reference 11, some of the flowmeter paths delivered an error signal which increased significantly the error of the meter.

This valve was installed on the test line with the following distances:

- 6 D (≈1m) between the control valve and the meter,
- 76 D of straight pipe upstream the flowmeter.

Several expansion rates have been created for the following flow rates:

Table 2: Expansion and flow rates tested.

Expansion rates	≈ 2	≈ 3.5	≈ 4.7	≈ 7.2
Flow rates (m^3/h)	500, 450, 250, 100	450, 250	100	100

The results are presented in Figure 11.

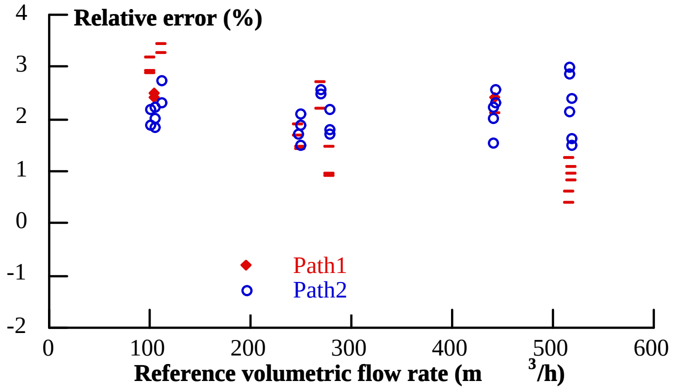

Figure 11: Relative error on volumetric flow rate for configuration test with valve

The relative error committed on the flow rate is higher than those obtained for the ideal configuration.

As the same manner as the baseline configuration, accuracy on the speed of sound measurement is evaluated and is shown in Figure 12.

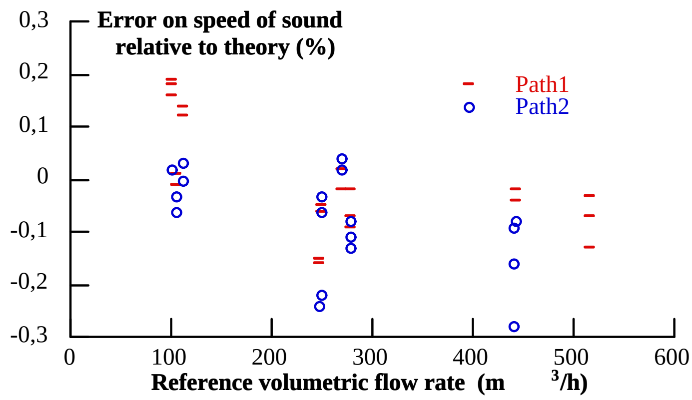

Figure 12: Relative error on speed of sound for configuration test with valve

No appreciable difference appears with the baseline configuration expected for low flow rates. Even in the vicinity of the valve, the ultrasonic signals remain very clean. The only perturbation the valve can generate is an increase in turbulence upstream its location. The poor repeatability may be explained by this phenomenon.

6 CONCLUSION

The technology employed allows to use signal processing absolutely immune to noise effects and providing accurate measurements of time propagation. An auto-calibration process is also developed providing a verification of the meter performances without removing it from the pipeline. This calibration consists in initialising the meter by evaluating the distance between the transducers using the speed of sound measurements. The complete process was validated with the tests carried out in natural gas. Finally, the effects of profile disturbances are not treated but the technology could be used for more complex meter geometry as multi-paths meters i.e. by multiplying chords around the cross section.

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