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Impedance frequency characterization of a vibrating wire viscosity sensor with multiharmonic signals

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ABSTRACT

This paper presents a method to estimate the impedance frequency response of a vibrating wire viscosity sensor. The method is based on the application of a multiharmonic signal to the measurement circuit, which includes the sensor. The signal is composed by the harmonics that correspond to the frequencies at which the sensor's impedance is to be estimated. The impedance is determined using least-squares (LS) multiharmonic fitting algorithms to obtain the amplitudes and phases of the harmonics of the impedance current and voltage. The stimulus generation, measurement and estimation procedure is performed by a dedicated developed measurement system. It includes a digital signal processor (DSP) to perform all the calculations, control the programmable gain instrumentation amplifiers (PGIAs) and communicate with the analog-to-digital converters (ADCs). The PGIAs and ADCs, respectively, amplify and acquire the signals across the sensor and a reference impedance which is used to limit and sample the current flowing through the wire of the sensor. An auxiliary processor connected to a digital-to-analog converter manages the stimulus generation. The system is connected by USB to a personal computer (PC) where the measurement results can be stored, interpreted and further processed.

1. Introduction

Viscosity measurements play a key role in several scientific and industrial fields as there is a significant variety of fluids with an extensive range of viscosity values with great economic importance [1]. Also, for many industrial processes, the speed at which the viscosity measurement can be performed is critical. In medicine, studies have shown that increases in the viscosity of blood and plasma can constitute a risk factor for certain vascular diseases [2]. The treatment of such diseases requires the control of blood fluidity, which is achieved by monitoring its viscosity. In the petroleum industry [3], reservoir fluid properties, including viscosity, are important for the exploration process where prior knowledge of the behaviour of fluids under a wide range of pressure and temperature conditions is required.

There are several methods to measure the viscosity of fluids. For example, capillary viscometers [4] operate based on the Hagen–Poiseuille equation of fluid dynamics. The viscosity is obtained from the measurement of the flow rate produced by a pressure difference along a tube of known diameter. The rolling ball viscometer is based on the falling body method [5], where Stokes' law is used to obtain the fluid's viscosity from the free fall time of an object. In this method, a sphere or cylinder falls, due to gravity, through the fluid of interest. The vibrating wire viscometer's [6,7] operating principle is based on the use of a metallic wire, of known radius and length, which is

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clamped at both ends. The wire is subject to an externally applied transverse magnetic field and immersed in the fluid whose viscosity is to be estimated. When an alternating electrical current is injected in the wire, the interaction between the current and the magnetic field causes periodic oscillations in the wire which depend on the viscosity of the fluid. Using a set of equations, based on the physical behaviour of the sensor, the fluid viscosity can be derived.

The typical measurement procedure, for a vibrating wire viscometer, is to perform a single-tone frequency sweep around the resonance frequency of the sensor to obtain its impedance frequency response [7]. This is the most popular method used in impedance spectroscopy (IS) techniques [8,9]. However, this measurement method can be time consuming, depending on the throughput capability of the measurement system, the number of points in the frequency sweep and the measurement time for each frequency value. For this reason, several studies have explored alternative methods to obtain the impedance frequency response of a given system by simultaneously collecting data on the entire range of excitation frequencies [10]. The objective of this work is to obtain the impedance frequency response of the sensor in a single acquisition/measurement by using a multiharmonic (MH) signal whose harmonics correspond to the frequencies at which the impedance response of the sensor is to be analysed. Least-Squares (LS) multiharmonic fitting algorithms [11,12] are used to estimate the amplitudes and phases of the harmonics and obtain the sensor's impedance. In [12], the efficient implementation of the multiharmonic LS fitting algorithms was described and demonstrated to be suitable for embedded systems with limited memory. There, a basic embedded system used an external generator to supply the MH stimulus. The work presented in this paper is a follow-up to that work in the sense that now a fully embedded system is used without an external generator. The measurement system is also now oriented to the measurement of the impedance frequency response of a specific vibrating wire viscosity sensor with substantially different stimulus, specifically tailored for the viscosity sensor.

In this paper, the traditional measurement approach, referred to as the single-tone sweep method, is compared to the multiharmonic approach, referred to as the MH method. The presented results are an extension of the results and methods presented in [13]. This extended version also includes a more detailed description of the sensor's working principle, the description of the new improved signal generation hardware which increases flexibility and portability of the system, a detailed noise characterization of the measurement system, further details on the signal synthetisation procedure, namely in the description of the used clipping algorithm to reduce the crest factor of the multiharmonic generated signal and the measurement results section has been significantly extended.

The viscosity sensor used during the development of this work is presented and its working principle is described in Section 2. An overview of the measurement system used to obtain the results shown in the paper is presented in Section 3. A description of the multiharmonic signals used to assess the performance of the proposed MH method is included in Section 4. The fundamental algorithms, necessary to estimate the sensor's impedance, are explained in Section 5. In Section 6, an analysis of the behaviour of the sensor, when stimulated by a multiharmonic signal, is presented. The obtained measurements are validated by comparing them to those obtained with a commercial device, and the measurement times of both the single-tone sweep method and the MH method are compared. In the end, the conclusions derived from the completion of this work are presented in Section 7.

2. Vibrating wire viscosity sensor

The vibrating wire viscosity sensor used in this work is shown in Fig. 1(a). The tungsten wire is clamped at both ends of the stainless steel sensor body and has a nominal radius of 40 μm. The magnetic field $\vec{B}$ is generated by permanent magnets placed transversely to the wire inside a cylindrical encapsulation. When an alternating current flows through the wire, it suffers a force, known as Laplace's force, in a direction perpendicular to the plane formed by the current direction and the magnetic field direction, as shown in Fig. 1(b). The two current directions, shown in Fig. 1(b), illustrate the alternating nature of the applied current. The resulting force imposes the movement of the wire, which oscillates with the alternating current.

Since the wire is moving inside a magnetic field, an electromotive force proportional to the wire's velocity is induced at its terminals. This effect is explained by Faraday's law of induction [14]. The velocity of the wire reaches its peak at its resonance frequency, which corresponds to its fundamental mode of oscillation, and it decreases its value as the signal's frequency shifts away from the resonance frequency. Since the wire's velocity is proportional to its impedance [14], the resonance behaviour of the wire's velocity can be obtained by measuring the current flowing through the wire and the voltage across it. It has been shown [15] that the viscosity of the liquid in which the sensor is immersed can be obtained from the resonance curve of the wire's velocity, and consequently from the impedance response of the sensor. The half-power frequency points of the resonance curve are used to solve a set of equations from which results the viscosity of the liquid [7]. The frequency range of interest when analysing the sensor resonance is in the order of hundreds of Hertz, going from 500 Hz to 2 kHz at most. Fig. 2 presents an example of the sensor's impedance magnitude and phase for a distilled water sample obtained with the HIOKI 3522-50 LCR HiTESTER impedance measurement device at ambient temperature and atmospheric pressure. The impedance amplitude is near 0.5 Ω with a resonance at about 800 Hz.

3. Measurement system

The measurement system used in this work (Fig. 3) is an upgrade from the previously developed system described in [16]. Programmable gain instrumentation amplifiers (PGIAs) and analog-to-digital converters (ADCs) are used