Main Index

North Sea
FLOW
Measurement Workshop

Paper ~~20:~~ 3 · 7

# DIAGNOSTIC OF INDUSTRIAL GAS FLOWS BY ULTRTRASONIC TOMOGRAPHY

**Authors:**
**Jacques Demolis, Pierre Gajan and Alain Strzelecki, O.N.E.R.A., France**

**Organiser:**
Norwegian Society of Chartered Engineers
Norwegian Society for Oil and Gas Measurement
**Co-organiser:**
National Engineering Laboratory, UK

# Diagnostic of Industrial Gas Flows by Ultrasonic Tomography

**Jacques DEMOLIS, Pierre GAJAN, Alain STRZELECKI**

O.N.E.R.A., France

## ABSTRACT

To minimise the influence of transversal flows or asymmetry of the axial profile, more and more manufacturers have resorted to ultrasonic multipath flowmeters.

Since a few years, some authors have shown that it is possible to get more information on the flow conditions using multipath systems. With numerous differences in transit times given by multiple transducers pairs, one can reconstruct the three components of the velocity field. This technique, called « Ultrasonic Tomography », has only been developed in laboratory environment. This present work has been carried out in order to apply tomography to the diagnostic of *in situ* industrial gas flows.

First of all, we have reached this goal for transversal components. For this, we had to design an operational device with 8 transducers in a reduced distance that means, to minimise ultrasonic transmission across the wall and to resolve mechanical restrictions due to the number of transducers. Then, as all the flight distances between transducers pairs are smaller than in classical flowmeters, we had to increase the accuracy in the determination of the transit times. Finally, it was necessary to perfect existing reconstruction algorithms to make them more robust and faster for the run-time.

## INTRODUCTION

A flowmeter, independently of its technology, must be used in reference conditions of calibration to be accurate, that is to say, in fully developed flow. In some industrial networks, it is very difficult to find these conditions, particularly downstream of a delivery station. In this case, some errors in the flow rate measurement will appear.

The studies conducted at ONERA have shown that singularities, for example pressure reducers, generate strong perturbations which propagate along the pipe until the flowmeter. And Strzelecki *et al.* [1] have shown that this kind of flow implicates supplementary errors. As it is very difficult to predict the kind of flow at the place of the meter regarding the installation geometry, it seems interesting to develop a diagnostic tool which would be able to give the maximum of information concerning it. As such a device has to be installed on an industrial set-up, it has to work in real conditions. Therefore, we tried to find a method which is non-invasive, which needs no artificial seeding, as few calibrations as possible, which is easily transportable on the study place and, consequently, robust while being reliable.

During the last decade, due to their efficiency, ultrasonic flowmeters have been widely used for gas applications. Furthermore, recent papers have shown that, combining information delivered by multiple transducers, it is possible to reconstruct the three components velocity profile through a test section. For these reasons, we have decided to apply this technique, called ultrasonic tomography, to diagnostic industrial flows. To verify the reliability of the developed device, swirling flows had been measured and compared to a hot wire characterisation. A last test shows that it is possible to reconstruct the Dean vortices downstream from a 90°-bend.

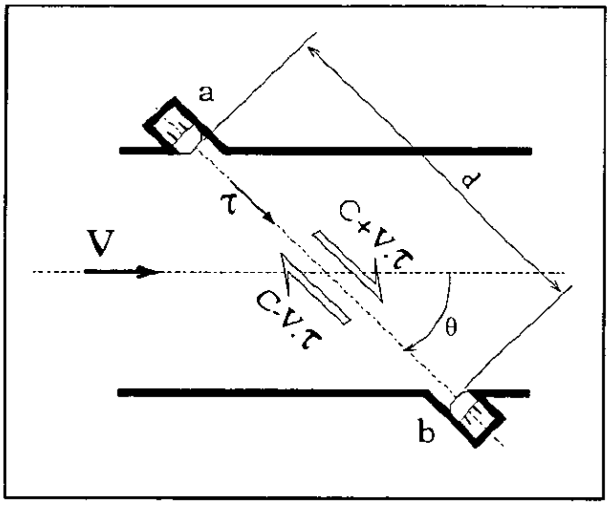

Figure 1. Ultrasonic flowmeter principle.

## ULTRASONIC FLOWMETER PRINCIPLE

Ultrasonic flowmeters measure the mean velocity of a flow from the modification of the sound velocity in it. If the wave propagates in the flow direction, the sound velocity increases ;otherwise, it decreases. Of course, this phenomena appears if the direction of propagation of the wave is not perpendicular to the flow direction. For this reason, in ultrasonic flowmeters, the couple of ultrasonic transducers is inclined at an angle $\theta$ to the pipe axes as it is shown in figure 1.

The time of flight of the wave from the upstream transducer *a* to the downstream one *b*, is given by the following equation :

$$t_{ab} = \int_a^b \frac{ds}{C + V \cdot \tau} \qquad (1)$$

and in the other direction :

$$t_{ba} = \int_a^b \frac{ds}{C - V \cdot \tau} \tag{2}$$

In many cases, the flow velocity can be considered much more inferior than the sound speed, then these two expressions become :

$$t_{ab} = \frac{1}{C}\int_a^b \left(1 - \frac{V \cdot \tau}{C}\right) ds \quad \text{and} \quad t_{ba} = \frac{1}{C}\int_a^b \left(1 + \frac{V \cdot \tau}{C}\right) ds \qquad \text{(3) and (4)}$$

Now, subtracting (4) from (3) and noting *d* the distance between the two transducers, it is possible to get the mean velocity $V_m$ of the flow :

$$\Delta t = t_{ab} - t_{ba} = \frac{-2}{C^2}\int_a^b V \cdot \tau \, ds = \frac{-2d\, V_m \cos\theta}{C^2} \tag{5}$$

## ULTRASONIC TOMOGRAPHY PRINCIPLE

The principle of the tomography is to use many transit time *Δt* obtained on numerous ultrasonic lines to determine the velocity profile through a pipe section. Ultrasonic lines are materialised by a couple of source/receiver transducers. To get the three velocity components, Johnson *et al.* [2] proposed the transducers distribution of the figure 2.

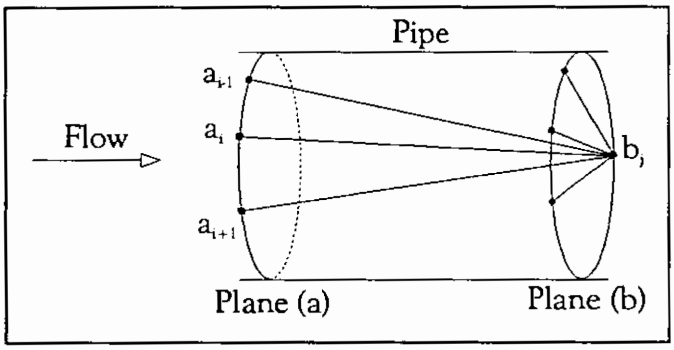

Figure 2. Transducers distribution on a pipe.

Assuming that flow conditions do not change between planes (*a*) and (*b*), the set of pairs $(a_i,a_j)$ allows the reconstruction of transversal components of the flow, while the pairs $(a_i,b_j)$ are used for the axial component.

The time of flight difference between the transducer $a_i$ and the transducer $b_j$, is expressed by an expression similar to equation (5). One has only to put $a_i$ in place of *a*, $b_j$ in place of *b*. The unit vector tangent $\tau$ to ultrasonic ray has to be expressed in the cartesian coordinate system (*x,y,z*), with z-axis in direction of pipe axis, by the following expression :

$$\tau = (\mathbf{x}\cos\theta + \mathbf{y}\sin\theta)\sin\gamma + \mathbf{z}\cos\gamma \tag{6}$$

Where $\gamma$ is the angle between $z$ and $\tau$ and, if $\boldsymbol{r}$ is the projection of $\tau$ on the plane ($xOy$), $\theta$ is the angle between $\boldsymbol{x}$ and $\boldsymbol{r}$.
So, we obtain the new expression :

$$\Delta t = T_0(a_i, b_j) = \frac{-2}{C^2}\int_{a_i}^{b_j} \left[\left(V_x \cos\theta + V_y \sin\theta\right)\sin\gamma + V_z \cos\gamma\right] ds \tag{7}$$

In the same way, an expression can be obtained for a time of flight difference measured uniquely in the plane (*a*):

$$T_1(a_i, a_j) = \frac{-2}{C^2} \int_{a_i}^{a_j} \left( V_x \cos\theta + V_y \sin\theta \right) dr \qquad (8)$$

If $a_j$ is the projection of $b_j$ along the cylindrical axis onto the plane (*a*), Johnson *et al.* [2] now define the fictitious time:

$$T_2(a_i, b_j) = T_0(a_i, b_j) - T_1(a_i, a_j) = \frac{-2 \operatorname{cotan} \gamma}{C^2} \int_{a_i}^{b_j} V_z \, ds \qquad (9)$$

which allows to reconstruct the component $V_z$ independently of the transversal components of the flow.

## TIME OF FLIGHT EVALUATION

For tomography to be effective, it is necessary to increase the number of ultrasonic paths (see figure 2) in order to cover the maximum of the test section. Moreover, because of the difference of acoustic impedance between the gas and the pipe metal which highly attenuate the acoustic wave, transducers are installed directly in contact with the fluid. Figure 3 represents the plane (*a*) of figure 2 with 12 transducers around the section. Lines materialise theoretic ultrasonic rays defined by one receiver and seven sources. Each of these couples defines one difference of transit time $T_1(a_i,a_j)$ given by relation (8).

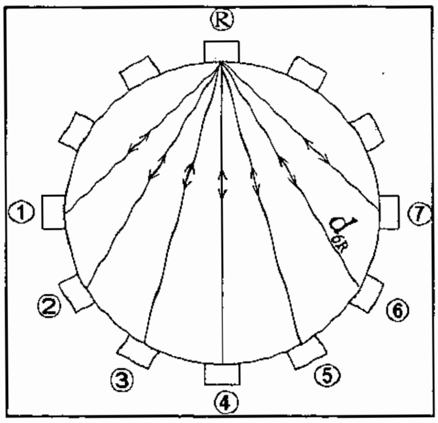

Figure 3. Transducers distribution for a perpendicular section.

From this figure, two remarks can be done. The first one concerns the angle directivity of sources, especially ① and ⑦. In this configuration, the directivity is at least 90° while in ultrasonic flowmeters, this angle is much smaller, that is to say a better signal-to-noise ratio and so, better quality of the reception signal. The second is about the length of ultrasonic rays. In a flowmeter, it is generally $\sqrt{2}D$ and it could be easily increased multiplying the number of reflections on the inner wall. Here, the minimal length is $D/\sqrt{2}$ and the maximal is D. Consequently, to obtain the same relative accuracy as for classical flowmeter in the determination of the time of flight measurement, the absolute accuracy have to be increased in the tomographic system.

To solve these problems, we have first chosen transducers which are able to emit a useful signal with an attenuation of less than 6 dB at an angle of 120°. They are of frequency 40 kHz and diameter 16 mm.

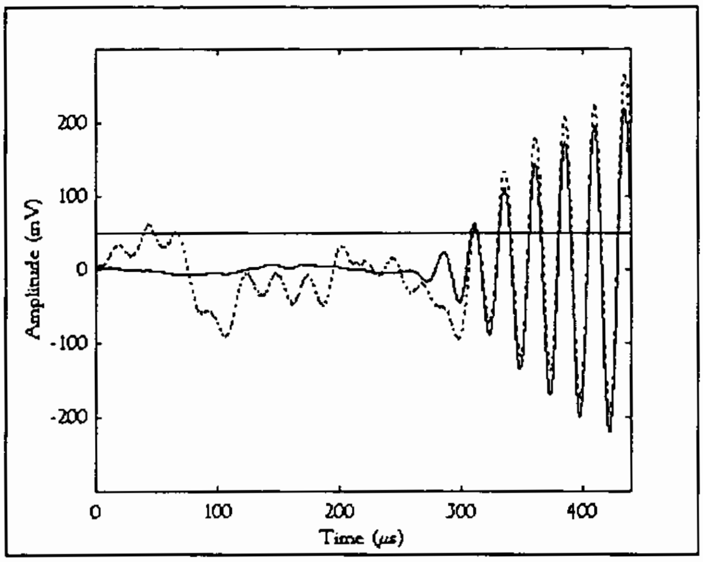

Figure 4. Comparison between raw signal and averaged signal.

Then, like Frøysa *et al.* [3], to reduce the noise which perturb the reception signal, an average is operated on a certain number of signals. For that, they are recorded with an analogic-numeric converter and, then, numerically averaged by a computer. Figure 4 shows the result of an average of 50 traces for the couple ®-① of figure 3. The raw signal without treatment is represented with solid line (—), and the averaged signal with the dotted line (- - -).

In fact, in the same time, this average can solve the problem of measurement accuracy of one transit time on a short distance. The method used for such averaged signals is said to be a « zero crossing » method. It is the measure of a first zero crossing point after the detection of a minimal amplitude threshold. On figure 4, this threshold is materialised by the horizontal line at 50 mV. The exact time of propagation from source to receiver is obtained by the subtraction of the number of periods preceding this zero crossing (in the case of figure 4, two periods are omitted, i.e. 50 μs).

From this operating procedure, the developed method gets a fairly good accuracy because, for 20 measures of transit time, the mean of the rms is about 2.5 ns whatever the separation length of transducers.

## MEASUREMENT TOOL

At the first stage of this study, only one section of the pipe is considered to reconstruct the secondary flow. Figure 5 shows this measurement tool. It is made of stainless steel, its internal diameter is D=100 mm and its length is 3D. Althoug there are only 8 transducers, the device can rotate around the conduit axis so, rather than limiting the distribution to one transducer at every 30°, experiences have been conducted considering one transducer every 10° (which is equivalent to a pipe with 36 transducers).

Electronic instrumentation includes : a signal generator, a scanner to select the source transducer, a preamplifier-filter and an ADC installed in a PC which manage the signal acquisition and the reconstruction of the velocity profile.

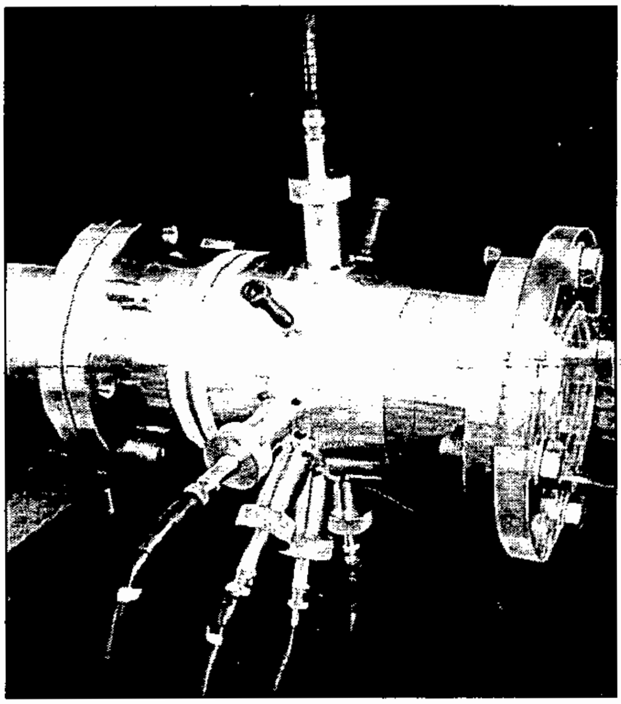

Figure 5. Measurement tool for transversal components.

## ALGORITHM OF RECONSTRUCTION

When we get all necessary transit time differences, these data have to be processed to reconstruct the initial speed profile.

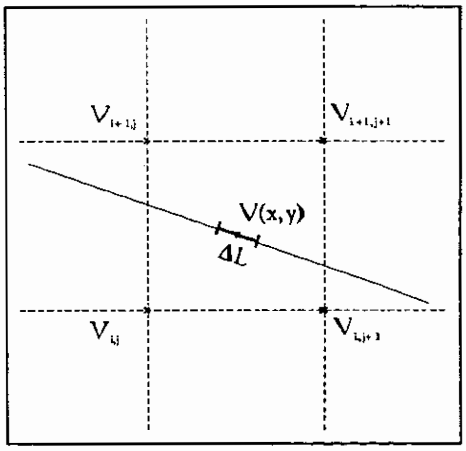

Figure 6. Bilinear interpolation on a cartesian mesh.

The reconstruction algorithm used here is a combination of the approach of Johnson *et al.* [2] and Herman's [4]. In fact, the integral in equation (8) is written in terms of an approximate sum by subdividing the segment $[a_i a_j]$ into elements of approximately constant length $\Delta L$. The velocity is considered constant on each element and equal to its value at the middle point $V(x,y)$. But, the reconstruction can only be done for a finite number of points which are the nodes of a square grid of discretisation of the test section. In this way, the velocity $V$ of any point $(x,y)$ placed in a mesh defined by the four speeds $[V_1, V_2, V_3, V_4]$ is expressed by the bilinear interpolation described in figure 6 and given by the following relation :

$$\begin{cases} V(x,y) = \varepsilon_{i,j} V_{i,j} + \varepsilon_{i,j+1} V_{i,j+1} + \varepsilon_{i+1,j} V_{i+1,j} + \varepsilon_{i+1,j+1} V_{i+1,j+1} \\ \varepsilon_{i,j} + \varepsilon_{i,j+1} + \varepsilon_{i+1,j} + \varepsilon_{i+1,j+1} = 1 \end{cases} \tag{10}$$

So, considering all the ultrasonic beams, equation (8) can become a set of linear equations (Démolis [5]) as :

$$A_{xy} V_{xy} = T_{xy} \tag{11}$$

where $A_{xy}$ is a matrix built from the mathematical decomposition of integral lines (8) of every transducers couples, $T_{xy}$ a column vector containing all transit time differences measured, and $V_{xy}$ the column vector corresponding to the solution, that is to say, the velocity on each point of the mesh.

If there are $N$ nodes into the pipe, $V_{xy}$ gets $2N$ coefficients with the $N$ first ones for the $V_x$ component and the next $N$ ones for $V_y$ component.

Because of the flow turbulence, the rms of the time measurement, which is 2.5 ns without flow, may reach 90 ns behind a bend. In these conditions to solve the system (10), one has to use an iterative algorithm to minimise the inaccuracy on time of flight measurement. That is why a quasi-solution algorithm, called « conjugate gradient method », is used here.

To test the algorithm, computer simulations have been realised on a theoretical vortex. The radial profile is strictly nil and the tangential profile is 1 $m.s^{-1}$ amplitude sinusoid. Figure 7 shows the quality of the reconstruction made with 126 equations on a 10×10 mesh for sinusoidal profile. With a solid line (—), theoretical velocities and, with plus (+ signs), reconstructed ones.

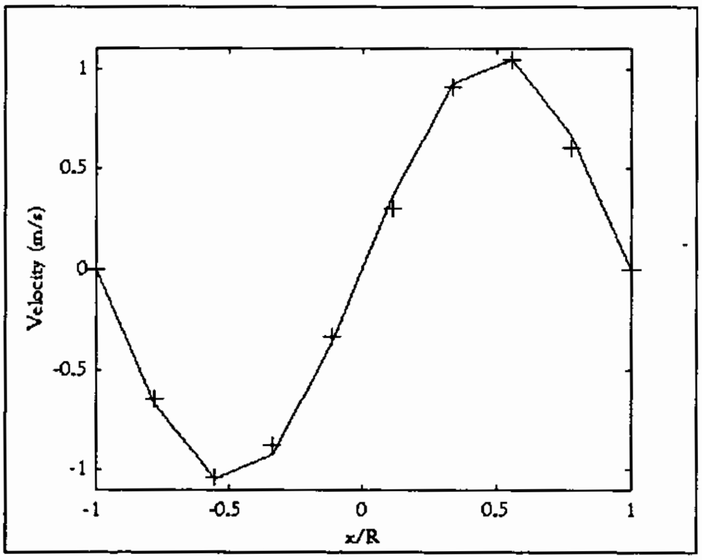

Figure 7. Comparison between a theoretical profile (—) and a reconstructed profile (+).

## EXPERIMENTAL SET-UP

The ultrasonic tomography device of figure 5 has been tested on the testing bench described in figure 8.First of all, we used swirling flows which are generated by a swirl generator and for which intensity is defined by the adimensional swirl number $S$ and the swirl angle $\alpha_s$ :

$$S = \frac{\int_0^R V_{axial}\left(\rho V_{tangential} r\right) r\,dr}{R\int_0^R V_{axial}\left(\rho V_{axial}\right) r\,dr} \tag{12}$$

$$\alpha_s = \arctan\left(\tfrac{3}{2} S\right) \tag{13}$$

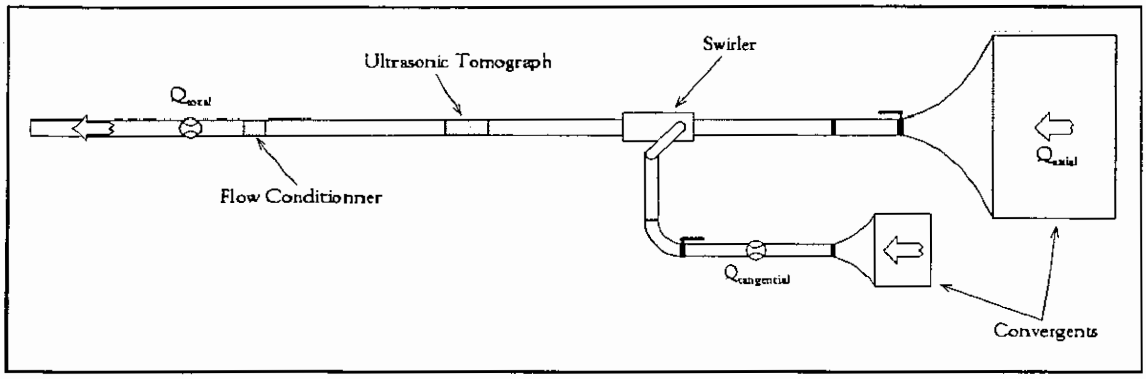

Figure 8. Testing bench.

Figure 9 compares the tangential profile obtained from the tomographic reconstruction, in dotted line (- - -), with the one measured by a hot wire probe, in solid line (—). The volumic flowrate is $Q_{total}$=200 m$^3$h$^{-1}$ and the swirl number $S$ = 0.46 ($\alpha_s$=34.5°). The turbulence is about 8% near the wall and can reach 20% on the pipe axis.

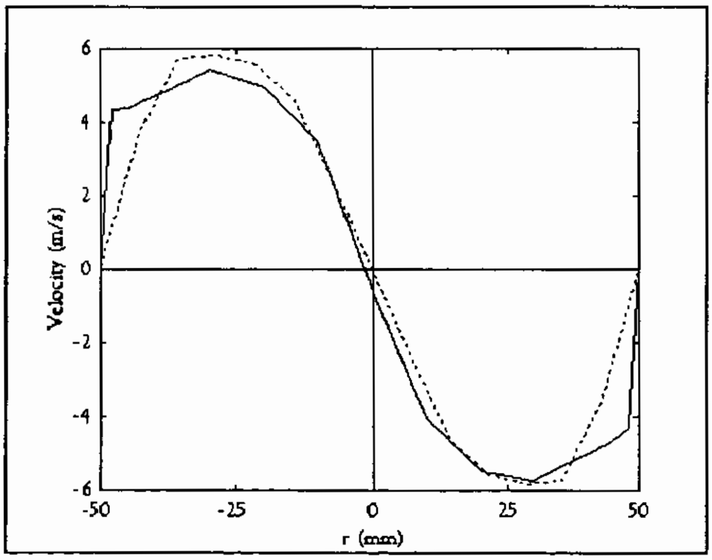

Figure 9. Comparison between an ultrasonic reconstruction (- - -) and a hot wire profile (—) for $S$ = 0.46.

The reconstructed profile can be decomposed in three parts. The first one, which is near the wall, because of the lack of meshes, is not so well reconstructed. The result will certainly be better if the discretisation of the section is thinner. The second part is around the maximum of the velocity profile. For r<0, the difference between the reconstructed profile and the hot wire one is about 9%. But it is not the case for r>0 where they are quite similar. Indeed, the dissymetry which appears on the hot wire profile is due to a blockage effect of the probe. As the ultrasonic tomography is a non-invasive technique, the dissymetry is not visible on the reconstructed profile. The last part of these profiles is at the pipe centre where the tomographic profile confirms the flow symmetry.

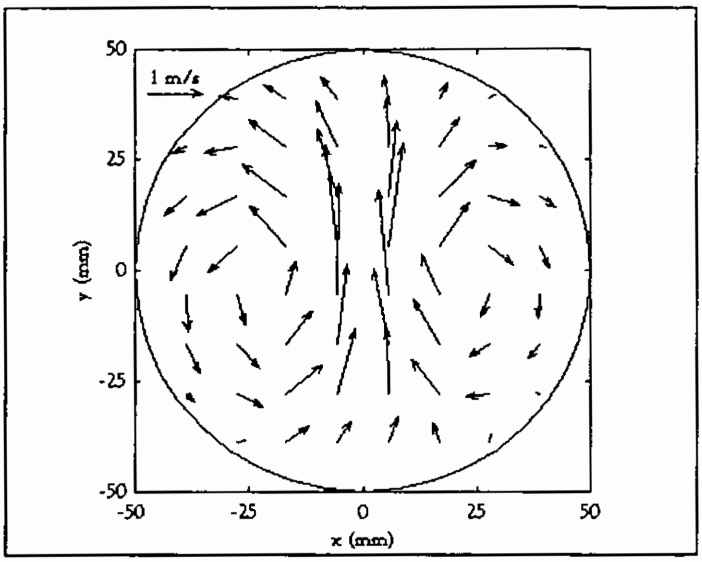

Figure 10. Reconstruction of Dean vortices behind a 90° bend.

The great difference between these two techniques is that hot wire anemometry can only give the velocity profile along a diameter whereas the ultrasonic tomography device gives it over the all section.

To illustrate this advantage and to show possibilities of such a device, an other example was conducted. The measurement section is put 2D downstream from a 90°-bend for which the ratio {curvature radius of the bend}/{pipe radius} is equal to 2. On figure 10, ultrasonic tomography has allowed to reconstruct Dean vortices which are characteristic of such a flow. They are symmetric to the symmetry plane of the bend. The curvature centre of the bend is at the bottom of the figure.

## CONCLUSION

A device using the ultrasonic tomography has been realised to reconstruct the secondary flow profile in a pipe. This diagnostic tool is compact and does not need sophisticated instrumentation. No speed calibration is needed, neither is artificial seeding (which is not the case for LDA). It does not disturb the flow because the measurement is non-invasive (as opposed to hot wire probe).

If the principle is near the one of ultrasonic flowmeters, we have had to improve the time of flight measurement for low level signal and difficult transducers positions. And we have had to develop a robust algorithm to reconstruct the flow profile.

Measurements made with success in flows encountered in industrial set-up (swirl, flow downstream from bends), the simplicity of the tool (compactness, transportability, adaptability to a pipe of fixed diameter), its mechanic robustness, and little electronic material, are many advantages for this tool to be developed to an industrial device.

# REFERENCES

[1]. Strzelecki A., Gajan P., Malard L., Donat D., Bosch M. : « Investigation of the influence of a pressure reducer placed upstream of a turbine meter », $3^{rd}$ *International Symposium of Fluid Flow Measurement*, San Antonio, Texas, U.S.A., 20-22 Mars 1995.

[2]. Johnson S. A., Greenleaf J. F., Tanaka M., Flandro G. : « Reconstructing three-dimensional temperature and fluid velocity vector fields from acoustic transmission measurments », *ISA Transactions*, Vol. 16, No. 3, pp 3-15, 1977.

[3]. Frøysa K. E., Lunde P., Sakariassen R., Grendstad J., Norheim R. : « Operation of multipath ultrasonic gas flow meters in noisy environments », *North Sea Flow Measurment Workshop*, Scotland, 28-31 Octobre 1996.

[4]. Herman T. G. : « Image reconstruction from projections, The fundamentals of computerized tomography », *Academic Press, Inc. (London)*, 1980.

[5]. Démolis J. : « Reconstruction du profil de vitesse d'un écoulement d'air en conduite par tomographie ultrasonore », *Thèse de l'Ecole Nationale Supérieure de l'Aéronautique et de l'Espace*, 1997.