Abstract

A new high sensitivity temperature-compensated reactance-to-frequency transducer with two quartz crystals oscillating in the switching oscillating circuit is presented. The novelty of this method lies in the switching-mode converter bringing a considerable reduction of the temperature influence of AT-cut crystal (the crystal's x axis is inclined by 35°15' from the z (optic) axis) frequency change in the temperature range between 10−50 °C and in the use of additionally connected sensing reactance in parallel to the shunt capacitances of the two quartzes. The oscillator switching method and parallel switching reactances connected to the quartz crystals do not only compensate crystals' natural temperature characteristics but also any other influences on the crystals such as ageing of both the crystals and other oscillating circuit elements. In addition, the method also improves reactance-to-frequency sensitivity, linearity and reduces the output frequency measurement error. The experimental results show that through high temperature compensation improvement of the quartz crystals' characteristics, this switching method theoretically enables a 100 zF resolution. It converts capacitance in the range 4−8 pF to frequency in the range 2−100 kHz.

Keywords: Dual quartz, Reactance-to-frequency transducer, Temperature compensation.

Introduction

The reactance-to-frequency conversion has become in recent years increasingly popular in a large variety of applications that are designed, for instance, for the measurement of a number of physical measurands, such as mechanical displacement, nanopositioning, eccentric motion, strain sensing [1-3], dielectric properties and density of liquids, small volumes or levels, pressure, flow, etc. Reactance-to-frequency conversion is also used in accelerometers, gyroscopes, and biosensors in medical and chemistry measurements. Typically, in many of them the reactance is first converted to the frequency signal and after that to physical or chemical quantity for analysis. Reactance-to-frequency conversion is also a well-established technique in microscale converters and represents a universal transduction mechanism for the measurements in which reactance changes need to be measured with great precision.

The idea for high resolution reactance-to-frequency transducer uses two quartz crystals with the switching oscillator circuit. Such use improves both reactance-to-frequency sensitivity and the linearity of the characteristics. It also compensates the temperature-frequency characteristics of two quartz crystals, enabling very stable transducer functioning in an extended temperature range. In addition, it also compensates the influence of any other electronic circuit element, and foresees the functioning of the sensitive capacitive element (in case reactances are capacitive) [4-7]. Temperature-wise, the new method makes possible a stable functioning of the small reactance conversion to a frequency signal with a small number of elements in a transducer.

Moreover, when compared also to some other methods [8-20] for the conversion of reactance to frequency, the newly proposed method also proved to have many advantages which include: compensation of quartz self-temperature characteristic, temperature compensation of all elements because of specific oscillator's circuit, compensated influence of the supply voltage on the oscillating circuit output signal, possibility to use of quartz crystals with different cutting angles [21,22], high circuit sensitivity and resolution. Another important factor of great importance is high dynamic stability during temperature changes in the extended operating range. The use of switching circuits in many instances improves electrical circuit characteristics and/or compensates certain influences [23-30].

Dual Quartz Crystal Impedance

The operation of a quartz crystal is frequently explained using the familiar “Equivalent Circuit”, illustrated in Figure 1 (Q1 and

Figure 1: Two quartz crystal equivalent circuits connected in parallel Q2) representing an electrical depiction of the quartz crystal unit [31-32].

In Figure 1, the capacitance labeled \( C_0 \) is a real capacitance, comprising the capacitance between the electrodes and the stray capacitance associated with the mounting structure. It is also known as the “shunt” or “static” capacitance, and represents the crystal in a non-operational, or static, state. The other components represent the crystal in an operational or motional state: \( L, C, \) and \( R \) identify the “motional inductance”, the “motional capacitance”, and the “motional resistance”, respectively. The capacitance \( C_x \) is a parallel load capacitance.

The series resonance frequency \( f_s \) of a single quartz crystal is

\[
f_s = \frac{1}{2\sqrt{LC}}
\]

The complex impedance equation for a single crystal equivalent circuit (Figure 1) is

\[
\tilde{Z}(\Omega) = \frac{1 + j\Omega R}{1 + j\Omega C_0} + \frac{1}{1 + j\Omega C_0}
\]

If we define the frequency ratio \( \Omega = \omega / \omega_0 \), which depends on \( \omega_0 = 1 / \sqrt{L \cdot C} \), and taking into account \( \omega_0 L = \frac{1}{\omega_0 C} \), the impedance equation for a single crystal unit is [31]

\[
\tilde{Z}_q(\Omega) = R \frac{1 + j\Omega R L}{1 + \frac{C_0}{C} (1 - \Omega^2) + j\Omega \frac{R C_0}{C_0 R_0} \Omega}
\]

The impedance equation for two quartz crystals connected in parallel can be written as a complex substitutional equation for both crystals

\[
\tilde{Z}_{qq}(\Omega) = \frac{\tilde{Z}_q(\Omega) \cdot \tilde{Z}_q(\Omega)}{\tilde{Z}_q(\Omega) + \tilde{Z}_q(\Omega)}
\]

As the capacitive load \( C_x \) in series with the crystal or capacitive load in parallel \( C_0 \) is varied, the crystal frequency is pulled (Figure 1). This change of the frequency with load capacitance is expressed by

\[
f_L = f_s \cdot \sqrt{1 + \frac{C}{C_0 + C_L}} \approx f_s \left(1 + \frac{C}{2(C_0 + C_L)}\right)
\]

The frequency pulling range \( \Delta f_L \) (Equation 6) of the element is defined as the change in frequency produced by changing the load capacitance \( C_x \) from one value to another (Figure 1).

\[
f_L = f_s \left(1 + \frac{C}{(C_0 + C_1) + C_L} - \frac{C}{(C_0 + C_2) + C_L}\right)
\]

Since

\[
\omega = \omega_0 \Omega = \frac{1}{2\sqrt{LC}}
\]

the capacitive reactance for the capacitance \( C_x \) can be written as

\[
\frac{1}{j\omega C_x} = \frac{1}{j\omega_0 \Omega C_x}
\]

The total impedance for the two crystals connected in parallel together with the capacitance \( C_x \) connected in parallel is expressed by

\[
Z_{ww}(\Omega) = \frac{Z_s(\Omega) \cdot Z_s(\Omega)}{Z_s(\Omega) + Z_q(\Omega) + \frac{1}{j\omega_0 \Omega C_x}}
\]

Figure 2 shows that when two crystals are connected in parallel, the total complex part of impedance \( Im(Z_{qq}(\Omega)) \) is reduced, while the resonance frequency in relation to the change \( \Omega \) remains at the frequency of 4 MHz approximately the same (\( \Omega = 1.0011 \)) compared to one single crystal. At frequencies of 10 and 19 MHz, the resonance frequency in relation to change \( \Omega \) is higher (at \( \Omega \approx 1.0022 \)) due to additional parasitic capacitance and inductance influences, however, compared to one single crystal it remains more or less the same. Reduced total reactance (due to connection in parallel) results in an easier crystal oscillation and pulling range increase by approximately 200% [6].
Reactance-to-Frequency Transducer Circuit

The proposed reactance-to-frequency transducer is based on an oscillator circuit with two quartz crystals and the switching part together (Figure 3). The novelty of the method described in this article lies in the use of specific symmetrical switching mode oscillator and additionally connected impedances $Z_x$ and $Z_r$ in series with digital switch to the shunt capacitances $C_{o1}$ and $C_{o2}$ of the quartz crystals (Figure 1). The conversion impedance $Z_x$ and reference impedance $Z_{ref}$ are connected to the quartz crystal alternately in parallel and enable significant reduction of temperature influence on frequency change because of symmetry of the circuit. This yields high impedance-to-frequency sensitivity and simultaneous compensation of all other disturbing influences. The switching between the oscillator frequencies $f_{o1}$ and $f_{o2}$ is performed through the switching signal ($Sw$, which can be 1 or 0) and an additional circuit of NAND gate ((Negative-AND) is a logic gate which produces an output which is false only if all its inputs are true) (Figure 3). Inductance $L_r$ is used for the simultaneous fine-tuning of the frequencies $f_{o1}$ and $f_{o2}$ and for the reactance $-j/\omega C_x$ to frequency sensitivity setting (in case the impedance $Z_x$ is capacitive). The signal corresponding to the frequency difference between the frequency $f_{o1}$ and reference frequency $f_r$, or difference between the frequency $f_{o2}$ and reference frequency $f_s$ enters the LP (Low Pass) (which is a pulse wide modulated signal [33-35]). With the help of the reference frequency $f_r$ both signals $f_{o1}$ and $f_{o2}$ (4 MHz) are converted to the range between 2–100 kHz, which is suitable for the further signal processing. At the LP filter (with the response time of 2 µs) output, the triangular signal (with the initial setting frequency of 2 kHz depending on $L_r$ and on $Z_{ref}$) is produced and then converted to a rectangular signal by Schmitt circuit representing the output signal. The output $f_{sw}$ thus represents the temperature and any other influence compensated frequency signal which is synchronously measured with regard to the switching frequency $f_{sw} = 10$ Hz (thus the converter response time is 100 ms). Capacitance $C_s$ serves to suppress the spurious responses to avoid crystal oscillation at higher or lower frequencies [4].

Figure 2: Phase diagrams for a) a single- and b) dual-crystal unit operating at the oscillation frequencies of 4, 10 and 19 MHz

Figure 3: Schematic representation of the switching mode reactance-to-frequency transducer by analog SPST (Single-Pole Single-Throw) switch

A list of abbreviations:

- SPST switch – DG417 (analog switch); Ref. Osc. OCXO – OC18T5S (oven-controlled oscillator);
- LP Filter – Low Pass filter; Schmitt – Schmitt hysteresis circuit; $Sw$ – low frequency oscillator (0.2 – 5 Hz); Counter – programmable counter HM8122; $Z_{conv}$ – conversion impedance; $Z_{ref}$ – reference impedance; $Q_s$ – quartz crystals; $L_r$ – inductance; $C_r$ – capacitor; $C_{s}$ – parallel load changeable capacitor; $Z_{ref}$ – reference load capacitor; $f_{sw}$ – oscillator frequency when SPST switch 1 is on; $f_{o1}$ – oscillator frequency when SPST switch 2 is on; $f_{r}$ – reference frequency; fout – output frequency

When impedances $Z_x$ and $Z_{ref}$ are the same, $f_{o1}$ and $f_{o2}$ remain almost the same at states 1 and 0 of $Sw$ signal $O\overline{O}\overline{O}$ and depend on the quartz crystal resonant frequency $f_{o1}$ quartz crystals’ temperature characteristics $\Delta f_o(T)$, its ageing $\Delta f_o(t)$, the $L_r$ and $Z_r$ and $Z_{ref}$ inequality. $\Delta f(T)$ However, when the impedances $Z_x$ and $Z_{ref}$ are different, the frequencies $f_{o1}$ and $f_{o2}$ depend on the state of $Sw$, the quartz crystal series resonant frequency $f_o$, quartz crystal temperature characteristics $\Delta f_o(T)$, its ageing $\Delta f(t)$, impedances $\Delta f_o(Z_x)$ and $\Delta f_o(Z_{ref})$, as well as $\Delta f_o(Z_x)$ and $\Delta f_o(Z_{ref})$ are compensated because only one temperature quartz characteristics is involved.
The output frequency \( f_{\text{out}} \) depends on the \( Sw \) signal, \( f_s \) and reference frequency \( f_r \) and can be expanded to (for \( Sw = 1 \) and for \( Sw = 0 \) in case \( Z_s = 1/j\omega C_s \) and \( Z_{\text{ref}} = 1/j\omega C_{\text{ref}} \)):

\[
f(Sw) - f_s = f_r + \Delta f'(T) + \Delta f_r(t) + \Delta f_s(L) + \Delta f(C) - (f_s(T) + \Delta f_s(T)) + \Delta f_r(t)
\]

where \( \Delta f' (T) \) in (10) and (11) represents the temperature instability of the reference oscillator signal, and \( \Delta f_{\text{err}} (t) \) the counter error. The joining of \( f_s \) and \( \Delta f_r (C) \) gives (12) which represents \( f_{\text{out}} \). The particularity of this equation lies in the fact that it takes into account the compensation \( C_{0\text{1}} \) and \( C_{0\text{2}} \) (Figure 1) and at the same time linearizes the quartz characteristics due to the \( \Delta C_s \) change (Figure 1) and allows for the sensitivity setting [6,7,22]

\[
f(Sw,k,C)=f + \frac{2\left[\frac{1}{k}(C_{0\text{1}}+C_{0\text{2}}+C_s) - \frac{1}{\omega_0 k L_0}\right]}{2\pi \sqrt{LC}} + \Delta f'(T) + \Delta f_r(t)
\]

where:

- \( k \) - sensitivity value (0.5, 1, 2),
- \( \omega_0 \) - quartz crystal series resonant frequency,
- \( T \) - temperature,
- \( t \) - time,

and \( \omega_0 \) is defined as (13)

\[
\omega_0 = 2\pi f_0.
\]

The joining of \( f_0 \) and \( \Delta f_0 (C_{\text{ref}}) \) gives (14) which represents \( f_{\text{out}} \):

\[
f(Sw,k,C_{\text{ref}})=f + \frac{2\left[\frac{1}{k}(C_{0\text{1}}+C_{0\text{2}}+C_{\text{ref}}) - \frac{1}{\omega_0 k L_0}\right]}{2\pi \sqrt{LC}} + \Delta f'(T) + \Delta f_r(t)
\]

Frequency sensitivity in (12) and (14) can be set with the value \( k \) [6], achieving at the same time instantaneous dependence linearization \( \Delta f_0'(C_{0\text{1}}+C_{0\text{2}}+\Delta C_s) \) [6,21,22,36]. At every switch between \( Sw \) signals, the frequency \( f_{\text{out}} \) is measured synchronously by the counter (Figure 3) [23] and its value is transferred to the LabVIEW software calculating the difference between the two frequencies. The switching between \( Sw \) signals \( Q \) also compensates the auxiliary frequency \( f_r \) and consequently its frequency temperature instability as well. This gives the frequency difference in (15) representing the temperature-compensated value of the output frequency \( f_{\text{out}} \) depending almost uniquely on the difference between \( \Delta C_s \) and \( \Delta C_{\text{ref}} \) change.

\[
\Delta f_{\text{out}} (C_s - C_{\text{ref}}) = \left( \int f(Sw,k,C) - f(T) + \Delta f'(T) \right) + \Delta f_{\text{err}} (t) - \left( \int f(Sw,k,C_{\text{ref}}) - f(T) + \Delta f'(T) \right) + \Delta f_{\text{err}} (t)
\]

This means that \( \Delta f_{\text{out}} (C_s - C_{\text{ref}}) \) is independent of the quartz crystals’ temperature characteristics \( \Delta f_r (T) \), its ageing \( \Delta f_r (t) \), frequency reference changes \( \Delta f_r (T) \), circuit element temperature characteristics influences, but, on the other hand, dependent on the counter error \( \Delta f_{\text{err}} (t) \) in (15) and (16):

\[
\Delta f_{\text{out}} (C_s - C_{\text{ref}}) = \left( \int f(Sw,k,C) - f(T) + \Delta f'(T) \right) + \Delta f_{\text{err}} (t) - \left( \int f(Sw,k,C_{\text{ref}}) - f(T) + \Delta f'(T) \right) + \Delta f_{\text{err}} (t)
\]

The quartz stray capacitances \( C_{0\text{1}} \) and \( C_{0\text{2}} \) include the pin-to-pin input and output capacitances of the oscillator at the crystals’ pins, plus any parasitic capacitances. The typical value of the stray capacitance is between 2.5 pF and 7 pF. This expands the possibility of the use of the frequency stable quartz crystal oscillator by influencing quartz crystal equivalent circuit as a capacitive transducer whose capacitance is in the range 4–8 pF. Stable oscillation and high sensitivity in this range [6,37–41] are thus one of this method’s major advantages.

**Frequency Stability of the Transducer**

The frequency stability of the transducer such as wide operating temperature range, the use of various types of crystals and drive level should be considered because a stable oscillator circuit is of vital importance.

Generally, different temperature frequency curves are represented as cubic parabola with temperature inflection point at 25 °C, depending on the crystal cut angle and the mechanical construction. When using AT-cut crystals (cut angle: 0°) (The plate contains the crystal’s x axis and is inclined by 35°15’ from the z (optic) axis). The frequency-temperature curve is a sine-shaped curve with inflection point at around 25–35 °C) in oscillators, a frequency change in the oscillation up to few Hz of the crystal can be detected in the range between 10–50 °C [4,21]. The crystals used in the experiment (Figure 1) were AT-cut (cut angle: 0°) [8] crystals with the temperature change ±3 ppm in the range 0–50 °C. The data of the electrical quartz crystals’ equivalent elements are \( f_0 = 4 \text{ MHz} \), \( R = 10 \text{ Ohm} \), \( C = 25 \text{ fF} \), \( L = 64 \text{ mH} \), \( C_s = 4 \text{ pF} \), quality \( Q = 80 \text{ k} \). The frequency \( f_0 \) was selected due to a greater oscillation amplitude and a higher Q value for the selected oscillation circuit. The new method (Figure 3) allows the AT-cut crystal temperature characteristics compensation (under 0.02 Hz) in the above temperature range through the switching circuit compensating this characteristics and reducing its influence to a minimum [22,37,42].

Stability of the electronic circuit depends upon the quartz crystal temperature stability and upon the circuit type and element quality (elements of the same values must be of the same quality). Oscillator frequency variation as a function of time is normally considered in short-term temperature stability (second-to-second) and long-term stability over years. The short-term stability of a quartz crystal depends on the actual oscillator
The switching method highly reduces the influence of the short- and long-term stability of the above described converter due to the compensation of the previously mentioned influences of the quartz crystals, the circuit as well as the influence of the difference method using additional reference frequency $f_r$. The reference frequency $f_r$ is OCXO (oven-controlled oscillator) OCXO-OC18T5S [43] (4 MHz) with frequency stability $\pm 0.01$ ppm in temperature range $0^\circ$–$+60^\circ$C following the warm-up time of 2 min. Through $Sw$ signals, the output frequency $f_{out}$ compensates all influences, including those of the reference frequency $f_r$. It is measured by the HM8122 counter (with the accuracy of $\pm 5 \times 10^{-9}$ (through the entire working temperature range from $0^\circ$–$50^\circ$C)) [23]. The counter measurement error is then minimised by the LabVIEW software by subtraction of the two frequencies depending on $Sw$ signals.

**Experimental Results and Discussion**

For this experiment, a prototype electronic circuit was produced guaranteeing physically stable conditions at the capacitance $C_x$, $C_{ref}$ settings and inductance $L_s$ (Figure 3). Stable parasite capacitances and inductances assure repeatability of the experimental results.

Figure 4 shows oscillator’s frequency characteristics $f_o$ with regard to the change of the capacitance $C_x$ and a comparison of the characteristics for various sensitivity values $L_s = (25 \mu H, 50 \mu H, 73 \mu H)$ and for state of $Sw = 1$ ($T = 25^\circ$C). The inductance $I_s = 73 \mu H (2Q - two quartz crystals in parallel)$ records the highest sensitivity, i.e. $24 \text{ kHz/pF}$ in the range 4–8 pF. The results show linearity of 0.1% of the capacitance-frequency characteristics ($2Q - 73 \mu H$) in the range 4–8 pF. The settings of $C_x$ is in steps of 1pF with laser trim capacitors which have tolerance of 0.1% [44]. However, for this particular experiment, the capacitors $C_x$ and inductance $L_s$ with tolerance of 0.1% were specially selected [45–48] by the measurement with HP 4194A impedance/gain phase analyzer.

Figure 5 shows capacitance-frequency characteristics $f_{out}$ ($Sw$) of the converter with regard to the change of the capacitance $C_x$ from 4–8 pF (linear dependency $f_o (C_x)$ for $2Q$ (Figure 4)) and a comparison of the characteristics for a single quartz crystal and two quartz crystals for sensitivity value $L_s = 73 \mu H$ (Figure 4) and for the state of $Sw = 1$. For two quartz crystals, the linearity and sensitivity is better than for a single one in the range 4–8 pF (Figure 4). The linearity with two quartz crystals is improved by $k$ value as shown in (12) and (14). The switching method compensates the temperature influence of the quartz crystal and oscillator circuit elements, and also compensates aging of all oscillator circuit elements as shown in (15) and (16). With the help of the reference frequency $f_r$, both signals $f_{o1}$ and $f_{o2}$ (4 MHz) are converted to the range between 2–100 kHz. If capacitances $C_x$ and $C_{ref}$ (Figure 3) are the same, $f_{o2} = 2$ kHz (for both $Sw$ signals), which means that $f_r$ is by 2 kHz higher than $f_{o1}$ and $f_{o2}$ (initial settings by $f_r$).

Figure 6 shows a typical frequency $f_{out}$ variation occurring when the transducer does not function as a switching mode transducer. The frequency $f_{out}$ in such a case stands for the difference of frequencies $f_{out} (Sw) = (f_r - f_o)$ where the output frequency changes depend on the temperature changes and the changes of the logical $Sw$ signal condition, which can either have the value of 1 or 0. The frequency difference in this experiment...
is set by the reference frequency $f_r$ to approximately 2 kHz as shown in Figure 6. The dotted line marks the frequency increase within the temperature range $T = 25 \, ^\circ C \pm 1 \, ^\circ C$. Otherwise, the variation of the frequency $f_{\text{out}}(t)$ for both conditions of the $Sw$ signal is roughly the same. The switching mode method, on the other hand, was introduced to compensate for the changing of $f_{\text{out}}$ resulting from the temperature changes. The idea behind is to have a capacitive frequency transducer with as high temperature stability and measurement resolution as possible. A comparison to the method using OCXO oscillators reveals that these have a greater stability in the range of 0.01 ppm, however, as they are hermetically closed, open access to the crystal which is required for the suggested method is not possible.

$$f_{\text{out}}(Sw=1) = (f_{o1} - f_r)$$

**Figure 6:** The frequency $f_{\text{out}}(t)$ variation occurring when the transducer does not function as a switching mode transducer

Generally, two oven controller techniques are in common use for the purpose of maintaining a constant temperature on the crystal assembly. They are the switching controller and the proportional controller. The switching controller turns the power off when the maximum temperature is reached and on at the minimum level much like a home thermostat. The proportional oven controller varies the current to the heater or the duty cycle of the heater voltage inversely based upon the oven temperature from the desired level [43]. The OCXO oscillator crystals have a different angle of cutting (SC-cut), a different temperature characteristics and a turnover point at 85 °C.

Figure 7 experimentally shows the switching mode extended dynamic stability – the frequency change of $f_{\text{out}}(Sw)$ (which in this experiment differs by 0.3 Hz) if the converter is influenced by a temperature changing from $T_1 = 24 \, ^\circ C$ to $T_2 = 26 \, ^\circ C$. Figure 7 also demonstrates that the temperature influence on $f_r$ and reference frequency $f_r$ (in the time span between 0–300 s) changes the frequency difference ($f_{o1} - f_r$) and ($f_{o2} - f_r$) representing $f_{\text{out}}$ in the same size class, which is why the $f_r$ and $f_r$ influence is compensated. Similarly, the frequency measurement error influence produced by the frequency counter (Figure 3) is significantly reduced. The dynamic change of both frequencies is approximately the same. The frequency shift between ($f_{o1} - f_r$) and ($f_{o2} - f_r$) depends on the difference between $C_r$ and $C_{\text{ref}}$.

**Figure 7:** Extended temperature dynamic frequency stability for $f_{\text{out}}(Sw=1) = (f_{o1} - f_r)$ and $f_{\text{out}}(Sw=0) = (f_{o2} - f_r)$

**Figure 8:** Short-term frequency stability ($f_{o1} - f$) and ($f_{o2} - f$) occurring when changing the temperature in the range 10–50 °C (measurement time: 1000 s)

Figure 9 illustrates frequency stability for $\Delta f_{\text{out}}(Sw)$ at frequency difference 57 Hz between ($f_{o1} - f_r$) and ($f_{o2} - f_r$) during the temperature change (Figure 8) in the range 10–50 °C determined by the fixed $C_r$ and $C_{\text{ref}}$ once both frequencies are deducted ($f_{o1} - (f_r + \Delta f_r))$ and ($f_{o2} - (f_r + \Delta f_r)$). Deduction of both frequencies in relation to Sw signals is performed by LabVIEW software. In addition, Figure 9 also illustrates the temperature compensation of the quartz crystal natural temperature characteristics. The comparison of results in Figure 8 and Figure 9 shows that the dynamic temperature influence (Figure 8) on the frequency change ($f_{o1} - f_r$) and ($f_{o2} - f_r$) in relation to Sw signal is approximately the same and well dynamically compensated at
the output of the transducer as illustrated by Figure 9. The latter also shows high frequency dynamic stability (Figure 9) (C) in the range ±0.002 Hz, in which the environment temperature does not change so quickly anymore (Figure 8). If the change of the output frequency sensitivity $f_{out} = 24 \text{kHz/pF}$ (Figure 5) (2Q-73 µH) is in the temperature range between 10–50 °C and the supply voltage stability is 5 V ±0.01 V, the frequency reference $f_r$ stability 0.01 ppm, then frequency stability at the output $f_{out} = ±0.002 \text{Hz}$, which gives the converter resolution ±100 zF.

Figure 9: Output frequency dynamic error $\Delta f_{out} = (f_{o1} - (f_{r} + \Delta f_r)) - (f_{o2} - (f_{r} + \Delta f_r))$ during the change of temperature from 10 °C to 50 °C and back to 10 °C (measurement time: 1000 s)

Experimental circuit (Figure 10) is divided into two parts, where the left part is a switching section for $C_x$, $C_{ref}$ and $L_s$ settings by dip switches. This design was used to achieve as stable parasitic capacitances and inductances in the circuits as possible. The right part is intended for the oscillator switch time settings and an appropriate switching logic. Temperature measurements were performed near both crystals in the middle of the experimental circuit to detect short-term temperature changes. Figure 10 (right side) also shows additional oscillator, the trimmer for the switch time settings, and the connection part to the computer. Every single time, the oscillator’s positive front triggers the measurement of the counter frequency. In this way, the frequency counter works synchronously with the $Sw$ signal. The counter measures the frequency $f_{out}$ one or more times at the $Sw$ logical conditions 1 or 0. In addition, LabView software driver also makes possible within one $Sw$ condition a statistical evaluation of a number of performed consecutive measurements. The left side (Figure 10), on the other hand, contains a room temperature measuring device measuring the temperature in the close vicinity of the quartz crystals and the experimental circuit. Its measuring probe is actually situated in the centre of the circuit. This position is particularly important for the measurement of the dynamical stability of switching mode reactance-to-frequency transducer during the temperature shocks produced by a hairdryer or uncontrolled temperature changing of the experimental circuit.

For this experiment, reactance-to-frequency converter was experimentally produced in the SMD technology on Al$_2$O$_3$ ceramics (Figure 10). At the front side of the housing, the converter has the pins for $C_x$, $C_{ref}$ ($Z_x$, $Z_{ref}$) and at the back side of the housing, it has pins for supply voltage 5V, $Sw$ signal and output frequency $f_{out}$. Capacitances $C_x$ and $C_{ref}$ can be directly connected to the pins as shown in the final design of the converter. From the practical point of view, parasitic capacitances otherwise added by the cables are reduced. For specific industrial purposes, capacitance $C_{ref}$ can also be placed inside the housing. The main advantage of such a construction is that it allows the connection of the capacitance sensitive elements to these pins without any additional wires with additional parasitic capacitances. Connections made in this way introduce minimal parasitic capacitances, and even these are reduced to minimum.

Conclusion

The experimental results show that the switching method excellently compensates quartz crystal non-linear frequency-
temperature characteristics, its ageing and oscillator circuit elements, the influence of the supply voltage on the oscillating circuit, as well as the reference frequency \( f_r \) temperature instability and reduces counter error. The great advantage of the proposed method is that it resolves the issue of high sensitivity, linearity and at the same time the temperature compensation of the crystal characteristics and those of other elements, as well as the frequency stability after temperature compensation. The experimental results shown in the article relate to a significantly wider frequency range (2-100 kHz) with zeptoFarad resolution than is usually covered by practical measurements. The reference frequency \( f_r \) instability and the frequency counter measurement error is also greatly reduced.

The results clearly show that the oscillator switching method for high-precision reactance-to-frequency transducing opens up new possibilities through the self-temperature compensation of the main oscillating element and other disturbing influences. This makes this switching method a very interesting tool for the reactance-to-frequency converter especially because of the zeptoFarad resolution which is highly promising in various fields of physics, chemistry, mechatronics, biosensor technology and in specific high-quality production industries.

References

23. Model HM8122 counter, Hameg Instruments (Germany).


