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Frequency Domain Sensors and Frequency Measurement Techniques

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Abstract. Getting fast and accurate information is of paramount importance for most monitoring, data acquisition, and monitoring systems; there are sensors that transform their input into a frequency domain output, this kind of sensors are known as Frequency Domain Sensors (FDS); when the value of the output frequency is measured in a FDS, the value of the sensor's input (measurand) can be calculated, that is why the frequency measurement in the output of FDS is critical for using such sensors. In this work different kinds of resonant sensors (FDS) are reviewed; also frequency measurement techniques are explored; finally a novel frequency measurement method is proposed and analyzed for resolution improvement in frequency domain sensors.

Introduction

Sensors are used to get information from the environment for monitoring and control where accurate and fast information is required. In such systems, the response and data processing time is critical. A sensor is a transducer that transforms a measurand quantity into another variable (usually electrical) that changes according to the changes in the measurand. In some cases the sensor's output are variations on voltage, current or frequency [1]. Measuring the frequency output value allows the data processing and control systems, to calculate the measurand value changes; unfortunately, frequency measurement is a time consuming task, in general to get more accuracy in measurement requires more time.

The main goal of the present work is to introduce the novel original method of frequency approximation by mediants and to show that our method in practice permits to increase significantly the parameter resolution, as well as to decrease the time of parameter quantification. Such a contribution is of paramount importance for the majority of applications of physical and chemical sensoring.

Frequency domain sensors

Frequency domain sensors (FDS) are a particular case of sensors. They convert a measurand into a frequency domain output. A frequency output signal has some outstanding characteristics like output of quasi-digital signals, high sensitivity, high resolution, wide dynamic range, anti-interference capacity and good stability [2]. There are sensors based on capacitive, inductive or resistive effects, such sensors when are connected on a specific array and they produce a frequency output. Specifically, FDS are built of piezoelectric materials (for example quartz) and they only

need to be connected in a specific circuit, to generate a stable and continuous frequency output. In Fig. 1 A, an FDS is connected in a resonant circuit configuration, the output is shown in Fig 1 B.

The FDS have a broad range of applications, when a high precision between the measurand to frequency conversion is required. There are three construction techniques for FDS, namely based on quartz crystal microbalances (QCM), surface acoustic wave (SAW) devices and microcantilevers (MCL).

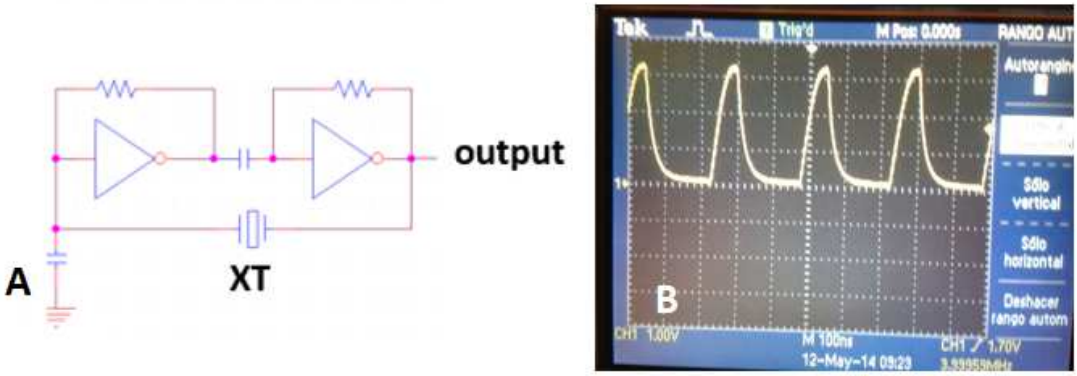

Fig. 1. Resonant circuit for piezoelectric elements (A), signal of a 4 MHz quartz crystal (B)

Quartz crystal microbalances (QCM).

A QCM is an ultra-sensitive weighing device that utilizes the mechanical resonance of piezoelectric single crystalline quartz [3]. A QCM works under the piezoelectric effect, where a piezoelectric element has a change on its electrical response when it is exposed to a change on the pressure applied on its surface (Fig. 2).

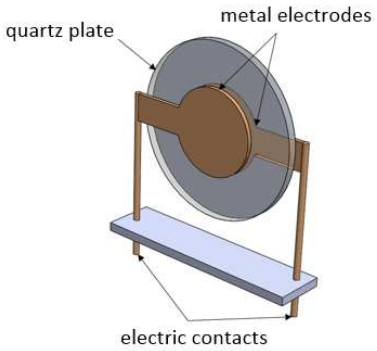

Fig. 2. In a QCM when the quartz crystal plate experiments a change on the pressure applied on its quartz plate, a frequency shift in the QCM is generated

The typical frequency response of QCM devices is from kHz to a few MHz. QCM's are used in health care systems for detecting chemical compounds of interest, some examples are the electric nose systems for detecting desfluranate, servoflurane and isoflurane anesthetics [3]. In other cases, using QCM's for detection of acetone in human exhaled breath allows the diagnosis of diabetes [4], [5]. Also QCM have been used as contamination monitors in spacecraft to measure film deposition on sensitive surfaces such as optical mirrors, thermal radiators, and solar arrays. Recently QCM have been used in a cryogenically cooled infrared space telescope and in the seeker of a missile or measuring optical contamination from outgassing materials [6], for properly adequate measurement of contamination on spacecraft surfaces, a standard has been already proposed [7]. For detecting dibutyl phthalate sensors based on QCM's have been proposed [8], in such experiments polyaniline nanofibers were deposited on the electrode of a QCM, a coated quartz crystal and a non-coated quartz crystal were mounted on a sealed chamber, and their frequency difference was monitored. When the gas to be analyzed was injected into the testing chamber, the frequency difference change was defined as the response of the sensor. Other reported experiments include zeolite coated QCM's. Frequency shifts and their differential values to time were measured while exposing zeolite coated QCM to single gases, such as NO, SO_2 and H_2O in He at 443 K [9]. Dimethylmethylphosphonate (DMMP) is a simulant structure of the nerve agent sarin. DMMP has been exhaustively investigated using QCM's coated with zeolites. Evaluations using nanosized zeolites ZSM-5 [10], Ag^+-modified ZSM-5 [11], and Cu-ZSM-5 [12], [13] were carried on, the frequency shifts were measured, and sensitivity of 8.8 Hz/ppm was

achieved. Other sensors that work under the same principle as QCM are pressure sensors such as the ones used on flight applications [14].

Surface acoustic wave (SAW) sensors

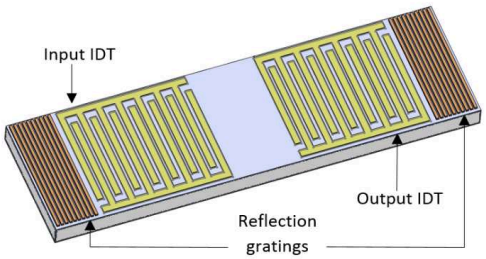

Fig. 3. Surface acoustic wave resonator

Surface Acoustic Wave (SAW) devices work under the inverse piezoelectric effect [15]. SAW is an acoustic wave that propagates on the surface of an elastic material, whose amplitude decays exponentially into substrates. It is common that in SAW devices, the acoustic wave propagation is generated and detected by interdigital transducers (IDT). An IDT is composed of two interlocking comb shaped metallic electrodes patterned on a piezoelectric substrate. When supplying voltage between differently polarized transducer fingers of an input or transmitter IDT, electric field is generated, this causes a wave-like mechanical deformation on the surface of substrate, from input IDT, an acoustic surface wave is transmitted and it travels parallel to the surface toward the output or receiver IDT, where it is converted again into an electrical signal (Fig. 3). Applications for SAW sensors focused on detecting pressure or force changes, which allows to make force sensors and very sensitive weighing devices; typical operating frequencies are in the order of hundreds of hertz. For the automotive industry are used SAW sensors for pressure sensing in engine test cells [16] or as torque sensors [17]; for chemical compound detection the SAW based device is modified with a sensitive material to the analyte to be detected; the use of polymer coated SAW sensor arrays combined with solid phase microextraction was used for quality control using a micronose for differentiation between apple varieties, ripe and unripe pineapple and detection of an off flavor in sugar [18]; a polymer coated surface SAW sensor for detection of buried/hidden explosives [19].

Microcantilevers (MCL)

A piezoelectric microcantilever in resonating mode shifts its resonance frequency due to mass loading [20], [21]. A cantilever is a rectangular microfabricated bar-shaped structure that is longer than its wide and has a thickness (t) that is much smaller than its length (l) or width (w). It is a horizontal structural element supported only at one end on a chip body and the other end is free [22] (Fig. 4). The MCL surfaces serve as sensor surfaces and allow the processes taking place on the surface of the beam to be monitored with very high accuracy, in particular the adsorption of molecules.

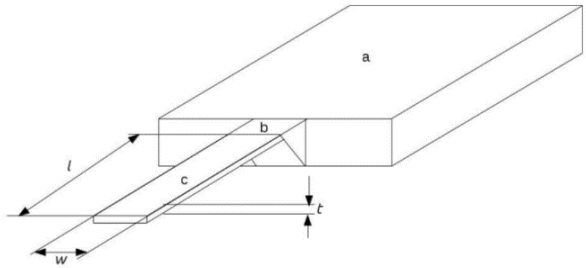

Fig. 4. Schematic diagram of a microcantilever: a) rigid body chip, b) solid cantilever-support structure, c) upper surface of the cantilever, on the opposite side is the lower surface. The geometrical dimensions are indicated.

The formation of molecule layers on the cantilever surface will generate surface stress, eventually resulting in a bending of the MCL, provided the adsorption preferentially occurs on one surface of the MCL. Adsorption is controlled by coating one surface of the cantilever, typically the upper surface, the coating is made of a thin layer of a material that exhibits affinity to molecules in the environment. The sensing surface is called the functionalized surface; the other surface of the cantilever, typically the lower surface, may be left uncoated or be coated with a passivation layer that does not exhibit significant affinity to the molecules in the environment to be detected. Freon gas sensor build with a piezoelectric microcantilever coated with zeolite has been developed, such sensor was able to detect a minimum mass loading of 3.5×10^{-9} g [20]. Very sensitive sensors based on microcantilevers have been developed, carbon-nanotube-based nanomechanical resonator with atomic mass resolution had

a mass sensitivity of 0.40 gold atoms [23], also mass sensing experiments with a resolution of 1×10^{-24} g were reported [24].

All of the reviewed sensors have a frequency domain output, where the measurand (mass, force) is converted into a frequency shift.

Frequency measurement techniques

The objectives of digital measurements for frequency-time parameters in a signal, are to increase accuracy, speed and metrological reliability of measurement of absolute and relative values; also it is desirable to expand functionality, measuring range, possibilities of measuring instruments and automatize completely all procedures of measurement, control, digital processing, parametric adaptation and self-testing, to reduce circuitry, cost, weight, dimensions and power consumption.

The conventional counting was the first frequency measurement method [25]. In this technique a counter register contains the number of cycles counted during one second. It is known the resolution of a conventional counter is bad for low-medium frequencies and adequate for high frequencies only. After the development of microcomputer based instruments the frequency reciprocal counting was used. In this method, the desired measuring time is set using the microcomputer, but the actual measuring time is synchronized to the input signal triggering. To obtain a higher resolution, the clock frequency could be incremented.

In the interpolating reciprocal counting of frequency, the resolution is improved by means of analog interpolation of the fractional clock pulse. They are not just counted the clock pulse edges to determine the time between start and stop trigger, also the fractional clock pulse in the beginning and end of the measurement is captured; the Pendulum timer/counter model CNT-81 combines interpolation techniques with 10 times increased clock frequency.

Methods of dependent count such as measurement of absolute values, measurement of relative values and universal method of dependent count, combine in themselves the advantages of the classical methods as well as the methods ensuring constant relative error in a broad frequency range [26].One of the advantages of MDC is that it practically does not depend on the measurand frequency. The reciprocal counters in their measurement process have a defined start and a stop, and before the next measurement, an additional dead-time between measurements is required for reading and clearing registers, also for doing interpolation measurements. In a time-stamping counter, events such as the input trigger and the clock cycles are continuously counted without a reset. At regular intervals, the momentary contents of the event count register and time count register are transferred to the memory. The read-out of register contents are always synchronized to the input trigger, this makes possible to time stamp the trigger event. Each stored time stamp is interpolated for improved resolution and the contents in the memory are post processed. Other fast processing counter for frequency measurement could contain hundreds or thousands of time-stamped events, this makes possible to use linear regression using the least-squares line fitting to improve accuracy. The Pendulum model CNT-90 uses the linear regression resolution improvement method. It is known that the conventional frequency standard comparison techniques have a high precision but the measuring frequency range is very tight; on the other hand, the frequency measurement techniques based on phase coincidence detection not only have a high precision, but also a wide frequency range [27].

The measurement method based on delay chain technique (DCT) is an improvement of counting based methods, in this measurement method a delay chain utilizes multi-path reference frequency signals. The relationship of these reference frequency signals transforms ±1 count error to ±1 delay time error of delay unit [28]. In the DCT for short time interval measurement, the rising and falling edges of a count gate are synchronous with the start and stop signal of the tested short time interval; when frequency is measured, the count gate is synchronous with the tested frequency signal. The reference frequency signal is not one-path but multi-path. In this method is used a delay chain which consists of the number of paths less one delay units to generate number of paths reference frequency signals, which are delayed uniformly in a reference frequency period. Then the number

of paths reference frequency signals are counted simultaneously under the same count gate. And the average of counts of the number of paths is used as the count of reference frequency.

Many algorithms based on Fast Fourier Transform (FFT) have been proposed for signal analysis [29]. In such methods, the signal's frequency value can be extracted using FFT. Frequency measurement using FFT requires a high computational power and long time for processing data.

Improving resolution in frequency measurement process

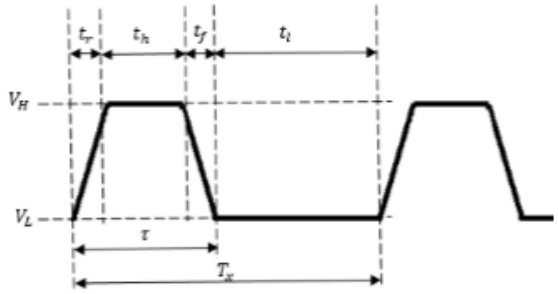

Fig. 5. Signal after conditioning process: time relationships

The frequency measurement principle of rational approximation was proposed by Sergiyenko-Hernandez [30], applications for the FDS in the automotive and aviation industries also have been proposed based on this method [14], [16], [17], and it has shown important advantages over other frequency measurement techniques [25], [26]. Among these improvements are invariance to timing jitter and the fact that uncertainty of the measurement does not depend on the time of measurement.

Before to be able to measure the frequency, the signal source needs to go through a signal conditioning process, where the raw signal is changed to a more convenient form while the original frequency is maintained. In this conditioned signal the time of the pulse width (τ) is less than the 50% of the unknown period time (T_x); this means that the relationship $\tau<t_l$ holds, where t_l is the lower level time. The characteristics of the conditioned signal are shown on Fig. 5.

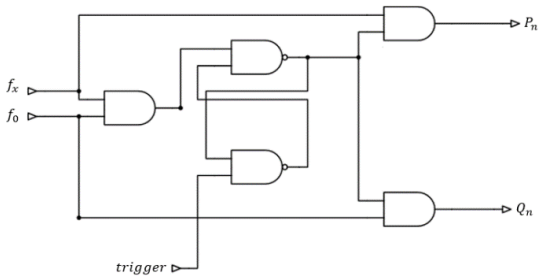

Fig. 6. Coincidence detector circuit

Besides of the restrictions on the time relationships required, it is also necessary to adjust the voltage levels for the signal source used, such voltage levels should be between a the high (V_H) and low level (V_L) needed for the measuring circuit. It is important to note that during the signal conditioning process is necessary to fit the pulse widths in such a way that the time of each pulse width is the same in both signals S_x and S_0. After the signal conditioning process is complete the sensor's signal (S_x) is compared with a reference signal (S_0) for measuring. A sensor's output has an unknown frequency value (f_x), it can be obtained by a comparison with the standard frequency (f_0) of the reference signal. In this process the zero crossings of both signals are detected and in each crossing a narrow pulse (S_x&S_0) is generated, a circuit for this purpose is shown on Fig. 6. In the Fig. 7 are shown S_x, S_0, and the narrow pulse train generated after the comparison of the two signals using an AND-gate. Before the first coincidence, each pulse in each pulse-train is counted for S_x and S_0, this means that the number of pulses is represented by P_n and Q_n also for S_x and S_0 respectively and in the first coincidence is assigned a zero value (Fig. 7).

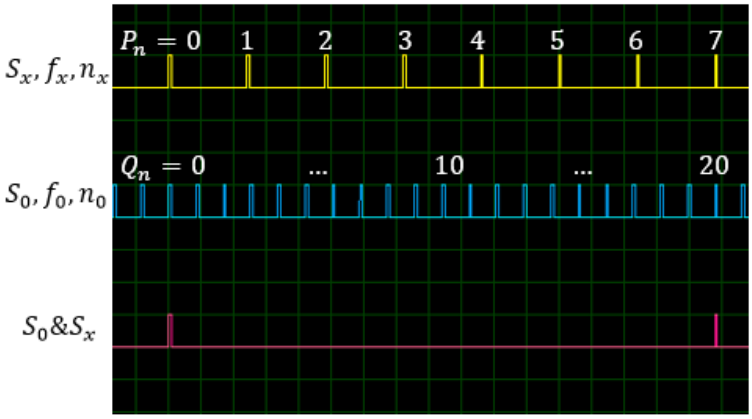

Fig. 7. Test signals S_x and S_0. Their frequency values are: f_x=35 kHz, f_0=100 kHz. Their comparison through an AND-gate ($S_x \& S_0$) is shown.

The example shown in Figure 7 illustrates that the second narrow pulse is generated when the values of the pulse counting are P_n=7 and Q_n=20. The unknown frequency value is obtained through the equation:

$$f_x = f_0 \frac{\sum_m P_n}{\sum_m Q_n} \tag{1}$$

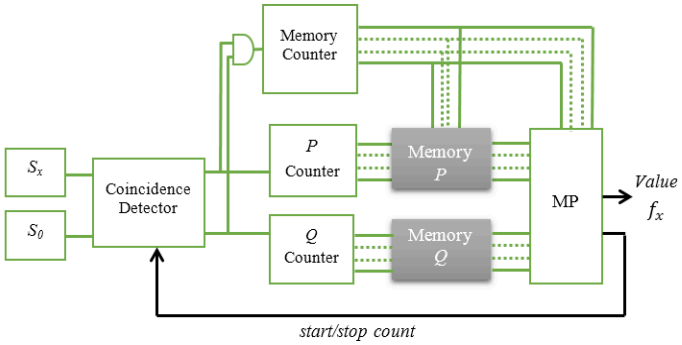

Fig. 8. Block diagram of frequency meter circuit

According to the Fig. 7 if the known frequency is f_0=100 kHz, the value of f_x can be calculated as equal to 35 kHz. For testing purposes a circuit that is able to apply the principle of rational approximation for frequency measurement was designed, the block diagram is shown on Fig. 8.

The designed circuit is based on low-cost components that can handle up-to 10 MHz. The circuit works as follows:

1. The signals S_x and S_0 enter in the coincidence detector, if the start/stop count signal is enabled (trigger); when the first coincidence occurs the coincidence detector allows to go to the counters P and Q the pulses from the input signals. The P counter counts the pulses from S_x, on the other hand the Q counter counts the pulses from S_0.

2. When a coincidence occurs the numbers P and Q are stored on a memory, and the memory counter increments in one position before the next coincidence occurs; this allows to keep on the memory each value of P and Q.

3. A microprocessor unit (MP) is ready to perform the operations required. Some of this operations include to start/stop the counting process through the coincidence detector, to perform the calculation of f_x, to send the information to another processing unit, for example to controllers of position, velocity and altitude, or to clear the memory units and counters.

The designed circuit uses only very cheap and reliable discrete components: it permits its application in hard or aggressive environments. It was simulated on the software Proteus Design Suite Release 8.0 SP1 mostly with the aim to check its performance under conditions and parameters values which was difficult to check on experimental setup. The circuit was designed to be able to obtain fast and accurate frequency measurements with low-cost affordable components (it is well known fact of reliability theory that use of simple components always increase the device security and reliability in general). The coincidence detector is based on a S-R Flip-Flop build with

TTL Logic-Gates, the counters blocks are based on the 4 bit digital counter 74F393, the memory contains the circuits 62256 that are 32,768-word × 8-bit High Speed CMOS Static RAM and quad bus transmitters/receivers 24LS243 circuits that handle the change of the reading/writing operations on the memory circuits; finally the MP is built on Atmel's SAM3X8E ARM Cortex-M3 CPU.

In Proteus also is possible to simulate the circuit under very specific operating conditions. From Fig. 4, it can be observed that after the signal conditioning process $\tau \neq t_h$, where t_h is the real time during the pulse is in the high state. The rising and falling times exist (t_r, t_f) because it lasts some time in reaching the high and low levels of the signal. In addition the MP works with a voltage in high-level of 3.3VDC and it is necessary to couple this high-level with the ones of the other circuits and the input signals. In our simulation the parameters of the input signals were $\tau=t_h+t_r+t_f=1\times10^{-6}$ s=1μs, particularly $t_r=t_f=1\times10^{-12}$ s=1ps. The relative error of the measurement (β) is given by [31]:

$$\beta = \frac{\left| f_x - \frac{n_x}{n_0} \right|}{f_x} \tag{2}$$

Where n_x and n_0 (Fig. 7) are the number of complete periods for S_x and S_0 respectively. After running simulations in the three different frequency values is possible to see the relative error in the frequency measurement process. From the simulation the n_x and n_0 values were obtained; the data simulated for a total time of 0.6 seconds are shown on Fig. 9. Our model shows, that in the first moments, when the measurement starts, the value of β has the highest level for all three of the frequencies examined. But, in fact in a very short time, less than0.1-0.2 seconds or 3499 full periods (T_x) of f_x=35 kHz, the error tends to zero for all examined frequencies, relative error (β) is shown on Fig. 9. This analysis can be extended for different frequency values for other FDS.

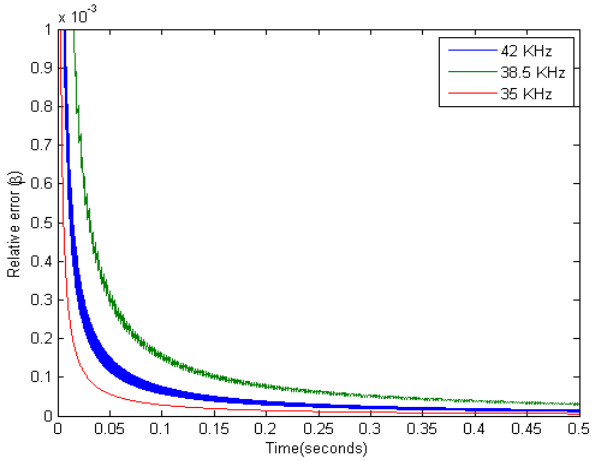

Fig. 9. Relative error in frequency measurement

Frequency measurement evaluation for FDS

A QCM coated with zeolite A layer was used for SO_2 detection [9]; in the reported experiment, the sensor's frequency output changed as consequence of the gas absorbed by zeolite. A frequency counter used Iwatsu SC 7201 was used for measuring the sensor's frequency changes; in that frequency counter the reciprocal counting technique is used for measuring, this means that for a frequency measuring with 9 digits of exactitude are needed 10 seconds [25].

Some representative frequency values were simulated and measured using the rational approximation principle (Fig. 10). From the data can be observed that since the beginning of measurement, the error becomes insignificant in less than 0.1 ms; this means that measuring time can be improved in three orders of magnitude.

From Fig. 9 and Fig 10, can be noted that for higher values of f_x, higher values of f_0 are needed; another characteristic arises: the measurement time needed depends on the number of coincidences, that number of coincidences increment when the value of f_0 is incremented; this leads to know that: when higher frequencies are measured, a shorter time is needed for measuring.

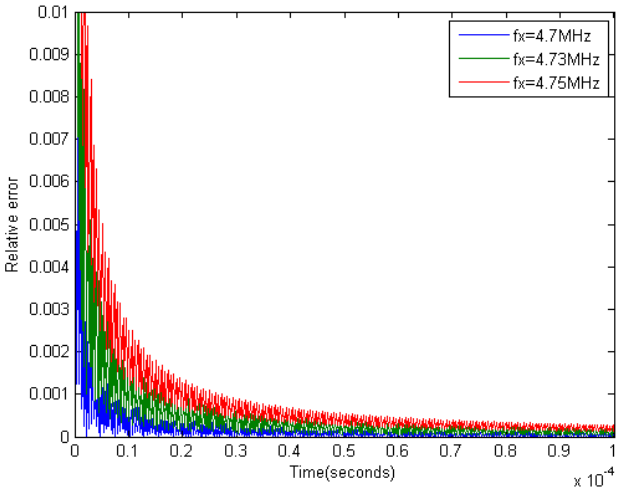

Fig. 10. Relative error in frequency measurement by rational approximations for QCM coated with zeolite A for SO_2 detection. With $\tau=0.03$ ns, and $f_x=10$ MHz.

Conclusions

Frequency domain sensors are highly sensitive devices that convert a measurand into a frequency output, FDS have some outstanding characteristics like output of quasi-digital signals, high sensitivity, high resolution, wide dynamic range, anti-interference capacity and good stability. In order to be able to use all the characteristics of FDS, fast, high-resolution and accurate frequency measurement devices are needed.

In the present work, a new method has been explored for improving resolution in frequency measurements; the frequency measurement using the principle of rational approximations is a tool that allows the use of all the characteristics of the FDS; in fact, such frequency measurement method can be used for improve any frequency measurement, where appropriate transducer is used.

The main advantages of such method were shown: resolution improvement and the significant reduction on measuring time needed for the parameter quantification.

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References

[1] E. Benes, M. Gröschl, W. Burger, and M. Schmid, Sensors based on piezoelectricresonators, Sens. Actuators Phys. 48 (1995) 1-21

[2] L. Huang, H. Yang, Y. Gao, L. Zhao, and J. Liang, Design and Implementation of a Micromechanical Silicon Resonant Accelerometer. Sensors 13 (2013) 15785-15804

[3] H.M. Saraoğlu and B. Kırankabeş, QCM Sensor Frequency Responses and MAC Values Comparison of Different Anesthetics used in Inhalation Anesthesia. 4th European Conference of the International Federation for Medical and Biological Engineering, (2009) 1092-1095

[4] H.M. Saraoğlu and M. Koçan, Determination of Blood Glucose Level-Based Breath Analysis by a Quartz Crystal Microbalance Sensor Array. IEEE Sens. J. 10 (2010). 104-109
[5] B. Du, S. Dong, Y. Wang, S. Guo, L. Cao, W. Zhou, Y. Zuo, and D. Liu, High-resolution frequency measurement method with a wide-frequency range based on a quantized phase step law, IEEE Trans. Ultrason. Ferroelectr. Freq. Control 60 (2013) 2237-2243
[6] O.M. Uy, R.P. Cain, B.G. Carkhuff, R. T. Cusick, and B.E. Wood, Miniature Quartz Crystal Microbalance for Spacecraft and Missile Applications, 20 (1999) 199-211
[7] Standard Practice for QCM Measurement of Spacecraft Molecular Contamination in Space. CERN Document Server, (2004)
[8] Y. Wang, P. Ding, R. Hu, J. Zhang, X. Ma, Z. Luo, and G. Li, A Dibutyl Phthalate Sensor Based on a Nanofiber Polyaniline Coated Quartz Crystal Monitor. Sensors 13 (2013) 3765-3775
[9] I. Sasaki, H. Tsuchiya, M. Nishioka, M. Sadakata, and T. Okubo, Gas sensing with zeolite-coated quartz crystal microbalances-principal component analysis approach. Sens. Actuators B Chem. 86 (2002) 26-33
[10] H. Xie, X. X. Sun, Q. Yang, J. Wang, and Y. Huang, Novel gas sensor based on nano-zeolite films for the nerve agent simulant dimethylmethylphosphonate detection, 7th International Conference on Solid-State and Integrated Circuits Technology, 4 (2004) 1719-1722
[11] H. Xie, Q. Yang, X. Sun, T. Yu, J. Zhou, and Y. Huang, Gas sensors based on nanosized-zeolite films to identify dimethylmethylphosphonate. Sens Mater. 17 (2005) 21-28
[12] W. Yao, Y. Hu, X. Ji, N. Ren, J. Zhou, Y. Huang, and Y. Tang, Absorption and desorption characteristic of zeolites in gas sensor system, 9th International Conference on Solid-State and Integrated-Circuit Technology, (2008) 2589–2592.
[13] X. Ji, W. Yao, J. Peng, N. Ren, J. Zhou, and Y. Huang, Evaluation of Cu-ZSM-5 zeolites as QCM sensor coatings for DMMP detection. Sens. Actuators B Chem. 166 (2013) 50-55
[14] M. Molina, F. Murrieta, O. Yu Sergiyenko, V. Petranovskii, and D. Hernandez-Balbuena, Frequency Measurement by Principle of Rational Approximation for Aerospace Frequency Domain Mechanical Parameter Sensors. J. Aeronaut. Aerosp. Eng. 2 (2013) 47-54
[15] A. Afzal, N. Iqbal, A. Mujahid, and R. Schirhagl, Advanced vapor recognition materials for selective and fast responsive surface acoustic wave sensors: A review. Anal. Chim. Acta 787 (2013) 36-49
[16] O.Y. Sergiyenko, D. Hernandez Balbuena, V.V. Tyrsa, P.L.A. Rosas Mendez, W. Hernandez, J.I. Nieto Hipolito, O. Starostenko, and M. Rivas Lopez, Automotive FDS Resolution Improvement by Using the Principle of Rational Approximation. IEEE Sens. J. 12 (2012) 1112–1121
[17] F.N. Murrieta R, O.Y. Sergiyenko, V.V. Tyrsa, D. Hernández B, and W. Hernandez, Frequency domain automotive sensors: Resolution improvement by novel principle of rational approximation. IEEE International Conference on Industrial Technology, (2010), 1313-1318
[18] N. Barié, M. Bücking, and M. Rapp, A novel electronic nose based on miniaturized SAW sensor arrays coupled with SPME enhanced headspace-analysis and its use for rapid determination of volatile organic compounds in food quality monitoring. Sens. Actuators B Chem. 114 (2006) 482–488
[19] G.K. Kannan, A.T. Nimal, U. Mittal, R.D.S. Yadava, and J.C. Kapoor, Adsorption studies of carbowax coated surface acoustic wave (SAW) sensor for 2,4-dinitro toluene (DNT) vapour detection. Sens. Actuators B Chem. 101 (2004) 328–334
[20] J. Zhou, P. Li, S. Zhang, Y. Long, F. Zhou, Y. Huang, P. Yang, and M. Bao, Zeolite-modified microcantilever gas sensor for indoor air quality control. Sens. Actuators B Chem. 94 (2003) 337–342
[21] C. Ziegler, Cantilever-based biosensors. Anal. Bioanal. Chem. 379 (2004) 946–959
[22] H. Lang, M. Hegner, and C. Gerber, Nanomechanical Cantilever Array Sensors, Springer Handbook of Nanotechnology (2007) 443–460.

[23] K. Jensen, K. Kim, and A. Zettl, An atomic-resolution nanomechanical mass sensor. Nat. Nanotechnol. 3 (2008) 533–537
[24] J. Chaste, A. Eichler, J. Moser, G. Ceballos, R. Rurali, and A. Bachtold, A nanomechanical mass sensor with yoctogram resolution. Nat. Nanotechnol. 7 (2012) 301–304
[25] S. Johansson, New frequency counting principle improves resolution. IEEE International Frequency Control Symposium and Exposition, (2005) 628-635
[26] N.V. Kirianaki, S.Y. Yurish, and N.O. Shpak, Methods of dependent count for frequency measurements. Measurement 29 (2001) 31-50
[27] K.D. Hurst and T.G. Habetler, A comparison of spectrum estimation techniques for sensorless speed detection in induction machines. IEEE Trans. Ind. Appl. 33 (1997) 898-905
[28] C. Wang, W. Zhou, Z. Li, S. Qian, W. Jiang, and C. Wang, A time and frequency measurement method based on delay-chain technique. IEEE International Frequency Control Symposium, (2008) 484-486
[29] S. H. Kia, H. Henao, and G.-A. Capolino, A High-Resolution Frequency Estimation Method for Three-Phase Induction Machine Fault Detection. IEEE Trans. Ind. Electron. 54 (2007) 2305–2314
[30] D. Hernández Balbuena, O. Sergiyenko, V. Tyrsa, L. Burtseva, and M. R. López, Signal frequency measurement by rational approximations. Measurement 42 (2009) 136-144
[31] O. Sergiyenko, D. Hernández Balbuena, V. Tyrsa, P.L.A. Rosas Méndez, M.R. Lopez, W. Hernandez, M. Podrygalo, and A. Gurko, Analysis of jitter influence in fast frequency measurements. Measurement 44 (2011) 1229-1242