

ULTRASONIC TIME OF FLIGHT ESTIMATION FOR WIND SPEED MEASUREMENT BASED ON TIME-FREQUENCY DOMAIN USING STFT

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Abstract- This paper presents a procedure for wind speed measurement using ultrasonic transducers based on short-time Fourier transform (STFT). The measurement of wind speed was performed by estimating the ultrasonic transit-time (ToF). For this purpose the estimated ToF was used the technique of digital signal processing, based on the STFT. The ultrasonic signal detection was performed by setting a threshold level equivalently half the maximum power for the operating frequency of the ultrasonic transducers. Simulation results are presented considering the influence of the additive noise Gaussian, and estimation of ToF considering the evaluation of STFT windows using Hamming, Hanning and Bartlett.

Keywords: -Ultrasonic transducers, time-frequency analysis (STFT), wind speed measurement.

I. Introduction

The ultrasonic sensors have many applications in science and engineering, such as measuring the wind speed (WS) for wind energy applications [1], detection of defects in metallic surfaces [2] and detection of atmosphere humidity variations [3]. For many applications, the principle of measuring with ultrasonic sensors is based on the time of flight estimation (ToF). It is the time that the ultrasonic waves need to cross the distance between the emitter transducer and the receptor transducer. The ToF estimation can be made with techniques such as threshold-detection (TH) and phase difference (PD). However, such techniques are sensitive to noise and distortion, indicating the need of a different approach. One possible solution is using a digital signal processing technique (wavelet transform and Kalman filter, for example), that need a high computational cost. Specifically, the wavelet transform decomposes a signal in high and low frequency energy coefficients. But, for a high level of decomposition, this method is impracticable. Instead, a promising technique based on Short-Time Fourier Transform (STFT), capable of representing signal energy in the time-frequency domain, can be used.

In this work, we developed a procedure for measuring the wind speed using ultrasonic transducers. For this purpose, the ToF is estimated based on time-frequency analysis by Short-Time Fourier Transform (STFT). Simulation results are presented for a configuration of ultrasonic transducers in the forward direction of the wind flow, and considering the influence of the additive Gaussian noise.

II. Preliminary Definitions

A. Measurement Setup

In Fig. 1 is shown the measurement configuration that consists in two aligned ultrasonic transducers inside a wind tunnel. The ultrasonic waves travel across the air with a velocity C , depending on the temperature. If the wind is also moving, a wind velocity component (with angle θ) will make the waves traveling faster. As a consequence, the time the waves need to cross a distance L between transducers is given by Eq. (1).

$$t_{ToF} = \frac{L}{C + \mathcal{V} \cos \theta} \quad (1)$$

The sound speed in air, which depends on the temperature and can be determined by measuring the temperature T_K (in Kelvin) [4]:

$$C = 20.074\sqrt{T_K} \quad (2)$$

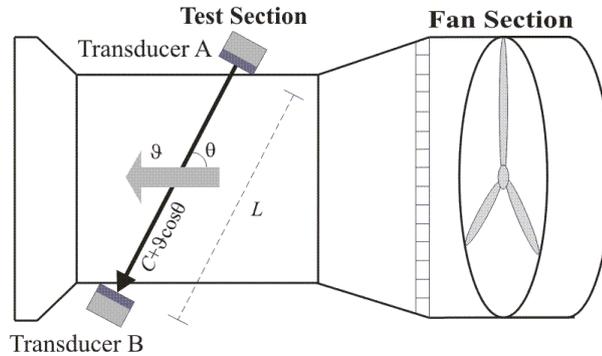


Figure 1. Setup configuration for wind speed measurement using ultrasonic transducers

In Fig. 2, the transmitted (Tx) and the received (Rx) signals at the ultrasonic sensors. The signal Rx is detected using a threshold after a time t_M . As the ultrasonic transducers have a delay time, t_E , the time of flight can be determined from the difference: $t_{ToF} = t_M - t_E$. From the ToF estimation we can determine the wind speed measurement given by:

$$\vartheta = \frac{1}{\cos \theta} \left(\frac{L}{t_{ToF}} - C \right) \quad (3)$$

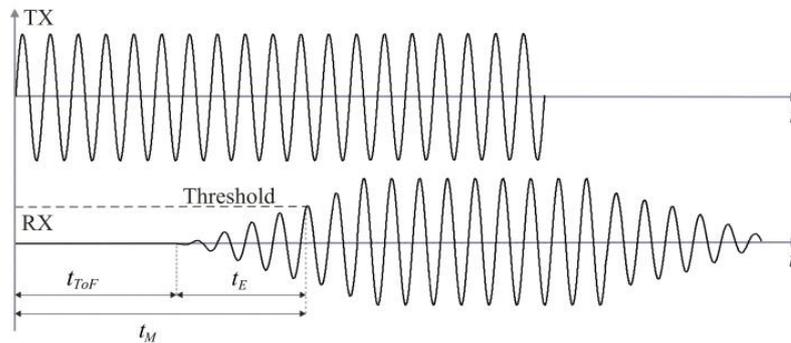


Figure 2. Ultrasonic transmitted and received signals.

In order to assess the quality of the measurement of wind speed based on the estimation of the ToF was used to guide expression and assessment of uncertainties (ISO-GUM) which establishes the procedures for the evaluation of the confidence interval of the measurement through the determination of the standard uncertainty or standard deviation [5]. Thus, from equation (3) was performed to analyze the propagation of uncertainties, considering negligible uncertainties associated with variables L , θ and temperature, given by:

$$\sigma_{\vartheta} = \frac{L}{t_{ToF}^2 \cos \theta} \sigma_{t_{ToF}} \quad (4)$$

B. Short-Time Fourier Transform (STFT)

The STFT is capable of providing information about signal behavior by performing a time-frequency analysis, from which it is possible to determine the time instants at which specific harmonics are present in the signal, as well as the power spectrum analysis. The definition [6] of the STFT is given by:

$$S_i(\omega) = \frac{1}{2\pi} \int e^{-j\omega t'} s(t') h(t'-t) dt' \quad (5)$$

where: $s(t')$ is the signal, ω is the frequency and $h(t'-t)$ is the window function. This feature, which can have various shapes, when multiplied by the signal $s(t')$, limits the analysis to a short time, centered at t . The size of this function will set the resolution both in time and in frequency.

III. Time-of-Flight (ToF) Estimation Based on Short-Time Fourier Transform (STFT)

Detection occurs when the ultrasonic component ($f_0 = 40$ kHz) of STFT spectrogram (Fig.3) exceeds a threshold, a minimum level of power that varies according to temporal resolution of the signal. A good temporal resolution can be obtained for small windows at the expense of frequency resolution. The loss in frequency resolution, however, was not significant enough to compromise our results. Then, the spectrogram of the signal can be constructed from the following equation:

$$P_S(t, \omega) = |S_i(\omega)|^2 \quad (6)$$

where: $S_i(\omega)$ is the issue of the Short Time Fourier Transform and $P_S(t, \omega)$ is the signal power

And the equation of the ultrasonic received signal contaminated by additive noise can be written by:

$$s(t) = s_m \sin(2\pi f_0 t + \varphi) + u_N(t) \quad (7)$$

where: s_m is the amplitude of the signal, f_0 is the frequency of the transducer ultrasonic, φ is the phase due to the interaction between the ultrasonic wave and the medium, and $u_N(t)$ is the noise modeled from the pdf Gaussian.

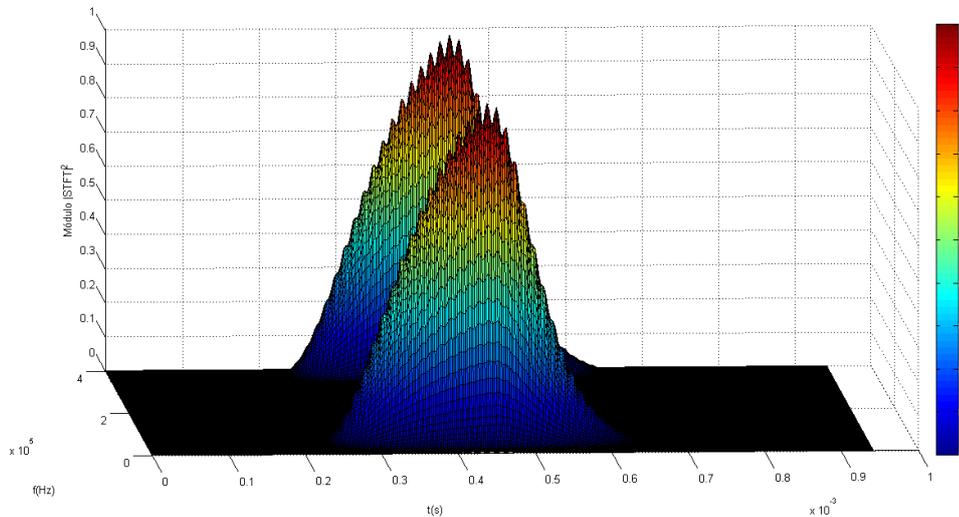


Figure 3. Ultrasonic signal spectrogram obtained from its STFT.

The estimation procedure consists in three steps (described in Fig.4 block diagram). The first is acquisition (sampling and quantization) of a time series of the signal received by the receiving transducer. Then, the time series is used to build a spectrogram and to identify the instant at which the ultrasonic element reaches half of its maximum power. His time is subtracted electronic depends on the characteristics of the receiving transducer (modeled as a filter) and the chosen window. For the Bartlett window, for example, electronic time was approximately around 96 μ s, in contrast to the time of 98 μ s obtained for the Hamming and Hanning windows. The electronic time also depends on the time resolution of the spectrogram adjusted to provide 1% of the signal power at the ToF, for a Bartlett window and a sample frequency of 400 kHz.

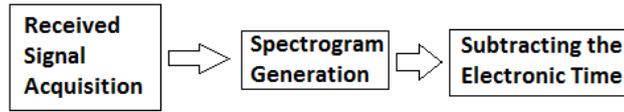


Fig. 4: Ultrasonic signal ToF estimation from STFT procedure block diagram.

IV. Simulation Results

In this section the ToF results for three different windows are presented: Bartlett, Hamming and Hanning. Two different wind speeds (5 and 10 m/s) and three different noise levels (2, 1.5 and 1% of received signal maximum). As can be seen in Fig. 5, the signal is transmitted in burst mode, to enable repeated detections per threshold. The ToF means and standard deviations (std) obtained from MATLAB @Simulink simulations of the proposed method are shown in Table 1. The received signal was normalized with 1V amplitude. It is possible observe the Hanning, Hamming and Bartlett windows had similar performances when compared to Bartlett window, since both provides estimated values closer to theoretical values, with low standard deviation. It becomes clear in Table 2, that shows wind speed and its uncertainties for Bartlett, Hanning and Hamming windows, obtained using Eqs. (3) and (4). The deviations computed as zero in the tables are approximations of very low values (picoseconds).

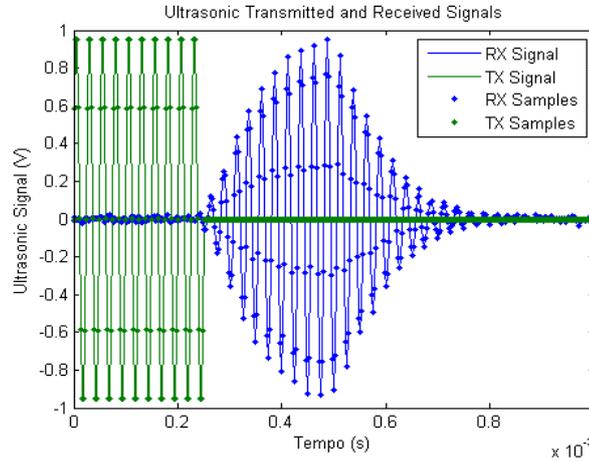


Figure 5. Transmitted (TX) and received (RX) normalized signals with 1% standard deviation noise.

Table 1. ToF estimated values and uncertainties for Bartlett, Hamming and Hanning windows and a 50% of threshold level.

Noise Level	ToF _{Theory} (μs)	Bartlett		Hamming		Hanning	
		5 m/s	10 m/s	5 m/s	10 m/s	5 m/s	10 m/s
2 %	ToF (μs)	231.35	228.93	231.19	229.15	231.26	228.98
	std ToF(μs)	0.8975	0.5330	1.0000	0.7129	0.7183	0.6228
1.5 %	ToF (μs)	231.19	229.04	231.19	229.05	231.19	228.99
	std ToF(μs)	0.0000	0.5208	0.0000	0.5324	0.0000	0.3811
1 %	ToF (μs)	231.19	229.02	231.19	228.93	231.19	228.93
	std ToF(μs)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 2. Wind Speed estimated values and uncertainties for Bartlett, Hamming and Hanning windows.

Noise Level	Wind Speed (m/s)	Bartlett		Hamming		Hanning	
		5	10	5	10	5	10
2 %	Wind Speed (m/s)	4.64	10.00	4.99	9.51	4.84	9.89
	Std WS (m/s)	1.9669	1.1929	2.1946	1.5925	1.5754	1.3933
1.5 %	Wind Speed (m/s)	5.00	9.76	5.00	9.73	5.00	9.87
	Std WS (m/s)	0.0000	1.1645	0.0000	1.1903	0.0000	0.8525
1 %	Wind Speed (m/s)	5.00	9.80	5.00	10.00	5.0000	10.00
	Std WS (m/s)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

To improve the results of Tables 2 and 3, the energy of the transmitted signal may be increased in order to increase the SNR. An alternative is to increase the energy of the received signal. Thus the standard deviations can be mitigated. In practice, the attenuation of the signal between the two ultrasonic transducers can be determined without undue difficulties. Once known attenuation, a new amplitude can be set to the transmitted signal.

IV. Conclusions

In this work we have developed a procedure to estimate the ToF based on the STFT using different windows such as Hamming, Hanning, and Bartlett. From the simulation results, it was observed that the Bartlett window has a lower uncertainty in estimating the ToF compared with other windows used. We have chosen a threshold level relation to at 50% of maximum signal power to ensure that the detection is performed within the bandwidth of operation of the ultrasonic transducer. It has been observed that the resolution of the estimate depends on the sampling frequency as well as the choice of the window to the STFT processing. An alternative to improve the uncertainties consists in grow up the SNR, based on experimental setup attenuation and noise levels.

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