Evaluating the Robustness of an Algorithm Determining Key Parameters of Resonant Sensors

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Abstract

Resonating sensors are commonly used for various measurement tasks, e.g., as microbalances as well as for viscosity and density measurements of viscoelastic media. The monitored parameters usually are the resonance frequency and the quality ($Q$) factor of the mechanical resonance which is measured electrically. The measurement is affected by parasitic effects induced by the sensor design but also by the measurement setup. Accurate calculation of resonance parameters from measured sensor data then is one of the most crucial points affecting measurement precision of such sensor systems. In this contribution we demonstrate the performance of a recently proposed algorithm used to accurately determine resonance frequency and $Q$–factor from sensor data that is significantly disturbed by parasitic sensor effects.

Keywords: estimation, resonant frequency, resonance frequency, $Q$–factor, resonating sensors

1. Introduction

Resonating sensors are commonly used for various measurement tasks, e.g., as microbalances as well as for viscosity and density measurements of viscoelastic media [1]. Typically the monitored parameters are the resonance frequency and the quality ($Q$) factor of the mechanical resonance. In many cases, these two parameters that can not be measured directly but have to be determined in a post processing step. The achievable accuracies are strongly influenced by the capability of the implemented approach. To achieve accurate measurement results, the calculation of the resonance frequency and the quality factor of a resonant device have to be robust against parasitic influences like changes in permittivity or conductivity of the sample, crosstalk in conductive loops (especially with electromagnetically actuated resonators), influences by the sensor interface of the measuring instrument but also errors induced by improper calibration. In particular for resonant systems with low $Q$-factors (e.g., electromechanical resonators in viscous liquids where $Q$ can be below 100) the measurement precision often suffers from various unwanted spectral components induced by parasitic effects of the resonator [2], or measurement errors. These unwanted influences have to be suppressed or compensated by the measurement setup [3, 4, 5, 6] or by a signal processing step [7, 8].

2. Resonator Model

Usually the resonance of these sensors is measured electrically and thus it is convenient to apply an electrical model to describe the behavior of the resonator. A widely used model is the Butterworth–Van Dyke equivalent circuit used for quartz crystal resonators (QCR) shown in Fig. 1, comprising a series resonant circuit representing the motional behavior accompanied by a $C_0$ in parallel representing the capacitance of the electrodes [2]. The complex
admittance spectrum $Y_R(f)$ of a series resonant RLC circuit is depicted in Fig. 1. In terms of $Q$–factor, resonance frequency $f_r$ and peak admittance $Y_{\text{max}}$ it is given by

$$Y_R(f) = \frac{Y_{\text{max}}}{1 + jQ\left(\frac{f}{f_r} - \frac{f_r}{f}\right)}.$$  

(1)

Including the effect of the sensor electrode capacitance the overall admittance is $Y(f) = Y_R(f) + j2\pi fC_0$.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig1.pdf}
\caption{Left: Butterworth–Van Dyke model of a quartz crystal resonator. Center: Bode plot and, Right: Locus plot of the motional admittance of such a resonator.}
\end{figure}

The investigated algorithm [8] decomposes the recorded spectral data $Y(f)$ of a resonator into a spectrum of a second order resonant system $Y_R(f)$ (which is the motional admittance, i.e. that of the $R_1$-$C_1$-$L_1$–branch in the Butterworth–Van Dyke model) and an unknown spectral contribution from parallel elements (background spectrum $Y_B(f)$)

$$Y(f) = Y_R(f) + Y_B(f)$$  

(2)

This background spectrum $Y_B(f)$ is modeled as a polynomial function of second order of $f$ and therefore comprises the parallel capacitance of the resonator as well as spurious conductances and contributions from the sensor interface (e.g., [9]).

3. Measurement Results

To verify the suitability of the proposed algorithm for post processing resonance data with severe distortions, we designed a simple experiment. A commercial 1.8432MHz QCR was fully immersed into 3 ml of DI–water and a grain of salt ($\approx 1$ mg NaCl) was put into the sample volume in order to obtain a large change in conductivity with a minimum effect on density and viscosity. While the salt is dissolved in the water the impedance spectrum of the QCR was recorded repetitively (90 spectra in $\approx 15$ minutes) using an Agilent 4294A impedance analyzer. Each sweep (one spectrum) comprises 401 data points captured equally spaced in a span of 40 kHz around the resonance frequency of the QCR and took approximately 11 seconds followed by a pause of 1 s. The rise of conductivity causes the resonance curves to be distorted and shifted as can be clearly seen in Fig. 2.

During each measurement the frequency around the resonance frequency is swept with a constant speed

$$\frac{df}{dt} = \text{const}$$  

(3)

and hence a change of the admittance over time appears as a frequency dependent distortion of the recorded spectrum.

On these data we applied the resonance base estimation (RBE) algorithm proposed in [8]. For the estimation of the background spectrum polynomial this algorithm performs best when using data 'outside' the resonance (off–resonance measurement). Due to the time dependent change of conductivity no separate off–resonance measurements (ORM) were acquired rather the first and last 50 samples of each spectrum were used as ORM for the algorithm.

In Fig. 3 the locus and magnitude plots of all 90 resonances are shown after the background spectrum was subtracted from the recorded data. As can be seen the proposed algorithm [8] is able to remove the drift and distortion of the resonance thoroughly.
Figure 2: Admittance of the resonator while the salt is dissolved in the water. The change in conductivity disturbs the resonances significantly.

Figure 3: Locus plot (left) and magnitude plot (right) of all 90 resonances superimposed after subtracting the estimated background spectrum. Offset and distortion of the resonances have been removed thoroughly.

The resonance frequency and quality factors as computed by the algorithm are shown in Fig. 4. One can see that the disturbance of the resonances has virtually no effect on the estimations of the resonance frequency and the quality factor.

4. Conclusions

It was shown that severe distortions of data obtained from electromechanical resonators can be handled with an appropriate signal processing algorithm for extracting $Q$–factor and resonance frequency [8]. The algorithm is suitable for any resonator that can be described as second order harmonic system.

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Figure 4: Shift of the resonance frequency and $Q$–factor during the experiment (salt crystal was inserted at $t = 0$). The estimates are obtained from the data shown in Fig. 2 by the proposed algorithm.

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