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Compact Python-based Control System for Q-factor Measurement of the Quartz Tuning Fork Probe in Scanning Probe Microscopy

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Abstract

The report presents a compact Python-based automatic control system for frequency-response and Q-factor measurement of the piezoelectric quartz tuning fork, widely utilized as the shear-force sensing probe in scanning probe microscopy (SPM). The frequency sweep of the driving signal and the signal readout of the QTF are controlled automatically by a Python-based software, developed in this research. The software provides a GUI front panel for users to choose the number of data points for the frequency sweep, the frequency range and the amplitude of the driving signal. Additionally, the frequency response curve and the Q-factor calculation can be displayed after the end of the frequency sweep. Such an automatic Q-factor measuring system will assist the design of efficient probes for SPM systems.

Keywords: Quartz Tuning Fork, Q-factor, Scanning Probe Microscopy, Near-field Scanning Optical Microscopy, Atomic Force Microscopy

1. Introduction

The quartz tuning forks (QTF) is a high quality factor (Q-factor) mechanical resonator and therefore high sensitivity to the surrounding environment. Attached with a sharp optical fiber or tungsten tip, QTF is widely utilized as probes in near-field scanning optical microscopy (NSOM) (1-2) or atomic force microscopy (AFM) (3-6). The topographical image of a sample's surface can be derived from the scan of the QTF probe across the surface and detection of deviation in amplitude or resonant frequency of the oscillating signals of QTF, caused by the shear force whose effects vary with the probe-sample gap distance. Owing to the piezoelectricity of the quartz, the QTF is a self-sensing probe whose oscillating characteristic can be detected electrically via the electrodes attached on it. As a result, the QTF probe provides more compactness to the shear-force sensing system in comparison with the optical methods (7-8). The amplitude and resonance frequency of QTF vary with the gap distance between the QTF probe and the sample surface owing to the shear force (9). Detecting these deviations with the readout electrical signal of the QTF probe scanning over the sample's surface and the feedback control system of the probe's height can render the topographical image of the sample. The sensitivity and response time of the feedback system is specified by the Q-factor which is the ratio of the resonance frequency to the full width at half maximum (FWHM) of the frequency response of the QTF (9-10). It has been suggested that the frequency resolution of the discrete data of the frequency spectrum should be around one tenth of the frequency bandwidth in order to determine the precise resonance frequency and FWHM (11). The resonance frequency of the QTF is 32.768 kHz and the Q-factor suitable for the QTF probe is around a thousand (12). That means the frequency resolution should be around few hertz and that requires the number of data around a thousand for the frequency scan in the range of 32 kHz-34 kHz. Obviously, such a measurement requires a computer-controlled automatic measuring system and LabVIEW software has been widely used to accomplish the task (13-15). However, the main disadvantage of LabVIEW is its high price which can be up to $5000 per year (16) and hinder low-budget research projects to acquire the license. During the past decade, the popularity of Python has increased significantly in scientific research communities owing to its open-source extensive libraries and frameworks which provide efficient tools for mathematical/ statistical calculation, simulation, and data analysis. Hence, this study proposes an alternative method of determining the Q-factor of QTF by a Python-based automatic control system equipped with a graphic user interface (GUI), similar to the LabVIEW's front panel, at which general users can insert parameters associating with the measurement of the frequency spectrum. After the end of each frequency scan, our system can provide the frequency response curve including the information of the resonance frequency, FWHM, and the Q-factor.

2. Materials and Experiment

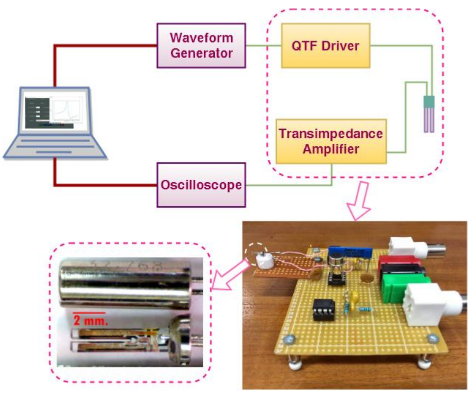

Figure 1 Overview of Python-based measurement system of the QTF frequency response.

Figure 1 shows the system overview for the measurement of QTF frequency response adopted in this research. The signal from the waveform generator (Rigol DG4062) was passed to a QTF driver circuit which is basically an op-amp circuit which attenuates the signal from the generator to get a small signal around tenths to hundreds of millivolts before directly driving the QTF. The QTF used in this research is a tuning fork taken out from the tin cap of a crystal oscillator (Hosonic) with the resonance frequency of 32.768 kHz. The small current in the order of picoamperes which corresponds to the oscillation of the QTF was picked up by a transimpedance amplifier (TIA) circuit. All the driver and TIA circuits are made on the same electronic board with the QTF. Details of the QTF driving unit and current signal readout unit are shown in Figure 2 which consists of three operational amplifier (op-amp) circuits. Part 1 on the left of Figure 2 is the QTF driver which attenuates the voltage signal from the waveform generator by a factor of 10. The driving signal is fed to the QTF. The piezoelectric current generated by the mechanical vibration of the QTF is converted to the voltage by the TIA circuit in Part 2 and then amplified by a signal amplifying circuit in Part 3 of the Figure 3 before measured by the oscilloscope (Rigol DG2010).

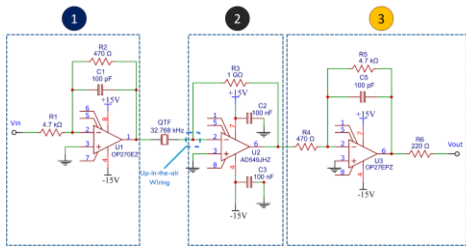

Figure 2 Circuit diagrams of the QTF driving unit and current signal readout unit.

Both driving of the QTF and retrieving the data of the QTF oscillation have been automatically performed by a Python-based control program developed in this research. The algorithm of the system control is explained by the flowcharts displayed in Figure 3 with the description of parameters in Table 1. Shown in Part I of the flowchart is the initial procedure before the start of the frequency scan in which the interfacing the waveform generator and the oscilloscope to the control program via USB ports is performed. The task can be achieved by the open-source Python package PyVISA. In case that there is a problem in communicating with the instruments, the system will notify the users to check the connection of instruments' data cables. Otherwise, the system will retrieve user-specified values of parameters from the control panel, which are the number of data points (*num*), the number of repeated measurement (*numread*), the input driving voltage (*Vin*), the initial (*fi*) and final frequencies (*ff*) of the frequency scan, the time delay for reading signals from the QTF after sending the driving signal (*delay*). There is also a procedure to check that the input driving amplitude should not be more than the maximum limit *Vlim* which is 1 V.

Part II of the flowchart in Figure 3 is the process of driving the QTF with various frequencies from *fi* to *ff*. The value of driving frequency increase (*fstep*) for each data point depends on the number of data points (*num*) and can be simply calculated from

$$fstep = \frac{ff-fi}{num-1} \tag{2.1}$$

At each driving frequency generated by the waveform generator, the frequency (*fout*) and voltage of the output signal (*Vout*) from the QTF are measured and recorded. This subprocess is explained in detail in Figure 4. After driving the QTF, there is a time delay as specified initially from the control panel before commanding the oscilloscope to detect the QTF's output signal. If an error code is found in the data sent from the oscilloscope, the auto-scale feature of the oscilloscope will be enabled and the process of reading signal from the QTF will be repeated. The control system also performed multiple measurements of QTF's signals, corresponding to the input parameter *numread* and then the average values are determined.

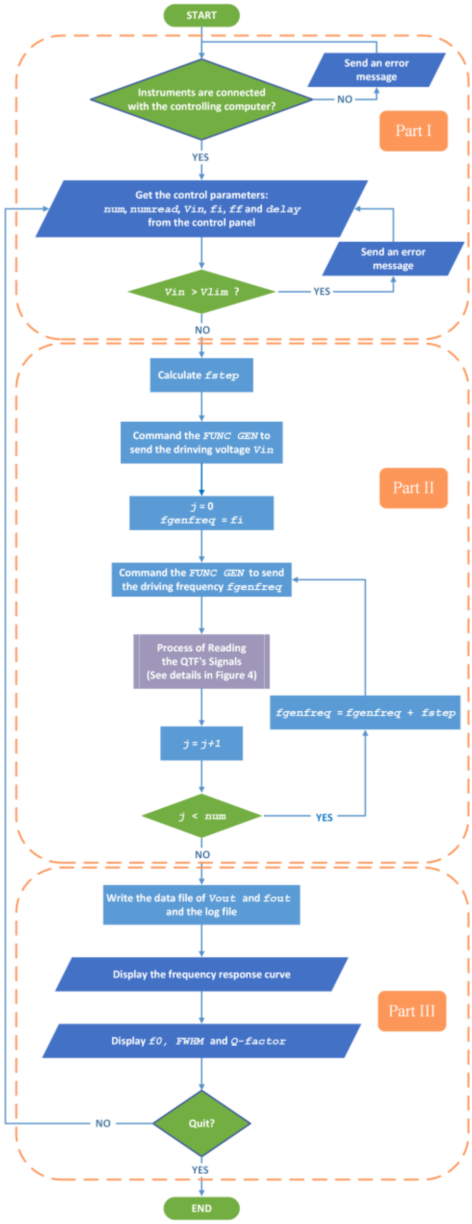

Figure 3 Flowchart of the control system for the QTF's Q-factor measurement.

Table 1 Description of the parameters used in the flowchart

Parameter	Description
num	Number of data points
numread	Number of repeated measurements
Vin	Input voltage
fi, *ff*	Initial frequency and final frequency
delay	Time delay before reading signals from the QTF
Vlim	Maximum limit of driving voltage for the QTF
fstep	Frequency increase for each data points
fgenfreq	Output frequency from the function generator
FUNC GEN	Function generator
OSC	Oscilloscope
Vout	Voltage of the QTF's output signal
fout	Frequency of the QTF's output signal
f0	Resonant frequency
FWHM	Full width at half maximum
Q-factor	Quality factor

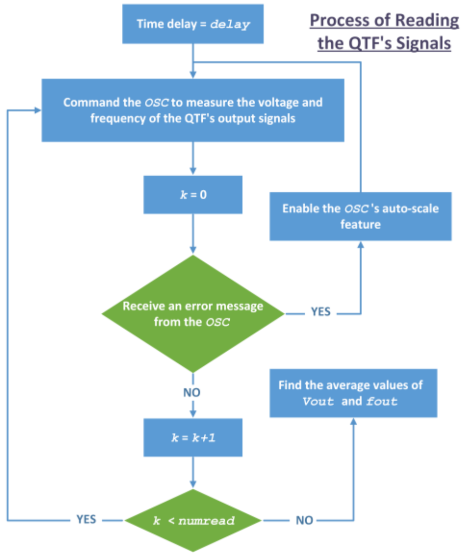

Figure 4 Flowchart of reading the QTF's output signal

The final process when the frequency scan is complete is shown in Part III of the flowchart in Figure 3. The data file of the QTF's oscillating frequency and voltage and the log file storing the parameters used in the measurement of the QTF's frequency response are exported from the control program. The graph window pops up to display the frequency response curve of the QTF with the report of the resonance frequency, the full width at half maximum (*FWHM*), and the Q-factor calculated from the linear interpolation of the data.

The source code can be viewed in this URL on the GitHub platform: https://github.com/tipsudac/QTF/blob/main/PythonBasedAutomaticControlSys.py

3. Results and Discussion

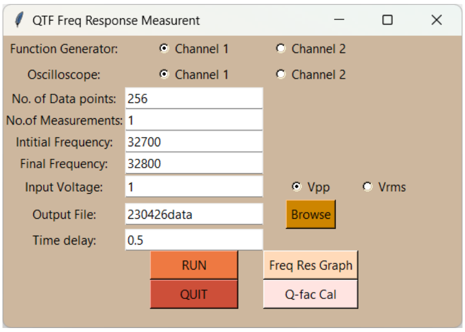

Figure 5 Front panel for general users to customize the frequency-response and Q-factor measurement of QTF.

Figure 5 shows the GUI front panel of the control system for the frequency-response and Q-factor measurement of QTF developed in this research. General users can customize the measurement of QTF frequency spectrum by specifying the number of data points to be collected within the driving frequency span starting from the initial frequency value to the final frequency value with the specified value of amplitude driving voltage. At each driving frequency, retrieving oscillating signal from the QTF will be delayed and repeated as specified by the parameters *Time Delay and No. of Measurements*. Users can also choose to export a data file of driving frequency and QTF's oscillating amplitude and frequency at the end of frequency scan.

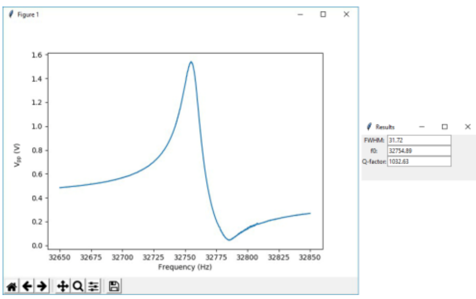

Figure 6 Frequency response curve of the QTF with the information of FWHM and Q-factor displayed automatically after the end of the frequency scan.

Figure 6 displays an example of QTF's frequency response curve rendered by the Python-based control program. The driving peak-to-peak voltage is 500 mV and the frequency scan is in the range of 32650 Hz-32850 Hz with 2^{10} data points or the frequency resolution of 0.2 Hz per step. The measurement of QTF's oscillating signals was repeated 3 times with the time delay of 0.5 second after the driving signal was sent to the QTF. The averaged data of the QTF's frequency response was analyzed. The resonance frequency of 32454.89 Hz, the resonance curve's full width at half maximum (FWHM) of 31.72 Hz, and the Q-factor of 1032.63 were displayed in the information window, besides the graph window of the resonance curve. Such a high Q-factor corresponds with values reported in other literatures (10, 17) and signifies high sensitivity of QTF as a shear-force sensor for SPM.

4. Conclusions

An automatic Q-factor measuring system for QTF probes widely utilized in scanning probe microscopy systems was presented. The Python-based GUI control panel of the system enables users to adjust the parameters of the measurement including the amplitude of driving voltage, the range of frequency scan, and the number of data. The characteristic of QTF's frequency response is analyzed by the control program which returns the resonant frequency, FWHM and the Q-factor. This Python-based Q-factor measuring system will be beneficial to the improvement of QTF probe's sensitivity.

Acknowledgements

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Declaration of conflicting interests

The authors declared that they have no conflicts of interest in the research, authorship, and this article's publication.

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