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ПРИМЕНЕНИЕ ВЫЧИСЛИТЕЛЬНОЙ ТЕХНИКИ В ЭКСПЕРИМЕНТЕ

A NOVEL PC-BASED ADMITTANCE ANALYZER FOR PIEZOELECTRIC VIBRATORS

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To obtain the electromechanical match at resonant frequencies for piezoelectric actuating applications, the impedance or admittance characteristics of a piezoelectric vibrator must be measured by a spectrum analyzer. In this paper, the admittance analyzer has been developed using an integration technique with a GPIB card, a data acquisition card and software LabVIEW tools. Based on the five built-in models of equivalent circuits as the basic evaluating functions in a HP-4194A impedance analyzer, the most suitable model has been identified to demonstrate the electromechanical features of a piezoelectric vibrator. The measured results from the admittance analyzer and actual data from an HP-4194A analyzer are compared to evaluate the performance of the admittance analyzer. The analyzer offers the complete functions of a hardware instrument for measuring admittance based on theory and experiments within the 120 kHz range.

INTRODUCTION

Piezoelectric vibrators, are the key components for many precise motion or ultrasonic systems, and their features have significant effects on the behavior of precision mechatronic devices [1–3]. Normally, in order to study the characteristics of the piezoelectric actuating components and to evaluate the efficiency of the electromechanical conversion, the measured admittance characteristics and the analyzed equivalent circuit must be obtained by hardware instruments.

For example, the HP-4194A impedance analyzer is often used to obtain the magnitude of $|Z|$ and the phase θ in the frequency response of a piezoelectric vibrator. These are standard measurements used to determine basic impedance features and operating conditions near the resonant and anti-resonant frequencies. However, a HP-4194A analyzer is a rather expensive piece of equipment, and the communicating interfaces are complex.

LabVIEW software, a programming tool based on a graphical user interface (GUI) language, has been developed by National Instruments (NI). GUI programming has the following advantages: 1) it is simple for a new user to learn or operate; 2) it is easy to modify; 3) it is capable of rapid re-design without extra hardware investment. The estimated cost of applying the LabVIEW system to control a set of instruments in a lab is much lower than that of a commercial hardware instrument.

For automated measurement systems, there is a new trend to control the experimental facility by using the communication or USB-driven interface [4–6]. Several past issues have adopted GPIB control cards to control experimental instruments, DAQ cards to access the measured signals, and LabVIEW software in programming [7–13].

In this study, two kinds of interface cards, including a GPIB card and a DAQ card, in conjunction with LabVIEW software tools, are integrated into a personal computer using the Windows operating system. Thus, a PC-based admittance analyzer has been constructed. Using the five built-in models of equivalent circuits as the basic evaluating functions in an HP-4194A impedance analyzer, the most suitable model for demonstrating the electromechanical features of the piezoelectric ceramic is identified.

The voltage is inputted into the piezoelectric ceramic and the current is sampled simultaneously. Thus, instantaneous admittance levels corresponding to frequencies are displayed in the front panel of the admittance analyzer and the parameters of the electrical components on the equivalent circuit of the piezoceramic are extracted by arithmetical calculation, without the use of additional instruments.

For the purposes of calibration, an accurate resistor was individually measured in the frequency of 1–120 kHz to assess the compensating parameters in the admittance analyzer. Next, the measured results of the admittance analyzer are compared with those of the

HP-4194A impedance analyzer in the frequency range of 1–120 kHz to verify the measured admittance validation for piezoelectric ceramics.

ELECTROMECHANICAL CHARACTERISTIC AND EQUIVALENT MODELS

For electromechanical coupling of a piezoelectric vibrator, the impedance measurement and analysis have become a standard process. The measured impedances of magnitude $|Z|$ and phase θ relative to frequency response, as illustrated as Fig. 1, represent the fundamental characteristics of energy conversion for a piezoelectric vibrator.

There are five built-in models of equivalent circuits used as the basic evaluating functions in a HP-4194A impedance analyzer, as shown in Fig. 2. These represent the fundamental characteristics of energy conversion for piezoceramic electromechanical coupling. The equations of the magnitude and phase for each model are as follows:

1) A-type model

$$|Y(j\omega)| = \sqrt{\frac{(R-\omega^2 RLC)^2+\omega^2 L^2}{\omega^2 R^2 L^2}} \qquad (1)$$

$$\angle Y(j\omega) = \theta_1 - \theta_2$$

where

$$\theta_1 = \tan^{-1}\left(\frac{\omega L}{R-\omega^2 RLC}\right), \qquad (2)$$

$$\theta_2 = 90°;$$

2) B-type model

$$|Y(j\omega)| = \sqrt{\frac{\omega^4 L^2 C^2 + \omega^2 R^2 C^2}{R^2+\omega^2 L^2}} \qquad (3)$$

$$\angle Y(j\omega) = \theta_1 - \theta_2$$

where

$$\theta_1 = \tan^{-1}\left(\frac{\omega RC}{-\omega^2 LC}\right), \qquad (4)$$

$$\theta_2 = \tan^{-1}\left(\frac{\omega L}{R}\right); \qquad (5)$$

3) C-type model

$$|Y(j\omega)| = \sqrt{\frac{1+\omega^2 R^2 C^2}{(R-\omega^2 RLC)^2+\omega^2 L^2}} \qquad (6)$$

$$\angle Y(j\omega) = \theta_1 - \theta_2$$

where

$$\theta_1 = \tan^{-1}(\omega RC), \qquad (7)$$

$$\theta_2 = \tan^{-1}\left(\frac{\omega L}{R-\omega^2 RLC}\right); \qquad (8)$$

4) D-type model

$$|Y(j\omega)| = \sqrt{\frac{\omega^2 C^2}{(1-\omega^2 LC)^2+\omega^2 R^2 C^2}} \qquad (9)$$

$$\angle Y(j\omega) = \theta_1 - \theta_2$$

where

$$\theta_1 = 90°,$$

$$\theta_2 = \tan^{-1}\left(\frac{\omega RC}{1-\omega^2 LC}\right); \qquad (10)$$

5) E-type model

The admittance Y (or impedance Z) is calculated in s-domain as

$$I = \frac{V}{\frac{1}{sC_0}} + \frac{V}{sL+\frac{1}{sC}+R} = $$
$$= V\left(\frac{s^3 LCC_0 + s^2 RCC_0 + s(C+C_0)}{s^2 LC + sRC + 1}\right) = VY = \frac{V}{Z}. \qquad (11)$$

The rearranged calculation for admittance Y in frequency domain is,

$$Y(j\omega) = \frac{1}{Z(j\omega)} =$$
$$= \frac{-\omega^2 RCC_0 + j(\omega C_0 + \omega C - \omega^3 LCC_0)}{(1-\omega^2 LC) + j\omega RC}. \qquad (12)$$

Since $\omega_0 = \frac{1}{\sqrt{LC}}$, then

$$Y(j\omega) = \frac{-\omega^2\omega_0^2 RCC_0 + j(\omega\omega_0^2 C_0 + \omega\omega_0^2 C - \omega^3 C_0)}{(\omega_0^2-\omega^2) + j\omega\omega_0^2 RC}. \qquad (13)$$

Thus,

$$|Y(j\omega)| = \sqrt{\frac{\omega^6 C_0^2 + \omega^4(\omega_0^4 R^2 C^2 C_0^2 - 2\omega_0^2 CC_0 - 2\omega_0^2 C_0^2) + \omega^2(\omega_0^4 C_0^2 + \omega_0^4 C^2 + 2\omega_0^4 CC_0)}{\omega^4 + \omega^2(\omega_0^4 R^2 C^2 - 2\omega_0^2) + \omega_0^4}} \qquad (14)$$

$$\angle Y(j\omega) = \theta_1 - \theta_2$$

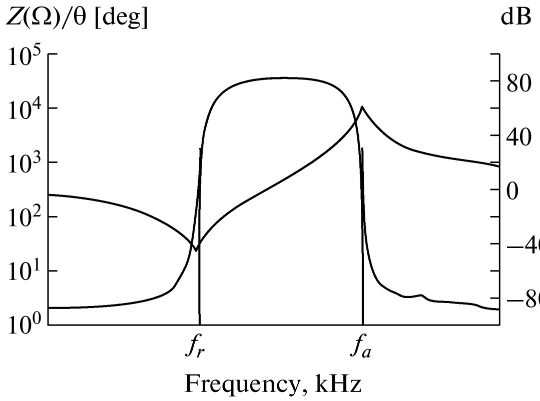

Fig. 1. Plots of impedance magnitude and phase nearby resonant and anti-resonant frequencies for a piezoelectric vibrator.

where

$$\theta_1 = \tan^{-1}\left[\frac{\omega\omega_0^2 C + \omega\omega_0^2 C_0 - \omega^3 C_0}{-\omega^2\omega_0^2 RCC_0}\right], \tag{15}$$

$$\theta_2 = \tan^{-1}\left[\frac{\omega\omega_0^2 RC}{\omega_0^2 - \omega^2}\right]. \tag{16}$$

Substituted and rearranged by $\omega_0^2 = \frac{1}{LC}$ into equations (13)–(16), then

$$|Y(j\omega)| = \sqrt{\frac{\omega^4 R^2 C^2 C_0^2 + (\omega C_0 + \omega C - \omega^3 LCC_0)^2}{(1-\omega^2 LC)^2 + \omega^2 R^2 C^2}} \tag{17}$$

$$\angle Y(j\omega) = \theta_1 - \theta_2 \tag{18}$$

where

$$\theta_1 = \tan^{-1}\left(\frac{\omega C_0 + \omega C - \omega^3 LCC_0}{-\omega^2 RCC_0}\right), \tag{19}$$

$$\theta_2 = \tan^{-1}\left(\frac{\omega RC}{1-\omega^2 LC}\right). \tag{20}$$

The conversion efficiency of a given piezoelectric vibrator may be predicted using the measured parameters of electrical components on the equivalent circuit. The operating frequencies of piezoelectric ceramics are always close to the resonant frequency f_r. The fundamental simulation, design, and measurement for a piezoelectric vibrator are usually based on the equivalent circuit.

INTERFACING CONFIGURATION

In this study, the admittance analyzer consists of LabVIEW programming software, a NI-PCI 6110S DAQ card, a NI-GPIB card and a Windows equipped personal computer. An AFG-310 digital arbitrary function generator was controlled via the NI-GPIB card through the personal computer, which continuously sent voltage of 1 V_{pp} in different frequencies into the piezoelectric ceramic. The input voltage signals and the output current signals were acquired via a PCI-6110S data acquisition card.

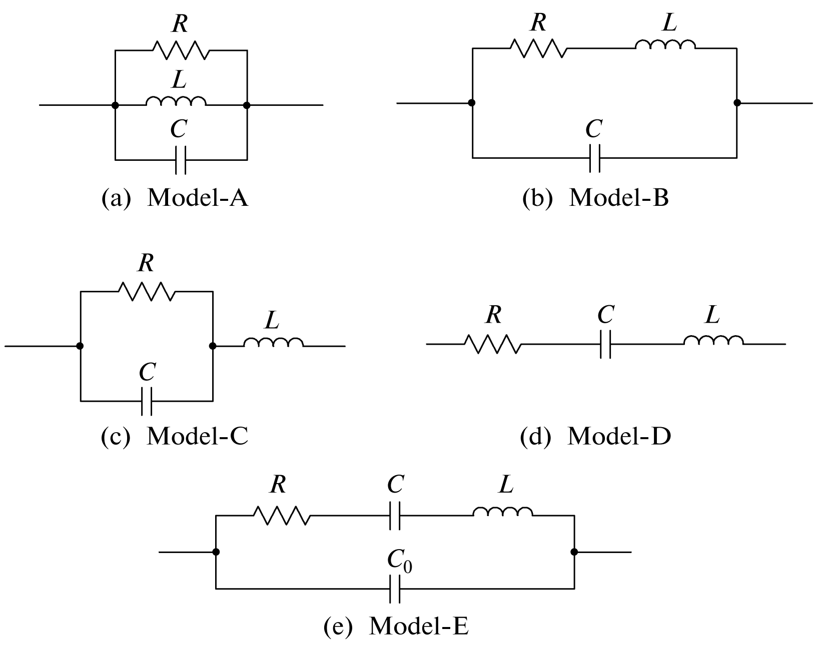

Fig. 2. Five models of equivalent circuits built in a HP-4194A impedance analyzer.

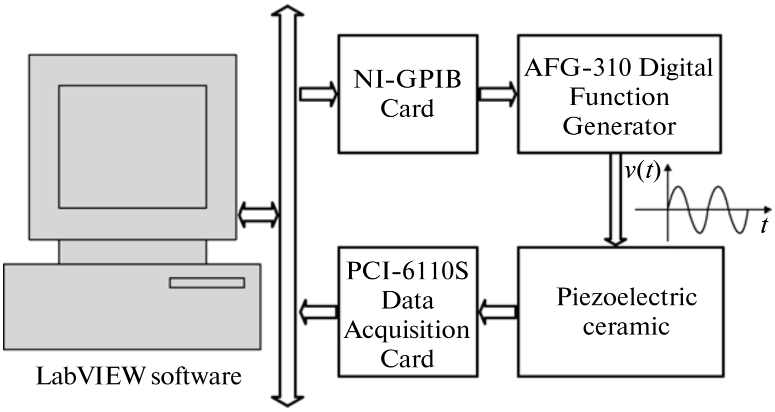

Fig. 3. Schematic diagram of the admittance analyzer.

After the calculation, based upon equations (17)–(20), the magnitude and phase degree of the admittance is obtained. A schematic diagram of the system structure is shown in Fig. 3. A Windows equipped personal computer is the information platform for the admittance analyzer, and NI DAQ cards are easily available on the retail market. The major specifications are listed as follows:

– The sampling rate of 5 MS/s is equivalent to a 1 MHz sampling frequency, roughly. However, according to the Nyquist-frequency criterion, the maximum acceptable measuring range ($2f_b$) is about half of the sampling frequency; that is less than f_b of 500 kHz. However, it is the limitation within 120 kHz of the proposed admittance analyzer in this study.

– It provides 12-bit resolution up to 42 V, with two or four pseudo differential analog inputs. For example, four analog simultaneous inputs, two 16-bit analog outputs, 8 digital I/O lines, two 24-bit counters, and analog triggering are provided. If we want the admittance analyzer to reach a higher performance, an advanced DAQ card with 16-bit resolution may be used.

To obtain the admittance feature, using a spectrum analyzer, the piezoelectric ceramic can be treated as a capacitor. As shown in Fig. 4, the current i flowing throughout the resistor R is directly acquired and the voltage v_0 on the leg of the capacitor should be measured. The flow chart illustrates the algorithm involving instrument communication and control, signal processing, and computations in the admittance analyzer, as shown in Fig. 5.

Additionally, to obtain the parameters of the electrical components on the equivalent circuit as shown in Fig. 2 for the piezoelectric vibrator, the computing procedure in the admittance analyzer follows the steps: (1) obtain the resonant frequency f_r and resistance R by the magnitude and phase plot of the admittance measurement as the initial coefficients; (2) inputting the coefficients into the Levenberg-Marquardt algorithm for curve fitting to obtain the new coefficients C_0, R, L, and C; (3) determine whether the least square set of coefficients properly fits the set of input data points; (4) obtain the final coefficients C_0, R, L and C.

EXPERIMENTIAL RESULTS AND DISCUSSION

A thin-disc piezoelectric vibrator as one of measured samples includes three layers: (1) the membrane, of piezoelectric ceramics; (2) the elastic metal sheet, of nickel alloy; (3) the cover with its diameter d of 19.50 mm silver sol-gel membrane used as an electrode, respectively. The piezoelectric ceramic is adhered to the metal sheet with its diameter D of 31.00 mm. The total thickness T is 0.20 mm and thickness t of the metal sheet is 0.10 mm, with its dimensions as shown in Fig. 6.

Calculation of the parameters of inductance and capacitance at the resonant frequency of 74 kHz based on Table shows that the impedance is about 14.75 Ω. When applying the proposed analyzer to the admittance measurement, the current i flowing throughout the resistor R was directly acquired, and the voltage v_0

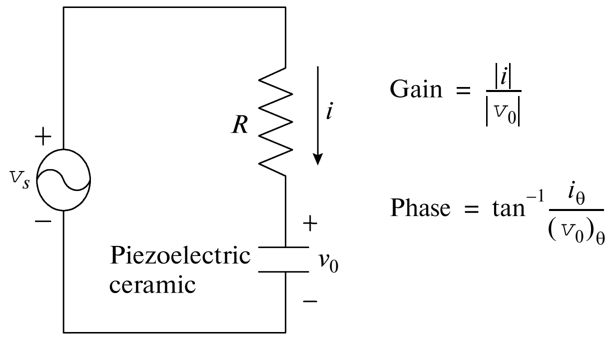

Fig. 4. Measuring concept of admittance for a piezoelectric vibrator.

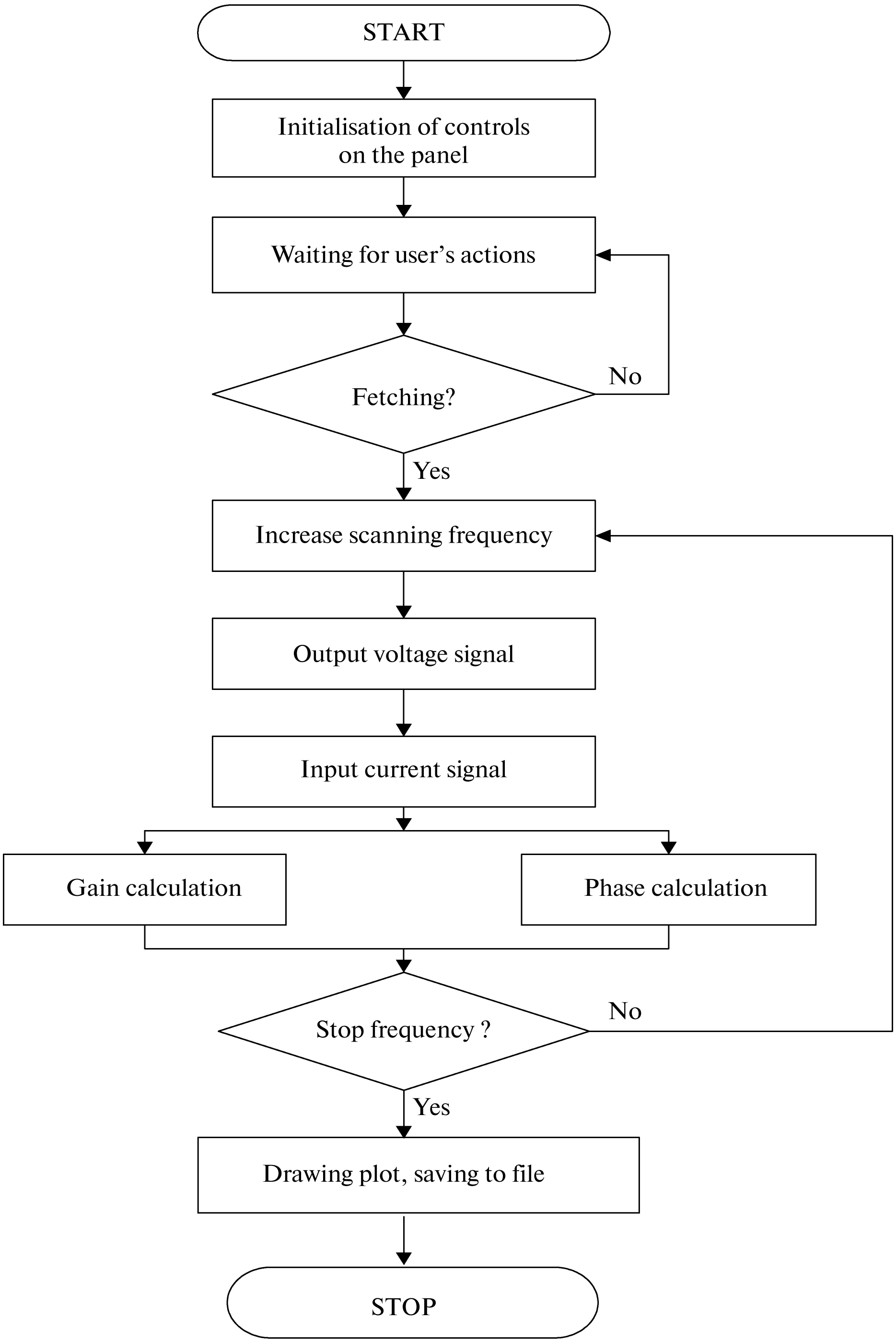

Fig. 5. Flow chart of GUI programming by using LabVIEW tools.

on the leg of the capacitor (piezoceramic) was measured. At the same time, the built-in program in the LabVIEW software computes and then plots the magnitudes and phase degrees of admittance.

Across the frequency range of 1–120 kHz, the results of admittance measurement demonstrate the consistency in the magnitude plot based on a precise resistor of 100 Ω chosen as the calibration basis and shown in Fig. 7. However, in the phase plot, the increment linear relationship of the phase degree is quite clear as the frequency increases. One explanation for this phenomenon is that the precise resistor for calibration was not ideally suited to the task, causing the phase degree to increase as the frequency rose.

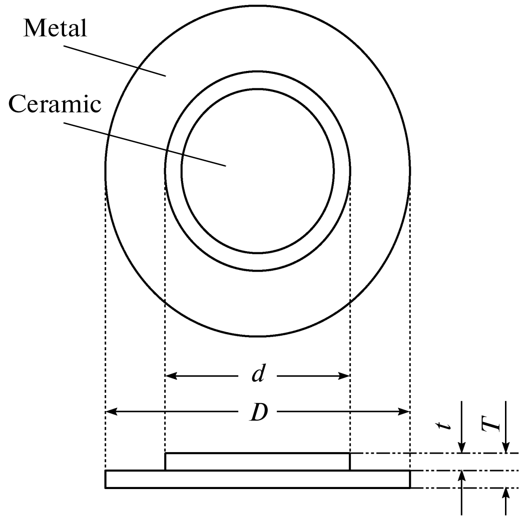

Fig. 6. Dimension marks of a thin-disc piezoelectric vibrator.

Table describes the comparison of parameters of the equivalent circuit using the built-in E type module of a HP impedance analyzer and the admittance analyzer, which are measured nearby resonant and anti-resonant frequencies. The component parameters of R, L, C, C_0, and the resonant frequency f_r as well as the anti-resonant frequency f_a of both analyzers are approximated to roughly 12% error or less. Yet, the difference of the blocking capacitance C_0 is quite large (error of about 26.86%).

However, in a practical application, the resonant frequency obtained from the equivalent circuit is lower than that of the specifications of the manufacturer. Based on practical usage and experimental experience, the actual operating frequency differs from the optimal operating frequency by less than 0.64–2.63% of the resonant frequency. Also we believe that the operating frequency must differ by the resonant frequency at a little bit less in order to excite the better effects of the electromechanical coupling.

A comparison of the performance of the admittance analyzer and a HP-4194A impedance analyzer in obtaining the admittance measurement of a piezoelectric

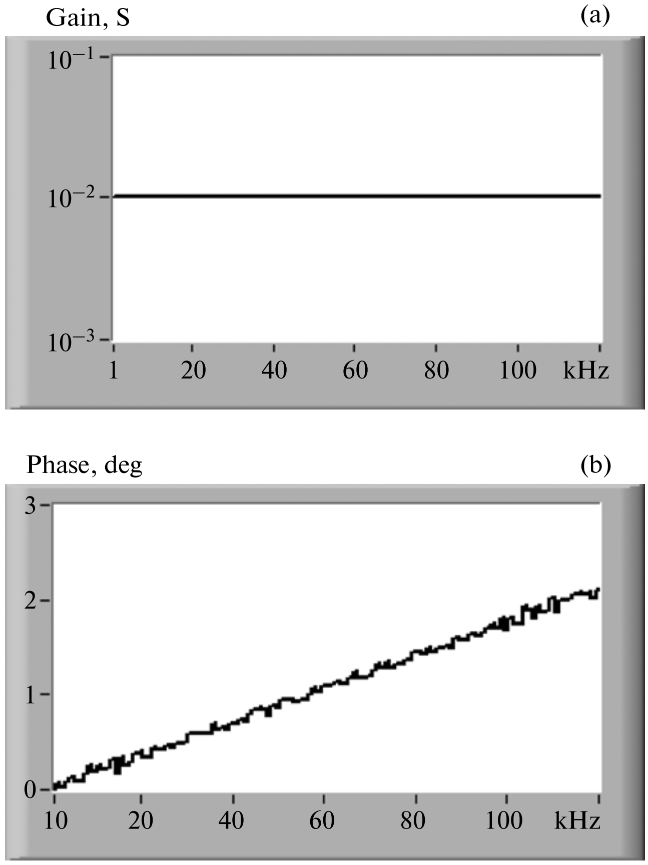

Fig. 7. (a) Magnitude and (b) phase of admittance for a 100 Ω precise resistor measured by the admittance analyzer (1–120 kHz).

vibrator is necessary to verify the performance of the admittance analyzer in this study (Fig. 8). From the known spectrum, the magnitude at the resonant frequency has a difference in magnitude, but the remainder has nearly the same amplitudes or overlap. The results demonstrate that the admittance analyzer is a competitive design when compared to the expensive HP analyzer. The phase plot has a few problems due to built-in errors in the VI software. To improve the distortion of the phase plot, it is necessary to re-code the

Comparison of the parameters in E-type model on the equivalent circuit using a HP-4194A impedance analyzer and the admittance analyzer

Electrical components	R, Ω	L, mH	C, nF	C_0, nF	f_r, kHz	f_a, kHz
HP-4194A Impedance Analyzer	10.1	1.1	4.1	56.6	74.0	77.5
Admittance Analyzer	10.7	1.0	4.6	41.4	75.0	77.5
Error, %	5.94	9.09	12.20	26.86	1.35	0.00

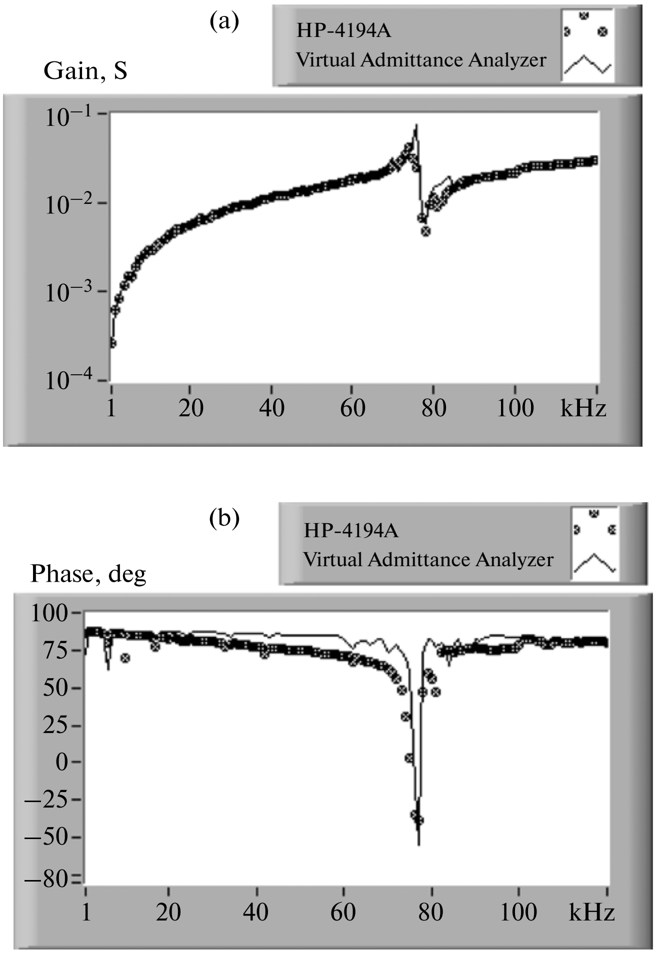

Fig. 8. Comparison of (a) magnitude and (b) phase plots by using the admittance analyzer and a HP-4194A analyzer (1–120 kHz).

calculating program and to consider the time delay effect during the signal acquisition and treatment.

CONCLUSIONS

The PC-based admittance analyzer contains the same five models of equivalent circuits as the HP hardware instrument does. The admittance measurement for the piezoelectric vibrator offers good performance in the 1–120 kHz range. Comparison with the component parameters for the E type model based on equivalent circuits shows that there is an acceptable error percentage. In other words, the proposed analyzer offers the complete functions of a hardware instrument, a HP-4194A analyzer, for measuring admittance based on theory and experiments within the 120 kHz range.

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