Viscosity Electronic Measurement Estimation System based on the Impedance Frequency response of a Vibrating Wire Sensor

Pedro Santos Rocha Madeira Marques
Instituto Superior Técnico, Av. Professor Doutor Anibal Cavaco Silva, 2744-016 Porto Salvo, Portugal
Phone: +351-927564125, e-mail: pedro.madeira@ist.utl.pt

***Abstract* — Nowadays, viscosity measurements play an important role in several areas, such as Industrial, Scientific and Technological, and have utility in various applications. In the Industrial area, viscosity measurements can be applied in several areas, such as the food, pharmaceutical, automobile, chemical and petroleum industries. Viscosity measurement brings benefits since monitoring it allows cost reduction as well as increased product quality and client satisfaction.**

This work aimed to develop a system capable of performing sensor's impedance measurements, characterization of that impedance for a particular range of frequency values and resonance frequency and half-height width estimations. Viscosity measurements are possible by using a vibrating wire Sensor.

The system developed is based on a DSP as the central processing unit and a signal generator whose reference clock frequency is defined by the DSP. This characteristic allows a synchronism between signal generation and signal acquisition, made by two ADCs, whose reference clock frequency is also be given by the DSP.

This new approach, regarding the synchronism between signal generation and acquisition, allows a reduction of the digital processing required to determine viscosity, making its process quicker. It was also implemented USB interface in order to allow the connection to a personal computer

***Index terms* – Viscosity, Vibrating Wire Sensor, DSP, Digital Processing, Synchronism**

I. Introduction

When it comes to predicting how a liquid material will behave in the real world, viscosity is an important measure that needs to be done and therefore gathering information in regards to this property is very relevant. It is important in several areas, such as food and petroleum industries, cosmetics, and pharmaceuticals.

In the food industry, viscosity plays a big role since measuring it will maximize production efficiency and cost effectiveness. For example, it affects the time a fluid takes to be dispensed into packaging, when talking about production efficiency and it is also a characteristic of food's texture which is important when talking about customer satisfaction. In cosmetics, viscosity should be considered when designing the feel and flow of cosmetic products for the skin. As for petroleum industry it is important to determine its economic viability due to the fact that the viscosity of a crude oil affects its ability to pump it out of the ground. It is also important in the automotive area to ensure the quality of motor and fuel oils. Taking into account the different uses for viscosity measurements, it is important to have measurement methods with the ability to conduct them in a fast, precise and reliable way [1]

Among the different methods for measuring viscosity, the method based on the vibrating wire sensor has proven itself quite versatile, since it presents greater ease in construction, can be operated remotely and can be used in a wide range of temperatures and pressures without the need for calibration on the ranges upon which the measures are made [2]. These advantages are mostly due to the fact that the vibrating wire sensor is entirely composed of solids, allowing accurate measures when submitted to temperature and pressure changes on the sensor's components. It is also supported by a rigorous theory, the vibrating wire technique, which does not require extensive calibration procedures [3].

One of the parameters that the vibrating wire sensor requires to measure viscosity is the sensor's impedance response for a certain range of frequencies around the resonance frequency. The impedance value is determined based on the voltage at the sensor's terminals and on the current applied to the circuit. Therefore, the method chosen and studied takes advantage of a reference impedance, whose value is well known, allowing the measurement of the sensor's impedance, by applying time and frequency domain algorithms on the processing unit.

II. Viscosity Measurement Methods Studied

There are several methods to measure fluid's viscosity. They can be divided into two categories, quasi-primary and secondary methods. There are no primary methods since the ones that were developed so far, to achieve high accuracy, need to involve instrumental parameters obtained through calibration, in other words, quasi-primary methods are the ones that make use of physically working equations that relate viscosity to parameters already measured experimentally.

A. Capillary Viscometers

Capillary Viscometers or U-tube Viscometers, are the ones used more extensively when it comes to measuring viscosity, especially in liquids. They consist in a U-shaped glass tube, which is held vertically in a controlled temperature bath. This type of viscometer is based on the dynamics of Hagen-Poiseuille Equation [4][5].

However, the use of this type of viscometer requires some calibration due to the extreme difficulty in measuring viscosity and involves some experimental difficulties, such as the requirement of special thermostatic baths that need a constant temperature control for large depths.

B. Falling Body Viscometers

Falling body viscometers make use of the time of a free falling body of revolution[1], normally a sphere or a cylinder, under the influence of gravity, through a fluid whose viscosity needs to be measured. This method is based on Stokes' law [2][6], which refers to the friction force that spherical objects suffer while moving within a viscous fluid

Even though this type of viscometers have multiple advantages when it comes to operations with high pressure or as relative instruments for industrial applications, they need calibrations by using standardized liquids, and present an uncertainty of around $\pm 3\%$ [2].

C. Oscillating Body Viscometers

Just like the previous method, oscillation body viscometers can be used with different shaped bodies, such as disks, cups, cylinders and spheres. Disks are currently the most accurate for measurements in both gas and liquid phases.

These types of viscometers require a perfect parallel alignment between the fixed plates and the disk, as well as their flatness, to achieve acceptable measurements. They work by applying a force on the oscillating body while the fluid involving it will exercise a contrary force to its surface, increasing the oscillating period and reducing the amplitude of the angular movement. This effect, along with the theoretical equations, allow an assessment of the viscosity. The most accurate measurements in the fluid state obtained with this type of device, are in the free-decay mode of operation, and uncertainties better than 1 % can be achieved [7].

D. Vibrating Wire Viscometers

Vibrating wire viscometers are in a way related with oscillating body viscometers, but instead of torsional oscillatory movements these use transversal movements. This type of viscometers involve the distortion, by an external applied field, of a solid body, normally a wire as it can be seen in Figure 1, immersed in the fluid. When working in a forced mode of operation, the characteristics of the resonance curve for the transverse oscillations of the wire are correspondingly determined by the viscosity and density of the fluid. In other words, the surrounding fluid will exert an effect on the period and amplitude of oscillation allowing viscosity measurements [7].

The vibrating wire sensor is placed inside a cell composed by two parallel magnetic plates on each end, with a wire fixed between them, submerged in the fluid to be studied [2][8]. Its principle of measurement is based on Lorentz Force , which is generated by applying an electric current inside a magnetic field, first to create the oscillatory movement and then to detect the vibration, since an electric voltage is induced.

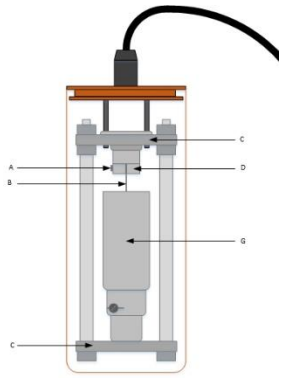

Figure 1 - Vibrating Wire Sensor.

A - Wires Tension adjustment Screw; B - Vibrating Wire; C - Fixing Plates; D – Magnets; G - Vase.

To perform measurements, an alternate current must be forced in the wire and a sweep in frequency around the resonance frequency must be made. Since the wire is subjected to a magnetic field, created by the parallel magnetic plates, the forced current will cause transversal oscillations on the wire allowing the current frequency to vary and therefore enabling to determine the sensor's response in frequency. By analysing the sensor's impedance for an interval where the resonance frequency is contained, it is possible to determine the resonance characteristics of the transversal oscillations of the wire [9].

III. Architecture

The architecture chosen, presented in Figure 2, was based on the I-V method and can be divided into two main parts, signal generation and signal acquisition.

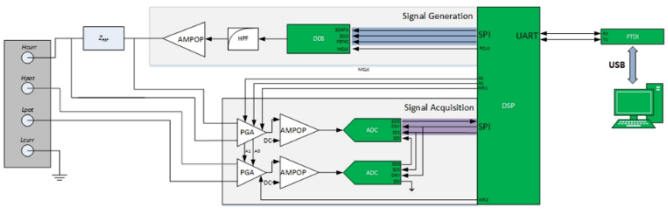

Figure 2 - System Architecture.

The signal generation in handled by the stimulus mode, and the main difference when comparing it to work already developed in this area, is the fact that the frequency reference for the clock is common for both the generation and the signal acquisition. This feature will allow the reduction of the processing needed to determine the sensor's impedance, amplitude and phase. The stimulus module studied is a DDS, used to generate the required signals.

[1] Surface created by rotating a curve around an axis of rotation.

As for the processing unit, was used a DSP, which presents high processing capabilities, and have the ability to provide clock references to the rest of the system and therefore allowing synchronism. In regards to the signal acquisition, two ADCs, one for each channel were used.

The processing unit, besides controlling both the generation and acquisition system, is also responsible for communicating with a personal computer, and therefore receive commands and send the information requested.

A. Devices Used

The chosen processing and control unit was the ADS-21489 SHARC processor from Analog Devices [10]. It is a processor based on a Super Harvard architecture, which has separate program and data memory, as well as I/O processor and buses, enabling direct interfacing with the processing core and the internal memory. It has 400 MHz core clock speed, features 32-bit fixed and floating-point arithmetic format and comes with 5 Mbits of on-chip RAM, a 16-bit wide SDRAM external memory interface and a DMA engine. It includes multiple communication protocols such as UART, SPI, I2C and PWM signal generator.

The ADCs chosen were the AD7988-5, which are 16-bit analog-to-digital converters of successive approximations that operate from a single power supply and offer a max of 500 kSPS throughput [11]. To develop this work two signals must be considered and therefore two ADCs, connected on a daisy chain mode, were used. Because of that, instead of 16-bit samples, 32-bit samples are acquired by DSP.

As for the stimulus module, was chosen a DDS, the AD9833, which is a low power, programmable waveform generator capable of producing sine, triangular and square wave outputs, that vary frequency from 0 Hz to 12,5 MHz [12]. The DDS was used to generate a sinusoidal signal with the desired frequencies, responsible of stimulating the vibrating wire sensor.

In Figure 3, a sinusoidal signal generated by the DDS with 1 kHz frequency and an amplitude of 0.6 Vpp, is represented and in Figure 4 the correspondent FFT is represented.

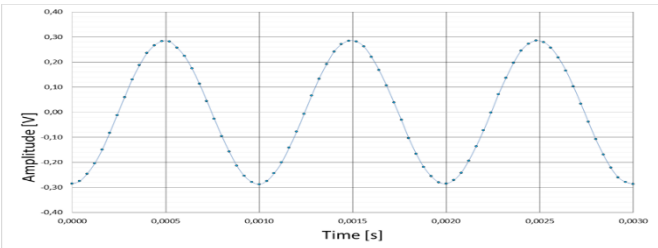

Figure 3 - DDS Signal of 1 kHz

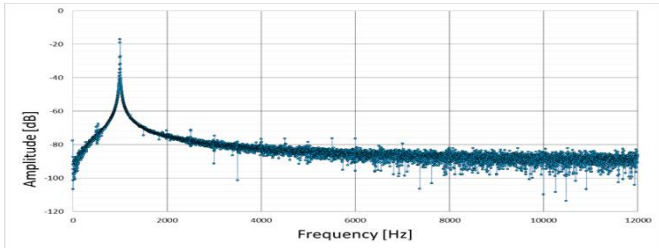

Figure 4 - FFT of DDS generated signal.

The measured signal was obtained with the NI USB-6251 from National Instruments, connected to LabVIEW, which is a USB high-speed multifunction DAQ device.

B. Signal Conditioning

As for the generated signal, it needs to be an AC signal and to insure that happens, a high pass filter was applied to the DDS. Secondly, since the signal is small, an amplification stage is required, which was implemented with the ADA4891 from Analog Devices [23].

As for the acquired signals by the ADCs, programmable gain amplifiers (PGAs) and operational amplifiers were used. The PGAs present two important functions, increase amplitude of the signals acquired by the ADCs, improve their resolution, as well as the introduction of isolation between the ADCs and the measured impedances. By doing that, the input impedance influence of the ADCs is reduced to a minimum. The operational amplifiers, one for each signal acquired, insure that the signals sent to the ADCs are only positive.

The PGAs chosen were the AD8250 from Analog Devices [24], and give the possibility to choose gains of 1, 2, 5 and 10. They can be controlled digitally by the DSP, making it easy to choose the desired gain. The operational amplifiers used were the ADA4891, from Analog Devices, and were implemented in a differential assembly.

V. ALGORITHMS

A. Frequency Domain

On the frequency domain, two different algorithms were studied. The IpDFT and the Goertzel. The Goertzel is very similar to the FFT algorithm, since both transpose the signal sample on the time domain to the frequency domain and therefore allowing to obtain the signal spectrum, used by the IpDFT algorithm.

Contrary to the FFT that always computes all the frequency components and most of them are discarded, as they present no interest, the Goertzel algorithm is specialized in computing a subset of output frequencies [13][14].

The basic relation of the discrete Fourier transform is

$$X[k] = \sum_{n=0}^{N-1} x[n] e^{-j2\pi n \frac{k}{N}}, \qquad (1)$$

where $x[n]$ is a discrete signal of length N and $X[k]$ is a kth bin of the Fourier spectrum. Function (1) can be put into a convolution form

$$y_k[n] = \sum_{n=-\infty}^{\infty} x[n] e^{j2\pi(m-n)\frac{k}{N}} u[m-n]. \quad (2)$$

An impulse response of the derived filter is then a complex harmonic signal

$$h(n) = e^{j2\pi\frac{k}{N}}, \quad (3)$$

of which length is constrained by a rectangular window. By applying the Z-transform[2] to the impulse response (3), it is possible to find the transfer function of the Goertzel filter

$$H(z) = \sum_{n=0}^{\infty} h(n) z^{-1} = \frac{1}{1 - z^{-1} e^{j2\pi\frac{k}{N}}}, \quad (4)$$

whose modified form is

$$H(z) = \frac{1 - z^{-1} e^{-j2\pi\frac{k}{N}}}{1 - 2z^{-1} \cos\left(2\pi\frac{k}{N}\right) + z^{-2}}, \quad (5)$$

which can be split into the real recursive and the complex direct computational parts, turning it more convenient for the implementation of the Goertzel algorithm. The realization of the transfer function (5) is shown in Figure 5

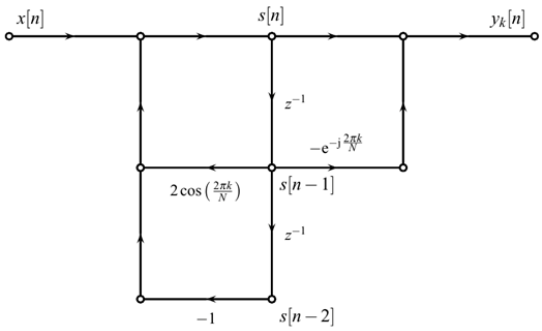

Figure 5 - Goertzel Filter. Taken from [13].

The IpDFT is used to determine with accuracy the signal's frequency, by searching the spectrum, obtained with the Goertzel, for the biggest element and the ones that are adjacent to it [27] and because of that, two situations can occur. First, if the larger neighbour is on left side of the maximum element, X(L) corresponds to the larger neighbour and X(L+1) to the maximum element. Secondly, if the larger neighbour is on the right side of the element, X(L+1) corresponds to the larger neighbour and X(L) to the maximum.

A. Time Domain

The three-parameter sine-fitting algorithm is a non-iterative algorithm that can estimate the amplitude, phase and DC component of an acquired sine wave of known frequency, which in this case was determined by the Goertzel and IpDFT algorithms, with a certain sampling frequency. The acquired sine signals can be represented by

$$u(t) = D\cos(2\pi f t + \emptyset) + C \quad (6)$$

where

$$D = \sqrt{A^2 + B^2}, \quad (7)$$

and

$$\emptyset = -atan2(B, A). \quad (8)$$

To measure parameters A, B and C, the algorithm starts by creating a matrix with three columns and N lines, that correspond to the number of samples acquired,

$$M = \begin{bmatrix} \cos(2\pi f t_1) & \sin(2\pi f t_1) & 1 \\ \vdots & \vdots & \vdots \\ \cos(2\pi f t_N) & \sin(2\pi f t_N) & 1 \end{bmatrix}. \quad (9)$$

After that, the parameters are estimated through the parameter vector

$$\hat{x} = [A \quad B \quad C]^T, \quad (10)$$

which is given by

$$\hat{x} = M^{\dagger} y, \quad (11)$$

where y is the sample vector and $M^{\dagger}$ the pseudo inverse matrix of M [15][16].

C. Impedance Measurement

To measure the impedance of the sensor, it is required to know the magnitude and phase of the signals passing through the sensor and reference impedance. Considering the circuit in Figure 2, amplitude and phase angle of the impedance under measurement are calculated by

$$|\bar{Z}| = |Z_{Ref}| \frac{|U_{Sensor}|}{|U_{Ref}|} \quad (12)$$

and

$$\emptyset = \phi_{Z_{Ref}} + \left(\phi_{U_{Sensor}} - \phi_{U_{Ref}}\right). \quad (13)$$

V. System Software

To communicate between the PC and the DSP, USB protocol was implemented. This was done by using an integrated circuit, the FT232RL, from Future Technology Devices International Ltd, which allows the interface between the UART module of the DSP and the USB from the PC.

The communication between the DDS and the DSP was made using the SPI protocol, since the DDS is written to via a three-wire serial interface. To insure that the reference frequency between the signal generated and the signal acquired was maintained, the clock signal used on the DDS was created by the DSP.

[2] Converts a discrete-time signal into a complex frequency domain representation.

The communication between the ADCs and the DSP was made by also using the SPI protocol on a daisy chain connection, as previously said.

VI. Control Program

The control program to communicate with the DSP, presented in Figure 6, was developed in LabVIEW, so that the user could execute it from a personal computer. The interface allows the user to get specific values that characterize the system, make a sweep in frequency, save values and run a specific command, like for example make a single acquisition.

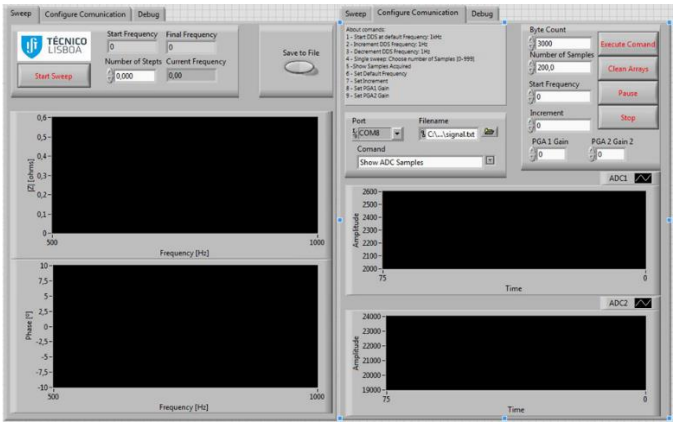

Figure 6 - Control Program developed in LabVIEW

VII. Experimental Results

To determine the range of frequencies upon which the vibrating wire sensor works and study its impedance behaviour when submitted to fluids with different viscosity values, a set of samples, presented in Table 1, were made

Table 1 - Samples Tested with HIOKI.

Sample	Water [%]	Glycerine [%]	Viscosity [mPa.s] at 20° C
1	100	0	1,005
2	50	50	6,000
3	25	75	35,500

The sensor's responses to these samples, whose viscosity values were taken from [17], are presented in Table 2, and were obtained with the 3522-50 LCR HiTESTER from HIOKI [18], by making a sweep around the resonance frequency, using the GPIB interface, commanded by a computer running LabVIEW.

Table 2 - Sensor Frequency Response Parameters for the various Samples.

Sample	F_R [Hz]	Z_{MAX} [Ω]
1	602	0,5761
2	588	0,4979
3	586	0,4726

VIII. Conclusion and Future Work

The main objective of this work was to characterize, implement and develop a system capable of measuring impedances and determine viscosity. For that, the frequency response of the vibrating wire sensor was studied so that the parameters required to analyse viscosity variations could be determined.

The system architecture was represented and described, as well as the LabVIEW interface developed to perform the communication between the system and the user. The developed system was designed so that it would be possible to connect it to the viscosity sensor and acquired samples from it, when stimulated by the sinusoidal signal, also generated by the system. The programing of the processing unit was implemented so that the system could receive commands and send information to the personal computer. Therefore, the LabVIEW program was implemented so that the user could configure the system, in order to set the systems conditions depending on the vibrating wire sensor behaviour.

It is important to state that the system developed remained unfinished since it did not include the processing and control unit in the final PCB. During this work, was used the evaluation system ADSP-21369 EZ-KIT Lite from Analog Devices, and the final footprint of the system, without the DSP, was 70 mm x 37 mm.

Some experimental results, obtained with HIOKI, were presented and was intended to use them as a reference and compare them with the system developed. Unfortunately, due to shortage of time and problems encountered in the final PCB, was not possible to acquire the results needed to compare with the experimental results previously obtained. Having said that, it was not possible to test the final PCB developed, however, the intermediate PCBs developed, with the different modules of the system, showed that it was possible to create the required control signals with DSP, and therefore maintain the synchronism between the signal generated and signals acquired.

In regards to the algorithms studied, the Goertzel algorithm was tested in MATLAB and developed in C language. However, for the reasons already mentioned, it was not possible to implement it in the DSP, as well as the IpDFT and the sine fitting of three parameters.

The future work suggested is the development of a system that includes the DSP, as well as the other modules. Besides that, it is also required to implement the required algorithms to determine precise values of impedance from the vibrating wire sensor, needed in order to determine viscosity.

There would still be the need of a personal computer running LabVIEW, so that the user could communicate with the system. Therefore, an interesting improvement to the system would be giving it some sort of mobility, by adding for example a tablet capable of running the required software, and

a battery so that it could be used if an environment where a wall socket could not be found.

REFERENCES

[1] .F.F. Regada, “The Measure of Viscosity of Liquids with a Vibrating Wire Cell,” Instituto Superior Técnico, 2012.

[2] F.J.P. Caetano, “Viscosimetria de Líquidos Novos Fluidos de Referência.”, Instituto Superior Técnico, PhD Thesis.

[3] A.A.H. Pádua, J.M.N.A Fareleira, J.C.G. Calado, and W.A. Wakeman, “Electromechanical model for vibrating-wire instruments,” in Rev. Sci. Instrum., vol. 69, no. 6, pp. 2392–2399, 1998.

[4] S.P Sutera, and R.Skalak, "The History of Poiseuille's,” 1993.

[5] J. Wilke, H. Kryk, and D. Wagner, “Theory and Praxis of Capillary Viscometry".

[6] K.D. Antoniadis, M.J. Assael, and W.A. Wakeman, “Transport Properties of Fluids".

[7] C.A.N. Castro, F.J.V. Santos, J.M.N.A Fareleira, and W.A. Wakeman, “Metrology of Viscosity: Have We Learned Enough? ", in Journal of Chemical & Enginneering Data, vol. 54, pp. 171–178, Feb. 2009.

[8] F.M. Janeiro, P.M. Ramos, J.M.N. Fareleira, J.C.F. Diogo, D.R.C. Máximo, and F.J.P. Caetano, “Impedance spectroscopy of a vibrating wire for viscosity measurements,” in I2MTC, Boston, pp. 1067–1072, 2010.

[9] N.M.R.F Santos, “Sistema de Medida de Impedâncias baseado num dsPIC para um Sensor de Viscosidade”, Instituto Superior Técnico, Master's Thesis, 2010.

[10] Analog Devices, "ADSP-21489 Datashee", March 2013.

[11] Analog Devices, "AD7988-1/AD7988-5 PulSAR ADCs DataSheet", 2014.

[12] Analog Devices, "AD9833 Programmable Waveform Generator DataSheet", 2012.

[13] P. Sysel, and P. Rajmic, “Goertzel algorithm generalized to non-integer multiples of fundamental frequency,” in Journal on Advances in Signal Processing., 2012.

[14] F. Záplata, “Using the Goertzel algorithm as a filter”, no. 3, pp. 14–16, 2014.

[15] P. M. Ramos and A. Cruz Serra, “A new sine-fitting algorithm for accurate amplitude and phase measurements in two channel acquisition systems,” Measurement, vol. 41, no. 2, pp. 135–143, Feb. 2008.

[16] P. Handel, "Evaluation of a Standardized Sine Wave Fit Algorithm".

[17] J.B. Segur, and H.E. Oberstar, “Viscosity of Glycerol and Its Aqueous Solutions,” The Miner Laboratories, Chicago,1951

[18] “HIOKI 3522-50 LCR Instruction Manual”, HIOKI E.E.Corporation, 2006.