

Measurement Time Optimization of Impedance Spectroscopy Techniques Applied to a Vibrating Wire Viscosity Sensor

José Santos¹, Fernando M. Janeiro², Pedro M. Ramos³

¹*Instituto de Telecomunicações, DEEC, IST, UL, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal, jose.dos.santos@tecnico.ulisboa.pt*

²*Instituto de Telecomunicações, Universidade de Évora, Rua Romão Ramalho 59, 7000-671 Évora, Portugal, fmtj@uevora.pt*

³*Instituto de Telecomunicações, DEEC, IST, UL, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal, pedro.m.ramos@tecnico.ulisboa.pt*

Abstract – This paper describes the optimization of the measurement time of the impedance frequency response of a vibrating wire sensor for viscosity estimation. The optimization deals with the assessment of the estimated viscosity as a function of the number of measured impedance frequency points as well as the selection of those frequencies. This speed optimization is important to ensure that the viscosity measurements are influenced as little as possible by external environmental parameters such as temperature and pressure.

I. INTRODUCTION

In-situ online monitoring of viscosity can have a significant role in many industrial processes. Currently, the methods used to measure viscosity changes are mostly performed in a laboratory environment using specialized, dedicated, expensive instruments that require skilled technicians to perform the measurements.

In recent years, the basic idea for a simple viscometer, initially proposed in [1], has been developed to produce an embedded viscosity measurement device capable of being used in the monitoring of industrial processes. The sensor is based on a vibrating-wire which is inserted into the liquid whose viscosity is to be monitored/measured. The wire is subject to a magnetic field created by permanent magnets placed around the wire. By measuring the wire impedance near the resonance frequency (which depends on the liquid viscosity and the physical dimensions of the wire), it is possible to estimate the liquid viscosity. This basic measurement method was validated in laboratory conditions for example in [2]. The next step has been the development of an embedded standalone measurement device that can directly estimate the liquid viscosity for real-time measurements [3]. This paper describes an optimization to that system, to reduce the measurement time when using the sweep procedure.

II. VIBRATING-WIRE VISCOSITY SENSOR

Fig. 1 shows the vibrating-wire viscosity sensor. It consists on a tungsten wire whose ends are fixed to the sensor cage structure. In the middle of the wire, a magnetic circuit encases the wire and establishes a magnetic field generated by permanent magnets. When an alternating current flows through the wire, a force transversal to the magnetic field causes a vibration of the wire. A mechanical adjustment positioning system enables the fine-tuning of the permanent magnets to ensure proper alignment with the wire.

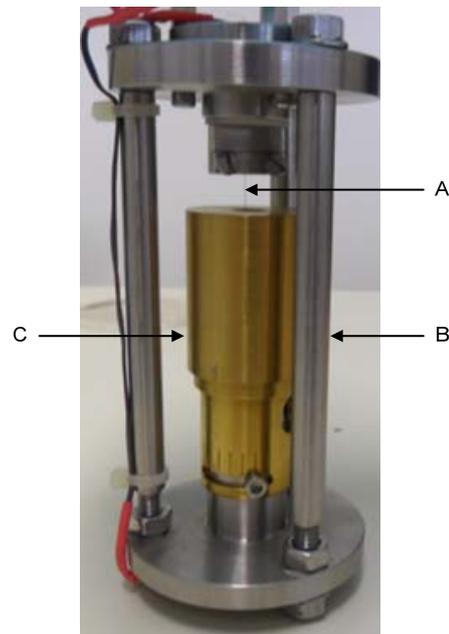


Fig. 1. Vibrating-wire viscosity sensor. A: Tungsten vibrating wire; B: Stainless steel spacers that form the sensor's structure; C: Magnetic circuit casing.

As the imposed current frequency changes, so does the wire impedance, depending on the viscosity of the liquid in which the sensor is inserted. The sensor's dimensions were set to ensure that the impedance resonance occurs near 800 Hz. Since the wire impedance is quite low, a four-wire impedance measurement procedure is used to minimize the influence of the connecting cables. The derivation of the 4-wire is placed as close as possible to the wire extremities.

III. EMBEDDED MEASUREMENT SYSTEM

To achieve fast measurements, an embedded measurement system was developed and implemented. The system is based on a DSP which is responsible for the control of the sinewave generator (setting the signal amplitude and measurement frequency), control of the analog amplification of the voltages across a reference impedance and the vibrating wire which are connected in series, thus with the same current. After the amplification of the two sinewaves, they are simultaneously sampled using two ADCs (16-bit SAR with sampling rate up to 10 MS/s - AD7980). The samples are sent to the DSP (ADSP-21489) where several algorithms are executed to estimate the liquid viscosity. The block diagram of the measurement system is shown in Fig. 2 while Fig. 3 shows the implemented prototype.

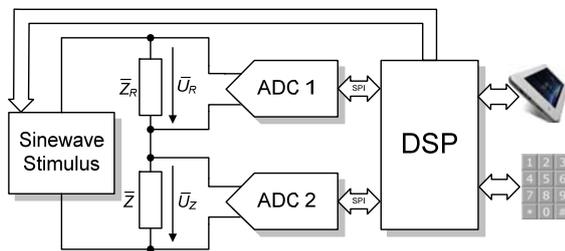


Fig. 2. Block diagram of the measurement system.



Fig. 3. Implemented prototype.

Regarding the algorithms implemented in the system to estimate the impedance and then the viscosity, the first algorithm is a seven parameter sine-fitting algorithm [4] which estimates the sinewaves amplitudes and phases. From these, the wire impedance is obtained. After performing a sweep of the measurement frequency and obtaining the impedance frequency response, the next algorithm estimates the parameters of the equivalent circuit. This is a Nelder-Mead simplex algorithm [5]

which estimates the five parameters of the vibrating-wire equivalent circuit [6]. The next step determines the vibrating-wire resonant frequency and the half-power frequencies using simple analytical equations. These frequencies are then used to determine the liquid viscosity. This last step involves the numerical solution of a set of two equations that include modified Bessel functions with imaginary arguments to yield the liquid viscosity [7].

Although all these steps consume a certain amount of time and resources of the embedded system, the steps that take longer are the repeated acquisitions for each measurement frequency and the execution of the sine-fitting algorithm to estimate the signals' amplitudes and phases [8]. The current setup acquires 8000 samples per channel at 8 kS/s, therefore the acquisition time is 1 s for each measurement frequency. Also, a 50 ms delay is used after each frequency change to ensure measurements in stationary conditions. The sine-fitting algorithms take 64 ms to estimate the sinewave parameters.

Fig. 4 shows the measured frequency response of the sensor for seven water/glycerol mixtures with different concentrations. The solution with the highest peak impedance magnitude has no glycerol while the solution with the lowest peak corresponds to the highest concentration of glycerol (60%) and had the highest value of viscosity. The viscosity ranges from 0.85 mPA.s up to 8.62 mPA.s. Notice that, as the viscosity increases (which corresponds to an increase in the glycerol content of the liquid), the resonance frequency decreases, the maximum impedance also decreases while the width of the resonance increases. Moreover, the impedance magnitude has a base value near 0.45 Ω and the maximum increase is only about 0.15 Ω . The results shown in Fig. 4, were acquired with a sweep step of 5 Hz which corresponds to 61 individual frequencies. For each solution, the complete measurement time is near 68.8 s.

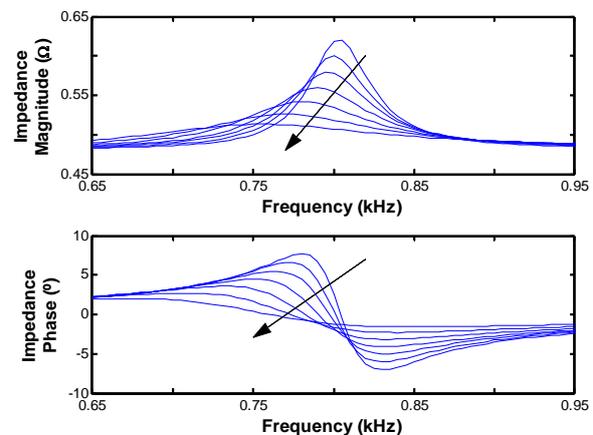


Fig. 4. Measured frequency response of the vibrating-wire viscosity sensor for seven concentrations of glycerol content in a glycerol/water solution. The arrows indicate increasing glycerol content and increasing viscosity.

IV. OPTIMIZATION

The objective of the optimization procedure is to determine the best strategy to decide which frequencies to measure, based on the results of the previously measured frequencies. By minimizing the number of measured frequency points, the total measurement time can be reduced and, consequently, the influence of external parameters (e.g., temperature and pressure) can be minimized.

The study presented in this manuscript is based on post-processing the measured results presented in Fig. 4. The first strategy considers acquiring a set of equally spaced frequencies in the 650 Hz to 950 Hz range. The reasoning is that as more frequency points are included in the estimation of the vibrating-wire equivalent circuit, the estimation of the circuit parameters, of the three characteristic frequencies and of the viscosity all should improve. The results for the seven liquids are shown in Fig. 5.

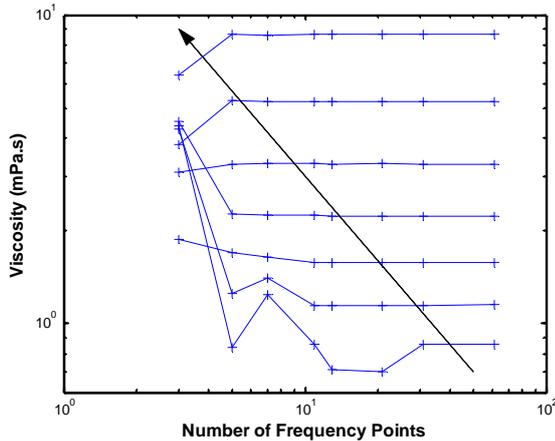


Fig. 5. Estimated liquid viscosity for the seven liquids as a function of the number of processed frequency points. The arrow indicates increasing glycerol content.

The results in Fig. 5 show that the estimated viscosity only stabilizes for a number of frequencies above 30. Although this is a 50% improvement when compared with the acquisition and processing of the 61 frequencies, further improvements can be obtained if the system can dynamically determine which frequencies to measure. Fig. 6 shows the evolution of the estimated 3 characteristic frequencies for the liquid with the lowest viscosity. Notice how the values stabilize for 30 or more frequency points.

As seen, in Fig. 4, for this liquid the resonance frequency (around 800 Hz) is nearly centered with the measurement frequency range. For the liquid with the highest viscosity the resonance frequency is near 750 Hz which is closer to the lower frequency bound.

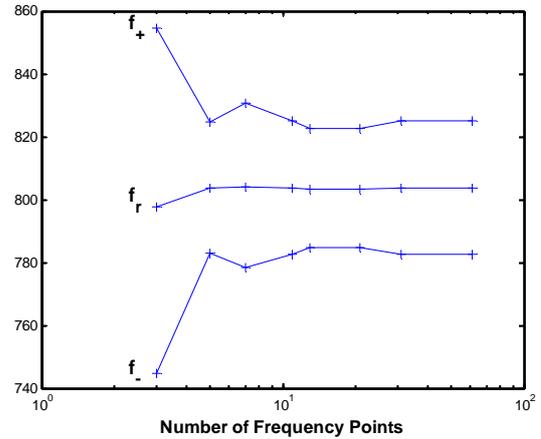


Fig. 6. Estimated evolution of the 3 characteristic frequencies for the liquid with lowest viscosity (i.e., pure water) as a function of the number of processed frequency points.

One possibility to reduce the number of frequency points is to start with just three frequency points near the center of the frequency range and then add neighbors at frequencies close to the highest sensor impedance magnitude. The results obtained with this method are shown in Fig. 7.

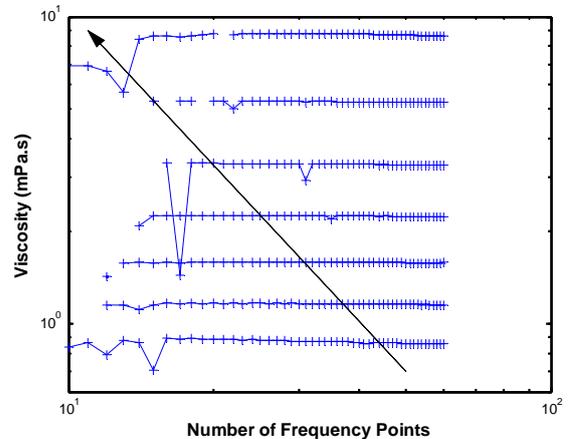


Fig. 7. Estimated liquid viscosity for the seven liquids as a function of the number of processed frequency points which are dynamically selected depending on the region with highest impedance magnitude. The arrow indicates increasing glycerol content.

The gaps in the viscosity values are caused by the fact that the algorithms fail to estimate the viscosity when the sensor frequency response is poorly defined. Also, it can be seen that there is no significant improvement when compared with the results from Fig. 5. The estimated viscosity values only converge for situations with 30 or more frequency points. This occurs due to the fact that, initially the sensor impedance frequency response is

poorly defined with few points and these points are quite close together. As the number of points increases, the impedance response becomes better defined and a correct estimation of the three frequencies is achieved. The failure of this strategy is due to the initially narrow frequency response that restricts the estimation of the three characteristic frequencies. The use of an initially wider range and then narrowing it would, in principle, improve this case.

In order to address the issues detected with the analyzed strategies, an adaptive procedure aimed at estimating and measuring the three characteristic frequencies was developed. The method begins with using three frequency points: the lower frequency bound, the higher frequency bound and the middle value of the frequency range. With these impedance values, the algorithm estimates the viscosity as described above.

Since, one of the by-products of the viscosity estimation algorithm are the estimated values of the three characteristic frequencies. The next step is to use these frequencies in the algorithm. In the final application, this means measuring the vibrating-wire impedance at these three frequencies. In the current simulation stage, the new frequency points are selected from those available and closest to the desired frequencies. Then, using all the available frequency points, the viscosity is again estimated and the estimates of the three characteristic frequencies are refined. This main algorithm cycle continues until the absolute viscosity difference from two iterations is below a preset threshold.

Fig. 8 shows the results obtained with this algorithm for a 1% threshold. The improvements to the previous methods (Fig. 5 and Fig. 7) are clearly visible. The algorithm can converge to very good viscosity estimations using at most 10 frequency points. The dashed lines included in Fig. 8 correspond to the estimations obtained using the full 61 measured frequency points (i.e., the best results from Fig. 5). The maximum error with this new method is 0.9%.

In Fig. 9 the evolution of the estimated three characteristic frequencies is shown for the liquid with lowest viscosity. In this case, the algorithm starts with using 3 frequency points. The initial estimations of the characteristic frequencies add two new frequency points (one for f_+ and one for f_- as the resonance frequency is near the central frequency, it is not added). Therefore the second iteration has 5 frequency points. The estimated characteristic frequencies now suggest different values for f_+ , f_- and even f_r which is now above 800 Hz. This originates three new frequency points for the next iteration. Since the viscosity estimated with 8 frequency points is still quite different from the viscosity estimated in the previous step, a new iteration is required. Since measurements near the characteristic frequencies are already available, the algorithm now picks a new measurement frequency based on the highest frequency

range without measurements. This ninth point does not lead to a significant improvement and therefore the algorithm has converged.

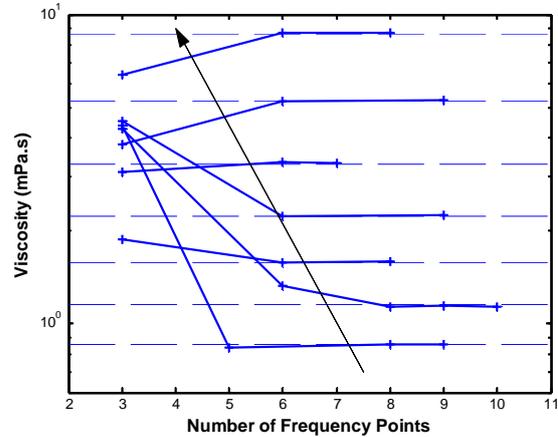


Fig. 8. Estimated liquid viscosity for the seven liquids as a function of the number of processed frequency points which are dynamically selected to include measurement frequencies near the three characteristic frequency values. The arrow indicates increasing glycerol content.

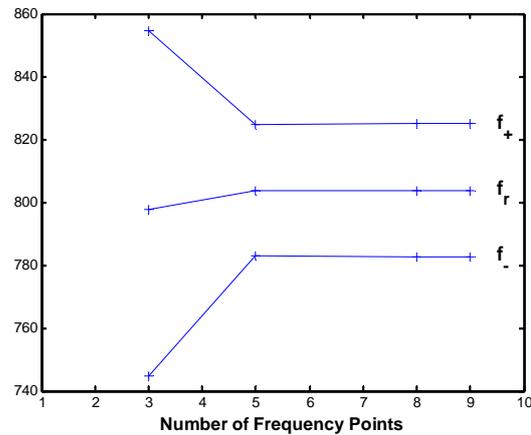


Fig. 9. Estimated evolution of the 3 characteristic frequencies for the liquid with lowest viscosity (i.e., pure water) as a function of the number of processed frequency points which are dynamically selected to include measurement frequencies near the three characteristic frequency values.

V. CONCLUSIONS

This work has presented a method to decrease the measurement time in impedance spectroscopy by carefully selecting which frequencies to measure. The decision is based on the analysis of the previously measured impedance values and on the estimation of the relevant frequencies that define the viscosity. Although the described method is specific to the vibrating-wire viscosity sensor, it can be adapted to other sensors with different responses and different working principles.

ACKNOWLEDGMENTS

Work sponsored by Fundação para a Ciência e Tecnologia (FCT) - Scholarship SFRH/BD/67103/2009 and Project PEst-OE/EEI/LA0008/2013.

REFERENCES

- [1] T. Retsina, S.M.Richardson, W.A.Wakeman, "The theory of a vibrating-rod viscometer", *Applied Scientific Research*, vol.43, No.4, December 1987, pp. 325-346.
- [2] F.J.Caetano, J.M.Fareleira, C.M.Oliveira, W.A.Wakeham, "Validation of a Vibrating-Wire Viscometer: Measurements in the Range of 0.5 to 135 mPa.s", *J. Chem. Eng. Data*, vol.50, No.1, 2005, pp.201-205.
- [3] J.Santos, F.M.Janeiro, P.M.Ramos, "Impedance frequency characterization of a vibrating wire viscosity sensor with mutiharmonic signals", *Measurement*, vol.55, No.1, 2014, pp. 276-287.
- [4] P.M.Ramos, A.C.Serra, "A new sine-fitting algorithm for accurate amplitude and phase measurements in two channel acquisition systems", *Measurement*, vol.41, No.2, February 2008, pp.135-143.
- [5] J.A.Nelder, R.Mead, "A simplex method for function minimization", *The Computer Journal*, vol.7, No 4, 1965, pp.308-313.
- [6] F.M.Janeiro, P.M.Ramos, J.M.Fareleira, J.C.Diogo, D.R.Máximo, F.J.Caetano, "Impedance spectroscopy of a vibrating wire for viscosity measurements", *Proc. IEEE I2MTC*, 2010, pp.1067-1072.
- [7] J.Santos, F.M.Janeiro, P.M.Ramos, "Embedded viscosity measurement system using a vibrating-wire sensor", *Proc IEEE I2MTC*, 2014, pp.824-828.
- [8] J.Santos, F.M.Janeiro, P.M.Ramos, "Impedance frequency response measurements with multiharmonic stimulus and estimation algorithms in embedded systems", *Measurement*, vol.48, No.1, February 2014, pp.173-182.