Digital phase-locked loop circuit for driving resonant sensors

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Abstract

Resonant mechanical sensors are powerful tools for measuring, e.g., physical properties of fluids. Suitable systems for real-time monitoring of a sensor’s resonance behavior are, e.g., oscillator circuits and phase-locked-loop circuits. In this contribution, we present a novel specific digital phase-locked-loop circuit with the ability to determine damping, as well as resonance frequency, and providing automatic compensation of spurious parallel capacitances of the sensor. Instead of a phase-frequency detector, the system measures phase and amplitude of the sensor signal with a 16-bit ADC and uses this information to control a numerically-controlled oscillator. Due to the used 4-channel digital synthesizer, the sensor can be excited with up to three frequencies at the same time facilitating enhanced performance in terms of simultaneous measurement of higher order resonances and compensation of spurious capacitances.

Keywords: Digital PLL, compensation of parallel capacitance, resonant sensors

1. Introduction

Resonant piezoelectric sensors are powerful tools for measuring physical properties (e.g., viscosity and density) of fluids. Comparable resonant sensors are also used for other applications. Suitable systems for real-time monitoring of a sensor’s resonance frequency and its loss resistance (associated with the sensor’s Q-factor) are oscillator circuits (e.g., [1]) and phase-locked-loop (PLL) devices (e.g., [2], [3]). Compared to oscillators, PLL systems are superior in terms of adaptability to different resonators and for driving heavily damped resonators. In general, PLL circuits are based on phase-frequency detectors or analog multipliers and voltage controlled oscillators (VCO). The VCO is used to generate the excitation signal of the sensor and a reference signal. The phase of the signal coming back from the sensor is compared with the phase of a reference signal. In resonance, the sensor does not shift the phase of the excitation signal, it equals the phase of reference signal. Out of resonance, the sensor and the reference signal possess different phases. An error signal, which is proportional to the phase difference, is generated. It is used to adjust the voltage and thereby the frequency of the VCO until zero phase difference is reached. Recently, more sophisticated PLL systems for the readout of resonant sensors having the ability to measure amplitude of the signal and to compensate spurious parallel capacitances of the sensor have been proposed (e.g. [2]). In this contribution, we present a further improvement of this concept where a digital phase-locked-loop is used and the entire functionality is incorporated in the core of the system.

2. PLL System

The main components of the system, which is based on the impedance analyzer we presented earlier [4], are a digital signal processor (DSP), a 4-channel direct digital synthesizer (DDS), a 16-bit analog-digital-converter (ADC) and a serial connection to a computer (see Fig. 1). The DSP is responsible for capturing and processing of the ADC data through the ADC.
data, the settings of the DDS channels and the control of the phase-locked loop. The DDS serves as numerically-controlled oscillator with adjustable amplitude and phase. For simultaneous excitation of the sensor at two frequencies, two channels of the DDS are added and fed to the sensor interface. A third channel of the DDS is used to generate a low jitter trigger signal for the ADC.

Phase and Amplitude of the sensor signal are calculated with the Goertzel algorithm [5], an algorithm for efficient computation of the amplitude and the phase of a specific spectral line. For improved signal-to-noise ratio, the signal is oversampled over multiple oscillation periods. Potential amplitude and phase errors due to the leakage effect [5] (which occurs if a captured signal cannot be periodically continued) are avoided by choosing the oversampling factor to be an even multiple of the excitation frequency and the number of samples to be an even multiple of the oversampling factor.

For the measurements of a high impedance 32.768 kHz tuning fork resonator, which is presented exemplary in this work, a sensor interface with one side of the quartz resonator connected to ground (see Fig. 2) was used.

2.1. Digital Compensation

Mechanical quartz crystal resonators can be described by electrical equivalent circuit models, the most common being the Butterworth–van–Dyke model [6]. It consists of a motional branch with a capacitance in parallel (see Fig. 4). The motional branch is a resonant circuit, formed by a series connection of resistor, capacitor and inductance, which corresponds to the mechanical resonance behavior of the quartz. The parallel capacitance comprises the static capacitance of the resonator and parasitic capacitances, e.g. stray or cable capacitances.

To gain information about physical properties of a contacting fluid, the PLL system has to be operated at the series resonance frequency of the motional branch. A spurious parallel capacitance introduces a phase shift to the resonator signal. If not compensated, the PLL circuit adjusts the oscillation frequency until the phase difference is zero again. At this frequency, the motional branch of the sensor is not in resonance, a deviation between the oscillation frequency of the PLL circuit and the series resonance frequency of the sensor occurs. The deviation can be avoided by compensation of the parallel capacitance. For the used sensor interface, the current through the motional branch
can be calculated by \( i_m = (u_{ex} - u_m)/R_m - u_m/Z_p \), were \( u_{ex} \) is the excitation signal, \( u_m \) is the signal captured with the ADC, \( R_m \) the shunt resistor, an \( Z_p \) the complex impedance of the parallel capacitance. The impedance of the spurious capacitance is determined by excitation of the sensor at a frequency off resonance, where the behavior of the quartz is dominated by the parallel capacitance, and measuring the phase and magnitude of the signal.

2.2. Measurement Cycle

The PLL is implemented as an infinite loop over the measurement cycle depicted in Fig. 3. The sensor is excited at two frequencies simultaneously, one being the resonance frequency of the sensor, the other is used for measurement of the parallel capacitance. The sensor signal, which is a superposition of the two signals, is captured by the ADC. Amplitude and phase for both frequencies are computed using the Goertzel algorithm. The parallel capacitance \( C_p \) is determined and the current \( i_m \) through the motional branch is calculated. The voltage and the current though the motional branch are in phase when the motional branch is purely resistive, i.e. the sensor is operated at its series resonance frequency. If the phase difference between the signals exceeds a certain threshold, the frequency of the NCO is adjusted. The loop then restarts with capturing of the sensor signal.

3. Results

The compensation of the parallel capacitance relies on its measurement at \( f_{PC} \), which was confirmed by measuring known capacitors by excitation of the circuit at \( f_{PC} = 4 f_{ex} \) (see Table 1). The deviation between measured and nominal values, which were obtained by measurements with an impedance analyzer, is less than 1.5% for all capacitors. Further sample measurements have been performed on a tuning fork resonator with one side of the resonator connected to ground. The influence of parallel capacitances on the accuracy of the tracked resonance frequency was investigated by purposely adding capacitances in parallel to the sensor and measuring with both, activated and deactivated compensation. The parallel capacitance is increased every 50 cycles. As can be seen in Fig. 5 and Fig. 6, the influence of a parallel capacitance was reasonably compensated. With activated compensation, the circuit locks to the frequency \( f_{0} = 32791.57 \) Hz and remains virtually constant for capacitances smaller than 50 pF (with the impedance analyzer \( f_s = 32791.17 \) Hz was found); the measured change of the frequency was smaller than 0.1 Hz. The determined loss resistance decreases slightly with increasing parallel capacitance, starting from a value of 177.8 k\( \Omega \) (182.2 k\( \Omega \) were measured with the impedance analyzer). Without compensation, the system looses track of the frequency with 10 pF or more being present and the determined resonance frequency changes strongly with only 5 pF being added in parallel to the resonator. The frequency of the loop is stable with frequency variations of less than \( \pm 0.04 \) Hz. Exemplary the frequency distribution of a 32.768 kHz resonator with a 50 pF capacitor in parallel to the resonator is shown (see Fig. 7).
Table 1: Comparison between values of capacitors obtained with an Agilent 4294A impedance analyzer (CIA) and the proposed circuit (CPLL), averaged over multiple measurements. $\sigma_{PLL}$ is the standard deviation of the measurement.

<table>
<thead>
<tr>
<th>$C_{IA}$ (pF)</th>
<th>$C_{PLL}$ (pF)</th>
<th>$\sigma_{PLL}$ (fF)</th>
<th>$\Delta C/C_{IA}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.050</td>
<td>5.045</td>
<td>8.87</td>
<td>0.99</td>
</tr>
<tr>
<td>22.29</td>
<td>22.09</td>
<td>7.31</td>
<td>0.90</td>
</tr>
<tr>
<td>31.30</td>
<td>30.61</td>
<td>6.8</td>
<td>1.35</td>
</tr>
<tr>
<td>484.1</td>
<td>476.9</td>
<td>213</td>
<td>1.49</td>
</tr>
</tbody>
</table>

Fig. 7: Frequency distribution of the PLL measured with a 32.768 kHz resonator with 50pF in parallel averaged over 1000 measurement cycles.

4. Conclusion

We presented the implementation of a digital PLL circuit. Measurements with a high impedance tuning fork resonator were performed. The digital compensation of spurious capacitances was successfully implemented, up to 50 pF in parallel could be added without a significant change of the resonance frequency. The simultaneous excitation of the sensor at two frequencies enables simultaneous measurement of the series resonance frequency of the sensor and its spurious capacitance. If continuous measurement of the spurious capacitances is not needed, the second channel can be used for the excitation a second sensor. The two sensors are then alternately excited and read-out. Due to the flexibility in terms of the sensor interface, the circuit can also be used with high frequency shear-mode resonators.

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References