**XVIII IMEKO WORLD CONGRESS**
**Metrology for a Sustainable Development**
**September, 17 – 22, 2006, Rio de Janeiro, Brazil.**

# UNCERTAINTIES PROPAGATION STUDY OF THE TRANSIT TIME METHODS IN ULTRASONIC ANEMOMETERS.

*Will Almeida*[1], *Bruno Costa*[1], *Raimundo Freire*[1], *Francisco Santos*[1], *Sebastian Catunda*[2]
[1]UFCG-CCT-DEE, LIMC, Campina Grande, PB, Brazil, willalmeida@dee.ufcg.edu.br, bitcosta@yahoo.com.br, catunda@dee.ufma.br, rcsfreire@dee.ufcg.edu.br, ffsantos@dee.ufcg.edu.br.
[2] UFMA-CCT-DEE, LIEA, São Luis – MA, Brazil, catunda@dee.ufma.br.

**Abstract:** The fluids speed measurement, particularly the air speed measurement is very important for industrial and laboratory applications. The ultrasonic method is among the most common methods used for determining the air speed. The basic principle to measure a fluid speed, using an ultrasonic transducer, is based on the modification of the apparent propagation speed of an ultrasonic signal caused by the fluid movement. Particularly, the method based on the Transit Time, which can use the techniques of Phase Difference and Time Difference, is one of the most used. In this work we carry on a comparative study of the uncertainty propagation employing these techniques in ultrasonic anemometers for determining the air speed.

**Keywords:** Air speed measurement, Uncertainty propagation, Ultrasonic anemometer.

## 1. INTRODUCTION

The fluids speed measurement is very important in the industrial sector and the laboratory applications. The instruments used with this purpose are called anemographs or anemometers, as they effect, or not, the register of the speed, or simultaneously of the speed and direction. The methods most common for determination of the air speed are: 1) methods of pressure, that it is based on the Pitot tube, where the air speed can be estimated by the pressure difference of this environment with regard to an environment of known air speed, normally equal the zero; 2) rotor method, that is based on the air speed calculation for the speed angular measurement of the rotor, that can be stimulated by one fan using or helices; 3) method of hot wire, that is based on the determination of the air speed by the removed amount of sensor heat in a forced convection; 4) ultrasonic, that is based on the determination of the air speed through the propagation of the ultrasonic waves, being able to use the methods of Transit Time and Doppler effect.

Knowing that for determination of the fluid speed using the Doppler method is necessary that has reflection and in the case of air this does not occur, then, it was opted to the Transit Time method application. The techniques more spread out from the Transit Time method are Phase Difference (DF) and Time Difference (DT). As we known there are practical limitations that introduce uncertainties in the measurement system and in the determination of the fluid speed, it is done a comparative study of the uncertainties propagation of each one from these methods in this paper (DT and DF), in the measurement of the air speed using ultrasonic transducers.

## 2. ULTRASONIC PROPAGATION TRANSIT TIME METHODS.

The principle to determine the fluid speed through the Transit Time methods, using ultrasonic transducers, is based on the measurement modification of the apparent propagation speed C' of a ultrasonic signal transmission in the fluid caused by the movement of the fluid itself. Among the most known, one has the techniques of the Phase Difference (DP) and the Difference of Transit Time (DT).

The ultrasonic vibrations are mechanical waves that transfer energy from one point to another and that propagate in a pressure wave causing the molecules agitation in the media they are propagating, making them to oscillate, for solid, liquid or gaseous environments [1]. These vibrations require an appropriate environment to spread [2]. The mechanical waves have a frequency superior to 20 kHz being, therefore, above of the audible humans threshold [3]. As the waves propagate through the media, they suffer alterations on their original characteristics, caused by reflection, refraction, attenuation and absorption phenomena. The acoustic waves propagation through a media depends on the environment physical characteristics. where they propagate (coefficient of attenuation, acoustic impedance, coefficient of absorption, speed of the wave, etc.).

### *2.1. Ultrasonic Anemometers*

The ultrasonic wave speed propagation through a fluid is the vectorial sum of its natural propagation speed (sound speed, C) with the fluid speed ($\vartheta$) [4].

$$\vec{C}' = \vec{C} \pm \vec{\vartheta} \qquad (1)$$

Consider that two transducers $T_A$ and $T_B$ can alternately transmit and receive, and that they are disposed at an angle $\theta$ with respect to the direction of the fluid flow. The direct transmission speed is defined as $C'_{AB}$, while the inverted transmission speed is defined as $C'_{BA}$. Thus, the signal transmission has resultant speeds express by:

$$\vec{C}'_{AB} = \vec{C} + \vec{\vartheta} \quad (2)$$

and

$$\vec{C}'_{BA} = \vec{C} - \vec{\vartheta} \quad (3)$$

The transit times can be determined through the inverse relationship between the propagation speeds and the length of ultrasound path *L* (distance between the transducers), considering that the resultant speeds are C′ = C ± ϑcosθ as the result of the vectorial sum, by:

$$t_{AB} = L/(C + \vartheta\cos\theta) \quad (4)$$

and

$$t_{BA} = L/(C - \vartheta\cos\theta) \quad (5)$$

### *2.2. Time Difference Method*

The Time Difference method (DT) accomplishes the direct measurement of the propagation times between the transducers, i.e., the time difference from the instant that sign is transmitted to the instant that it is detected, normally through threshold detection. Thus, based on the existent relationship between $t_{AB}$ and $t_{BA}$ one can determine the fluid speed without the knowledge of the sound speed, and consequently, the knowledge of the environmental quantities that affect it (temperature, pressure, viscosity and density). From the equations (4) and (5), the fluid speed can be determined as [5]:

$$\vartheta = \frac{L}{2\cos\theta}\left(\frac{1}{t_{AB}} - \frac{1}{t_{BA}}\right) \quad (6)$$

For the practical measurement of the transit time one must consider that the measured value includes, besides the propagation time in the environment, the delay time of the electronic circuit. The electronic delay time is due to mainly the dynamic response of the ultrasonic transducer and it must be taken into account, needing a calibration of the measurement circuit. In this case, the measured transit time can be represented by $t_M = t + t^E$, where t is the time interval from the signal transmission until its reception and tE is the interval value of the signal reception until its detection.

In that way, for the DT method, the fluid speed can be determined by:

$$\vartheta = \frac{L}{2\cos\theta}\left(\frac{1}{t^M_{AB} - t^E_{AB}} - \frac{1}{t^M_{BA} - t^E_{BA}}\right) \quad (7)$$

### *2.3. Phase Difference Method*

In this method, the ultrasonic signal is transmitted continuously between a pair of transducers, or transmitted until the signal is detected in the receiving transducer. Therefore, the electronic delay due to dynamics of the transducer can be neglected. The fluid speed is determined measuring the phase difference between two signals transmitted in opposing directions. The angular phase of the signals received in both directions, for the transducer operating frequency f, is defined as:

$$\Phi_{AB} = 2\pi\, f\, t_{AB} \quad (8)$$

and

$$\Phi_{BA} = 2\pi\, f\, t_{BA} \quad (9)$$

With $\Delta_\Phi = \Phi_{BA} - \Phi_{AB}$ as the phase difference and from the difference between the equations (8) and (9), ϑ can be determined by:

$$\vartheta = \frac{\pi f L}{\cos\theta}\left(\frac{1}{\Phi_{AB}} - \frac{1}{\Phi_{BA}}\right) \quad (10)$$

For the two methods (DT and DP), in order to determine which is best to be used in the fluid speed determination, a study of the uncertainties propagation is carried out in the next section.

## 3. PROPAGATION OF UNCERTAINTIES

The most used method for determining the uncertainty propagation is from Kleine and McClintock [6]. For a variable $y = f(x_1, x_2, x_3,..., x_n)$, according to this method, the resultant uncertainty on y is a function of the independent variables and the uncertainties associates to each variable ($u_1$, $u_2$,..., $u_n$). In this way, considering the uncertainties not correlated, the total uncertainty uy, is given by:

$$u_y^2 = \left(\frac{\partial f}{\partial x_1}u_1\right)^2 + \left(\frac{\partial f}{\partial x_2}u_2\right)^2 + ... + \left(\frac{\partial f}{\partial x_n}u_n\right)^2 \quad (11)$$

For the total uncertainty estimate, it is necessary calculate the contribution of each uncertainty source separately. As each source of uncertainty is raised to the square, $\left[(\partial f_i/\partial x_i)u_i\right]^2$ , we may consider only those that have a significant contribution on the total uncertainty.

### *3.1. Uncertainty in the Time Difference*

Assuming that the average transit time is defined as μt and from the independent uncertainties propagation [7], the value of uϑ can be approached by:

$$u_\vartheta^2 = \left(\frac{K_1 L}{\mu_{t_{AB}}^2}\right)^2 u_{t_{AB}}^2 + \left(\frac{K_1 L}{\mu_{t_{BA}}^2}\right)^2 u_{t_{BA}}^2 \quad (12)$$

where $K_1 = 1/2\cos\theta$ and $\mu_{tAB}$ and $\mu_{tBA}$ are the expected value of $t_{AB}$ and $t_{BA}$, respectively.

### *3.2. Uncertainty in the Phase Difference*

Again assuming that the phase value is $\mu_\Phi$, from the independent uncertainties propagation, it can be approached $u_\vartheta$ by:

$$u_\vartheta^2 = \left(\frac{K_2 L}{\mu_{\Phi_{AB}}^2}\right)^2 u_{\Phi_{AB}}^2 + \left(\frac{K_2 L}{\mu_{\Phi_{BA}}^2}\right)^2 u_{\Phi_{BA}}^2 , \quad (13)$$

where $K_2 = \pi f/\cos\theta$ and $\mu_{\Phi AB}$ and $\mu_{\Phi BA}$ are the expected values of $\Phi_{AB}$ and $\Phi_{BA}$.

## 4. SIMULATIONS

For a comparative analysis of the methods DT and DP regarding to the measurement uncertainty, the measurement system was simulated to realize the transmissions, the receptions and the conditioning of the received signal. The transducers are considered to have the same dynamic characteristics and that the sound wave amplitude attenuates as it spreads through the environment [7].

### *4.1. Simulation of DT.*

For the Time Difference method analysis, a circuit that accomplishes the transmission and reception of a train of sine waves was simulated. The signal conditioning circuit carries out amplification, envelope detection and the received signal level comparison. figure 1 shows the simulation of the received signal conditioning where one can notice the representation of the electronic delay $t^E$.

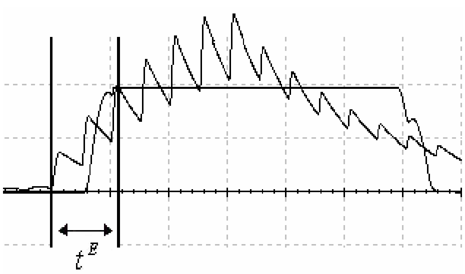


**Fig. 1. Representation of the received signal conditioning and determination of $t^E$.**

For the analysis of uncertainty propagation on the air speed estimation, we have considered uncertainties, $u_{t^E}$ , of 1, 3, 5 and 10 µs on the determination of $t^E$ (which correspond nearly to 1, 3, 5 and 10% of the value of $t^E$, which is normally around 100 µs).

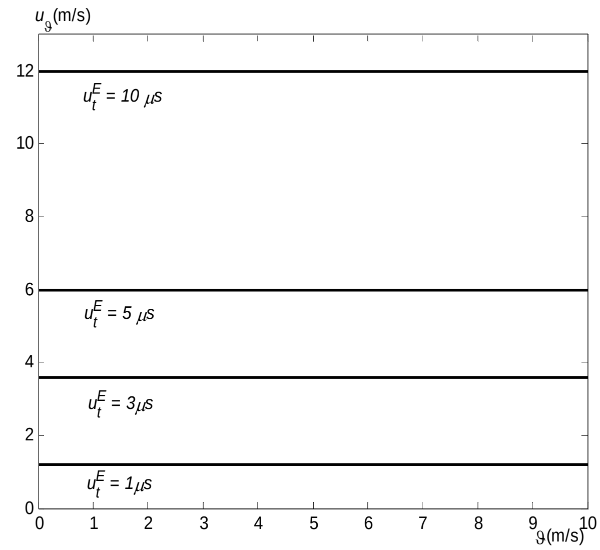


**Fig.2. Air speed uncertainty versus air speed for several values of the uncertainty on $t^E$.**

The final uncertainty on the determination ϑ as function of the fluid speed ϑ is shown on figure 2, where it can be seen that it remained almost constant. Though, the DT method has not so good applicability for low speeds, as the percent error increases very much.

### *4.2. Simulation of DP*

For the Phase Difference method analysis a circuit that accomplishes the transmission and reception in continuous sine wave was simulated. The conditioning circuit performs the amplification of the received signal following by zero-crossing detection and phase comparison. figure 3 shows the simulated waveforms that are used for phase difference calculation. The phase difference is calculated by $\Delta_\Phi = 2\pi f \Delta t$.

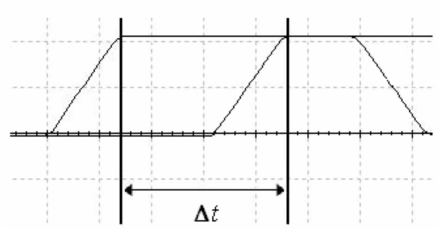


**Fig. 3. Representation of the received signal conditioned for determination of the phase difference.**

For the Phase Difference method simulations we considered the uncertainty values to be 1, 3, 5 and 10°. The graphics of the uncertainty in the determination of ϑ as function of ϑ are presented in the figure 4.

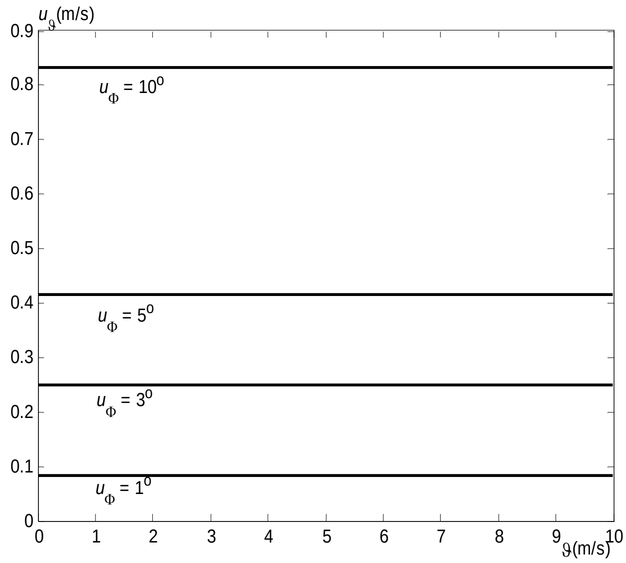


**Fig. 4. Air speed uncertainty versus air speed for several values of the uncertainty on Φ.**

From the simulations, it can observed that the air speed determination uncertainties are much smaller for the Phase Difference than for Time Difference method.

## 5. EXPERIMENTAL RESULTS

From the simulation results we chose to develop the measurement circuit for the Phase Difference method. The system uses two transducers placed on the tube side walls, facing each other. The transducers were lined at an angle of 45º from the flow direction and separated by a distance of 0.1 m. As schematically depicted on figure 5, the tube used for ultrasonic measurement had the same form and size as the tube used in a commercial anemometer, which was used as reference.

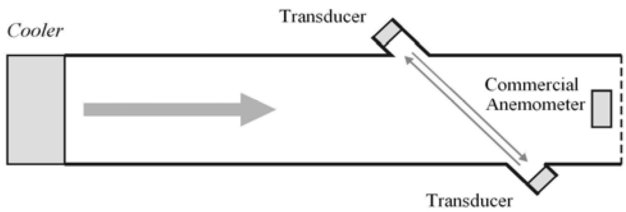


**Fig. 5. Measurement arrangement using ultrasonic transducer.**

The measurement system was implemented using the microcontroller PIC18F452 with clock frequency of 40 MHz, which can count pulses with 100 ns of width. The transducers had the same dynamic characteristics, with central frequency of 40 kHz. The measurement system can be represented as the block diagram presented on figure 6.

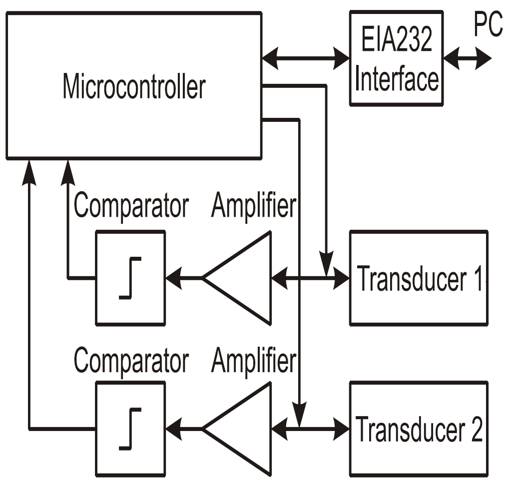


**Fig. 6. Block diagram of the speed measurement system using the DP method.**

The experimental speed results obtained by the DP method are comparable with those obtained with a commercial anemometer. The values of air speed had been gotten in different speeds. (0 to 4 m/s), as show in figure 7. Each speed value predetermined were gotten becoming an average of 100 consecutive samples of 5 samples per second. Later these experimental results are compensated with the initial phase value, without air flow.

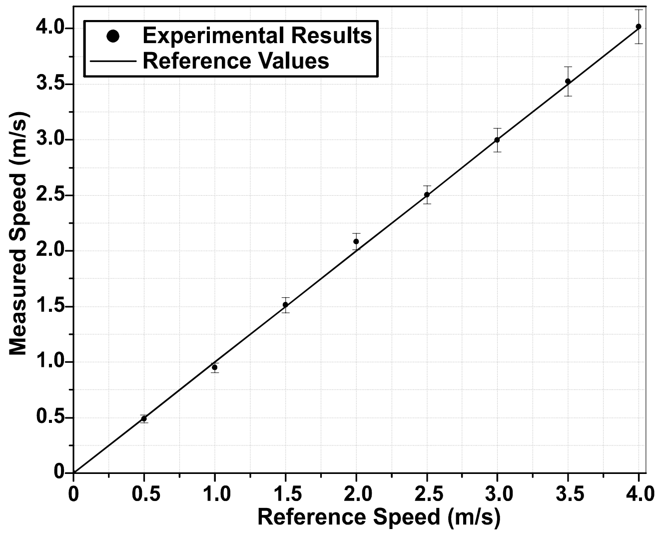


**Fig. 7. Comparative graphs of speed measurement versus anemometer reference values.**

## 6. CONCLUSION

In this paper, the Time Difference and Phase Difference methods based on ultrasonic transducers are described for estimating air speed using the uncertainties propagation study. From the simulations obtained results in the DP method provides less uncertainty value and it was chosen for implementation. The experimental results value speed obtained by the method DP have speed values very close by the reference values when are comparable with those measurement with a commercial anemometer, evidencing that the proposed method is suitable for the determination air speed. The uncertainty obtained air speed value is approximately 4% of the reference speed value. This uncertainty value is inside of the uncertainty phase band obtained by simulation, validating the proposed system.

## ACKNOWLEDGMENTS

The authors wish to thank the received financial support of the National Program of Academic Cooperation – CAPES, CNPQ, COPELE/CCT/UFCG and FAPEMA-MA during the development of this project.

## REFERENCES

[1] Ter Haar, G., Basic Physic of Therapeutic Ultrasound, Physiotherapy, Vol 64, Mar, 1978.
[2] Kitchen, S. and Partridge, J., A Review of Therapeutic Ultrasound Physiotherapy, Vol 76, 1990.
[3] Ter Haar, G., Physic of Therapeutic Ultrasound, London, Physiotherapy, Vol 73, Mar, 1987.
[4] Aziz, E., Barboucha, M. and Starosweicki, M., "An Flowmeter Designed According to Smart Sensor Concept," Electrotechnical Conference MELECON '96, pp.1371-1374, 1996.
[5] Moore, P., Piomelli, Espina, P., "Simulation of Transit Time in a Fully Developed Turbulent Flow using a Ray-Tracing Method," Sea Measurement Workshop, 2002.

[6] Fialho, A. B., Instrumentação Industrial - Conceitos, Aplicações e Análises, Editora Érica Ltda. 2ª ed., 1998.
[7] Halit, E., "Accuracy in Real Time Applications and Transit Time Flow Meters," IEEE-Instrumentation and Measurement Conference Technology; Canadá, May, pp. 18-21, 1998.