

## Ultrasound measurement apparatus for liquids characterization

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**Abstract:** The present paper discloses the validation of an experimental ultrasound apparatus and method for liquids characterization. The research aims to establish a simple, reliable, accurate and portable way to identify contaminants in hydrocarbon substances, such as adulteration in gasoline. The results depicted so far demonstrated a general uncertainty of speed of sound assessment less than  $10 \text{ m s}^{-1}$ , and distance accuracy of less than 1%. Those figures are good enough for an in-site device to evaluate possible contamination of fuels or other liquids.

**Keywords:** Ultrasound, liquids characterization, uncertainty.

### 1. INTRODUCTION

Despite of the rigid control of Brazilian authorities, gasoline adulteration is much more often than reasonably. This practice results in loss of money for users and for the Government. The Brazilian regulations for gasoline [1][2] adopted many types of tests to assess its quality, but most of them are expensive, not self-conclusive or demand too much time to get results. Gupta and Sharma [3] worked on this subject and proposed a new experimental approach using ultrasonic parameters. In the work of Wiedermann et al. [4], the tests used in some fuel quality assurance regulations were tested and the results suggest a lack of confidentiality to be investigated further. It was decided to use ultrasonic measuring facility because it would allow saving time, as ultrasonic parameter determination is straightforward. So, they could differentiate one sample from another, readily. The wave propagation velocity (WPV) and the acoustic attenuation through materials are the so called ultrasonic parameters. They are dependent or directly related to variation of temperature, density and viscosity. The ultrasonic wave's energy attenuation, during propagation through the medium is an important parameter to help on material's characterization.

Ultrasound has been proved so far to be an interesting and reliable parameter to be used to assess fluid characterization. Within the research to which this paper belongs, a new apparatus was developed and evaluated regarding the precision and accuracy. The aim of this apparatus is to determine ultrasound parameters such as sound velocity and attenuation. Within this paper, the results regarding sound velocity assessment will be disclosed.

### 2. THEORETICAL BACKGROUND

The wave propagation velocity (WPV) is calculated from taking the specific medium's extension value and the time taken by the acoustic wave to pass through it, named time of flight ( $t_{of}$ ) [5].

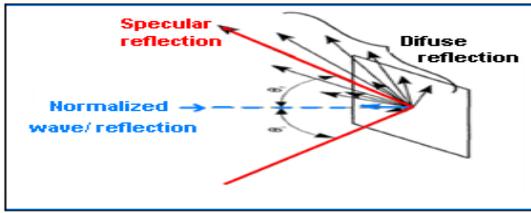
$$c = \frac{\Delta x}{\Delta t} \quad (1)$$

$c \rightarrow$  wave propagation velocity (WPV), in  $\text{m s}^{-1}$

$\Delta t \rightarrow$  time of flight ( $t_{of}$ ), in s

$\Delta x \rightarrow$  distance, in m

In a pulse reflection scheme, the ultrasonic wave behavior is specular, i.e., the reflected wave direction is perpendicular to the incident surface. The following figure illustrates the phenomena.



**Figure 1.** Acoustic wave's Behavior (adapted from McCluney, 1994) [6].

Water's WPV is a function of temperature, and Lubbers and Graaff's simplified equation's result is in equation (2) (see [6]).

$$c = 1404,3 + 4,7T - 0,04T^2 \quad (2)$$

$c \rightarrow$  wave propagation velocity (WPV), in  $m s^{-1}$   
 $T \rightarrow$  temperature in the medium, in  $^{\circ}C$

Water's density can be estimated as function of temperature according to equation (3) [8]

$$\rho = 1000 + 0,0134T - 0,0058T^2 \times 10^{-5}T^3 \quad (3)$$

$\rho \rightarrow$  density in the medium, in  $kg m^{-3}$   
 $T \rightarrow$  temperature in the medium, in  $^{\circ}C$

### 3. METHODOLOGY

The experimental apparatus consists in a metal tube (diameter equals 31,775 mm) which is filled with the liquid under test (LUT). As reflecting target, a specially developed cylinder made of aluminum was constructed. The cylinder length was defined so that a 20-cycle, 5 MHz, ultrasonic burst can propagate through its extension without interfering, as reflected wave, in the incident wave (about 85 mm long). The ultrasonic signal was delivered by an arbitrary waveform generator model 33500B series (Agilent, USA) to an ultrasonic transducer model A307S- 5 MHz (Olympus-NDT, USA). The reflected signal was digitalized with an oscilloscope model DSO-X 3024A (Agilent, USA), and all calculations were performed in a dedicated spreadsheet.

#### 3.1 Dimensional measurement

The system was designed to allow the ultrasonic propagation inside the cylinder with two different distances. The sound velocity is assessed with better accuracy if two different propagation paths

are used with the same emitting and reflecting system. The difference is accounted in the time domain subtracting the two reflected echoes (sequentially, not simultaneously measured).

A mechanical gauge was used to determine the difference of the two propagations paths, as disclosed in figure 2. Its length was determined with the aid of a calibrated Vernier caliper model CD8" AX-B (Mitutoyo, Brazil), with expanded uncertainty of 30 micrometers ( $p = 0.95$ ).



**Figure 2.** Homemade measurement apparatus. The distance gauge is disclosed in the right hand side of the figure with the Vernier caliper.

#### 3.2 Ultrasonic measurement

For the system and the method validation, water at room temperature was used. The speed of sound was assessed using equation (2). The reflector was positioned in two different distances from the transducers. Increasing the distance, the time of flight will increase accordingly, as far as the speed of sound remains the same. The results were statistically compared. The measurement uncertainty was determined following the GUM guidelines [9].

#### 3.3 Fluid density measurement

The system will be used to characterize fluids of dissimilar physical properties, for instance density and viscosity. Within the validation experiment described in this paper, the density was assessed according to equation (3) to evaluate the amount of mass to be filled in the tube. The results were compared with the amount of substance measured with a gravimetric method.

#### 4. RESULTS

The dimensional measurements are presented in table 1.

**Table 1.** Tube and gauge dimensional measurement.

	Dimensions (mean value) [mm]		Unc. [mm]
Tube	diameter	<b>31,775</b>	<b>0,031</b>
GAUGE	length	<b>85,009</b>	<b>0,020</b>

Density assessed after temperature measurement is disclosed in table 2.

**Table 2.** Density value and uncertainty for  $T = 22\text{ }^{\circ}\text{C}$ .

Sample's T [°C]	Source	Result			
22	Equation (3) $\rho$	<b>997,99 [kg m<sup>3</sup>]</b>			
	Equation (2) $c$	<b>1488,34 [m s<sup>-1</sup>]</b>			
<b>Sample's mass</b>					
Mean value [g]		<b>81,312</b>			
Uncertainty [g]		<b>0,005</b>			
<b>Tube</b>					
<b>Diameter</b> (vernier caliper)		<b>Time of flight (t<sub>of</sub>)</b> (through the sample)		<b>distance</b> $c \equiv (2)$	<b>area</b>
Mean value	Std. dev.	Mean value	Std dev	$\frac{t_{of} \times c}{2}$	
0,0318 [m]	3,064E <sup>-5</sup> [m]	1,37E <sup>-4</sup> [s]	1,80E <sup>-7</sup> [s]	0,102 [m]	7,93E <sup>-4</sup> [m <sup>2</sup> ]
Sample's volume $V = \text{area} \times h$		<b>0,0000809 m<sup>3</sup></b>			
Sample's density $\rho = \frac{m}{v}$		<b>1005,09 kg/m<sup>3</sup></b>			
Diff [m]	<b>7,1</b>	Diff%	<b>0,0071%</b>		

The volume was assessed both with a gravimetric method and dimensional method. The length was measured with the Vernier caliper and the ultrasonic time of flight method. All results are disclosed in table 3.

**Table 3.** Volume measurement.

Measurement by mass				
Temp [°C]	Equation (2)		Equation (3) $\mu$ [kg m <sup>-3</sup> ]	Vol [m <sup>3</sup> ]
22	WPV [m/s]	Max. error [7] [m/s]	<b>997,8</b>	<b>0,0815</b>
	<b>1488,34</b>	<b>0,18</b>		
Measurement by ultrasound				
WPV (eq.2) [m/s]	$\Delta t$ [s]	$\Delta x$ (eq.1) [m]	Tube basis area [m <sup>2</sup> ]	Vol [m <sup>3</sup> ]

<b>1488,34</b>	<b>0,000137</b>	<b>0,1015</b>	<b>0,000793</b>	<b>0,0805</b>
Std dev	<b>1,804E<sup>-7</sup></b>	Difference [mm]		<b>1,0</b>
		Difference [%]		<b>1%</b>

The dimensional gauge length was assessed with the pulse echo ultrasonic measurement method, and the result is disclosed in table 4 along with its uncertainty. In the table 4,  $t_1$ ,  $t_2$  and  $t_3$  are the time of arrival for the three first echoes.

**Table 4.** Gauge's length measurement using ultrasound.

		Repet. 1	Repet. 2	Repet. 3
t <sub>of</sub>	t <sub>1</sub> [μs]	29,432	29,434	29,436
	t <sub>2</sub> [μs]	58,324	58,334	58,330
	t <sub>3</sub> [μs]	86,954	87,036	87,033
	$\Delta t_{(2-1)}$	$\Delta t_{(3-2)}$	$\Delta t_{(2-1)}$	$\Delta t_{(3-2)}$
	28,89	28,63	28,90	28,70
Mean value $\Delta t$ [μs]	28,76	28,80	28,80	
Mean $\Delta t$		28,79 [μs]		28,79E <sup>-6</sup> [s]
Mean Velocity (c)		2953		[m/s]
Uncertainty-velocity		17		[m/s]
Uncertainty-velocity [%]		0,59		%
Gauge length $c = \frac{\Delta x}{\Delta t}$		<b>0,085017</b>		m

The final results comprise the speed of sound measurement and comparison with the temperature dependent formula (2). Table 5 discloses the results and the comparison of them.

**Table 5.** Speed of sound measurement.

	Ultrasound measurements	Vernier caliper measurements
Gauge's length	$c = \frac{\Delta x}{\Delta t}$	Mean value
	<b>0,085017 m</b>	<b>0,085009 m</b>
Water sample's WPV	Equation (2) at 22°C	
	<b>1488,34 [m/s]</b>	
Water sample's density	Ultrasound measurements	Equation (3) at 22°C
	$\rho = \frac{m}{v}$	$\rho = 1000 + 0,0134T - 0,0058T^2 \times 10^{-5}T^3$
	<b>1005,09 kg m<sup>3</sup></b>	<b>997,99 kg m<sup>3</sup></b>
Difference [m]		<b>7,1</b>
Difference %		<b>0,0071%</b>

#### 5. DISCUSSION

Ultrasound is an usual tool to identify materials properties, such for fluids (liquid or gases) as for solids. However, specific application demands dedicated assemblies of devices, transducers,

accessories and equipment. The objective of the present research is to develop and validate an apparatus able to deliver ultrasound to a liquid medium and, further, assess its physical characteristics.

To evaluate the accuracy of the device, we used pure water as known medium. The dimensional quantities of the recipient were firstly measured with a Vernier caliper, and in sequence estimated using ultrasound waves. The results agreed of 8  $\mu\text{m}$  (see Tables 1 and 4). The speed of sound within the tube was determined with uncertainty of less than, 0,6% (Table 4).

Another way to validate the system is to consider the speed of sound after a well established relation between water temperature and speed of sound. The quantities to be assessed are linear and volumetric dimensions, indirectly determined. According to results disclosed in Tables 2, 3 and 5, one can observe that the ultrasound method was able to achieve about 7 ppm for density measurement with the aid of a gravimetric method (Tables 2 and 5) and 1% for volume (Table 3).

## 6. CONCLUSIONS

Applying ultrasound for liquids characterization shows confidence and accuracy which is desirable for technical application. Further work will deal with gasoline and other hydrocarbons substance to evaluate the applicability of this approach to identify the presence of contaminants.

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