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Synthesis and Analysis of PZT Using Impedance Method of Reactance Estimation

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ABSTRACT

This study presents an analysis of equivalent circuit namely Butterworth Van Dyke (BVD) [1,2] by using impedance method to stimulate Zirconate Titanate (Piezoelectric ceramic) which is initially synthesized from Lead Oxide (PbO), Zirconium Dioxide (ZrO_2) and Titanium Dioxide (TiO_2) and vibrated in thickness mode. The reactance was estimated in the frequency range lower than the resonance frequency and then compared to the impedance obtained from measurement using impedance analysis machine model HP4192A and HP4194 [3]. The results from HP4194 were analyzed for BVD parameters: Motional resistance (R_1), Inductor (L_1), Capacitor (C_1), and Capacitor corresponds to the electrostatic capacitance (C_o). Another accuracy analysis was compared by the calculation results using the method of IEEE 176-1987 [4] to the impedance values measured by HP4192A. In this study, there were two conditions for experiment and consideration of parameter variation in BVD equivalent circuit: variation of temperature and mechanical force. These parameters are evaluated to design the efficient circuit for PZT utilization to obtain the optimal efficiency.

Keywords: BVD; Capacitance; Force; Frequency; Impedance; Inductance; PZT; Temperature

1. Introduction

Electronic circuit using BVD analysis for effectively stimulating PZT can be designed by adopting, for example, IEEE Standard [4,5], Smits [6], Sherrit [7], and Xu [8]. Smith's method and Sherrit's method would consider those parameters as complex numbers. Xu's method would be similar to Smith's method which considers the impedance of piezoelectric measured at the frequency values ranging from resonance frequency (f_r) and anti-resonance frequency (f_a) as well as under mechanical force *i.e.* elastic, piezoelectric constant and coupling coefficient. In this study, five pieces of PZT, namely O01, N01, N02, N03, and N04, were synthesized from ratio of PbO:ZrO_2:TiO_2 (100:52:48) and burned at 700˚C for 1 hour [9,10] in order to experiment the density (ρ), PZT constant (d_{33}), dielectric constant (K) at 1 kHz, electromechanical coupling coefficient (k_t) and mechanical quality factor (Q_m). In addition, the PZT were utilized in an ultrasonic cleaner.

2. Theory and Fundamental Method

2.1. Equivalent Circuit of BVD

Electrical characteristics in thickness mode of PZT [3] tested in this study were comparable to the BVD equivalent circuit, which consists of R_1 connected serially to C_1 and L_1 then all parallelly connected to C_o [1,2,11] as shown in **Figure 1(a)**. The resistance, the capacitance, and the inductance were comparable to the force friction (η), spring constant (k), and mass, respectively as shown in **Figure 1(b)**.

Assuming R_1, C_1, L_1, and C_o were constants and independent on frequency and impedance [5] as given in Equation (1), the impedance equation at PZT resonance frequency (Z_r), f_r and f_a, in terms of BVD relating parameters was obtained. In **Figure 2**, the impedance responding to f_r and f_a of PZT is shown.

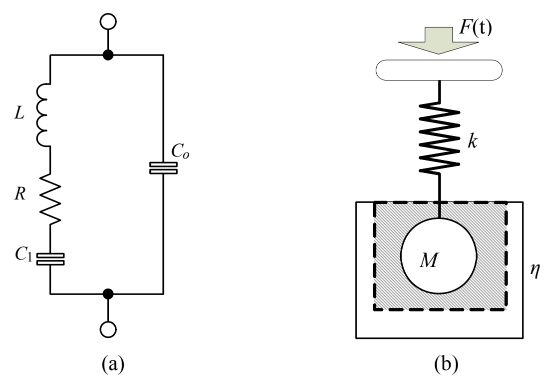


Figure 1. Equivalent circuit of PZT compared to mechanical characteristics: (a) The BVD model; (b) Mechanical model.

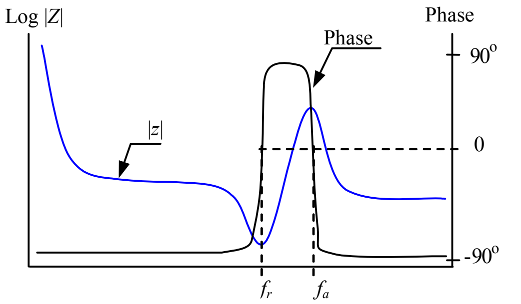


Figure 2. Frequency response characteristic of piezoelectric ceramic.

$$Z = \frac{R_1 + j\left(\omega L_1 - 1/\omega C_1\right)}{1 + j\omega\omega_0\left[R_1 + j\left(\omega L_1 - 1/\omega C_1\right)\right]} \quad (1)$$

The calculation of BVD circuit using impedance method by the capacitor ratio (r) is as shown in Equation (2), where ω_a is the angular velocity of the anti-resonance frequency ($2\pi f_a$) and ω_r is the angular velocity of the resonance frequency ($2\pi f_r$).

$$r = \frac{C_1}{C_o} = \frac{\omega_a^2 - \omega_r^2}{\omega_r^2} \quad (2)$$

The reactance values of C_1 and L_1 in BVD circuit at low frequency range was observed. It was noted that the reactance of PZT was performed as a capacitor as shown in Equation (3).

$$j/\omega C_1 \qquad j\omega\omega_1 \quad (3)$$

Therefore,

$$\left(R_1 + j\omega\omega_1 - j/\omega C_1\right) \approx \left(R - j/\omega C_1\right) \quad (4)$$

Then the impedance equation of PZT can be revised as shown in Equation (5).

$$Z = \frac{R_1 - j/\omega C_1}{\left[\dfrac{\omega_r^2 - \omega^2}{\omega_a^2 - \omega_r^2}\right] + jR\omega R_0} \quad (5)$$

C_1 can be calculated as given in Equation (6) by choosing the impedance measured at low frequency range where ω is the angular velocity of the selected frequency and R is $|Z|$ measured at resonance frequency.

$$C_1 = \frac{1}{\omega\sqrt{\left[\dfrac{\omega_r^2 - \omega^2}{\omega_a^2 - \omega_r^2}\right]^2 |Z|^2 - R^2}} \quad (6)$$

2.2. Measurement of Dielectric Constant (K)

Measurement of K or relative permittivity (ε_r) of PZT is to test for the electrical characteristics which can be calculated by using Equation (7), where C_f is the capacitance at 1 kHz, t is the thickness of PZT measured from both metal poles, A is the area of metal pole, and ε_o is the dielectric constant of vacuum. The dielectric constant can be varied depending on the temperature (T) of substance based on Curie-Weiss Law [12] where T_c is the temperature of PZT with zero polarization, and C is Curie constant (10^3 to 10^5) as given in Equation (8).

$$K = \varepsilon_r = \frac{C_f t}{\varepsilon_o A} \quad (7)$$

$$K - 1 = \frac{C}{T - T_c} \quad (8)$$

Equations (7) and (8) can also be revised as shown in Equation (9).

$$\varepsilon_r = \left[\frac{C}{T - T_c}\right] + 1 \quad (9)$$

2.3. Measurement of PZT Constant (d_{33})

The value of d_{33}, measured by Piezo-D meter model CADT (Channel Products Inc.), implies the ability to emit the electric charge of PZT when it is stimulated by mechanical force. Number 33 represents the three perpendicular directions of compression force on PZT.

2.4. Measurement of Electromechanical Coupling Coefficient (k_t)

Electromechanical coupling coefficient (k_t) represents the efficiency of transformation from electrical energy to mechanical force. In Equation (10), Δf is the difference between f_r and f_a.

$$K_t^2 = \frac{\pi}{2}\frac{f_r}{f_a}\tan\left(\frac{\pi}{2}\frac{\Delta f}{f_a}\right) \quad (10)$$

2.5. Measurement of Mechanical Quality Factor (Q_m)

Q_m represents the maximum ability of mechanical vibration in f_r range where R_1 is the impedance at resonance frequency as given in Equation (11).

$$Q_m = \frac{f_a^2}{2\pi f_r R_1 C_f\left(f_a^2 - f_r^2\right)} \quad (11)$$

3. Analysis of BVD Equivalent Circuit

The PZT with 40 mm of diameter and 3 mm of thickness is electrode by silver paste at the top and the bottom as shown in **Figure 3**, and then connected to the system as

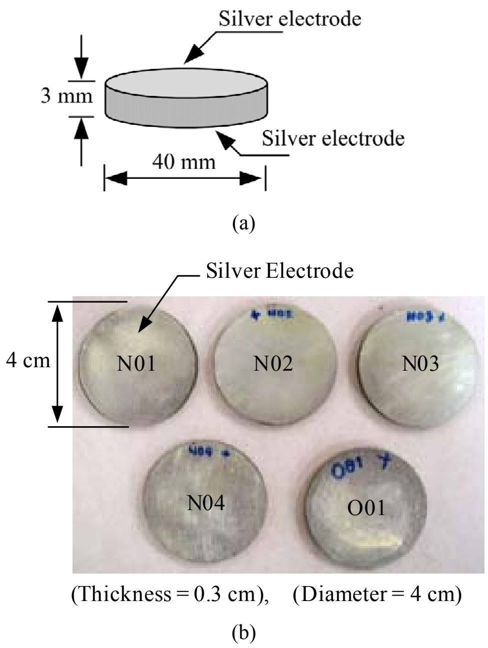


Figure 3. Physical of PZT sample: (a) Dimension of PZT; (b) Top view.

shown in **Figure 4**. The HP Vee program is applied to control the impedance analyzer model HP4192A via HP-IB interface and collect the impedance at 100 Hz to 1.3 MHz [4]. Then, the resonance frequency and the impedance at resonance frequency and lower resonance frequency will be applied to calculate R, L, and C_o. The calculated value will be evaluated and compared with the value calculated by using Equation (1). In this paper, only the fundamental resonance is considered regardless the resonance frequency at harmonic period.

From experiment and measurement of PZT impedance, the calculated parameters from BVD model are as shown in **Table 1**. **Figures 5** and **6** are illustrated the comparison of size ($|Z|m$) and phase of the impedance at 100 Hz to 100 kHz measured by impedance analyzer model HP4192A and the calculated impedance ($|Z|cal$ and Phase Cal). The impedance at 1 kHz is selected to calculate in Equation (6). To obtain the appropriate value of C, the impedance at lower resonance frequency is suggested such as 100 Hz, 1 kHz, 2 kHz, 3 kHz, 6 kHz, and 14 kHz. The BVD parameters are as shown in **Table 2** and the percentage of error is shown in **Figure 7**.

4. Experiment of PZT under Temperature Control

Physical characteristics of PZT were experimented by considering ρ, PZT constant (d_{33}), k_t, and Q_m of electrical charge at 1 kHz. In this study, only the results from N01 and N04 (details are given in **Table 3**) were compared under room and controlled temperatures. **Figure 8** shows

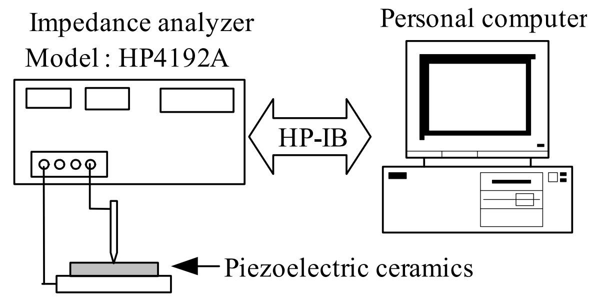


Figure 4. Impedance of PZT measurement diagram.

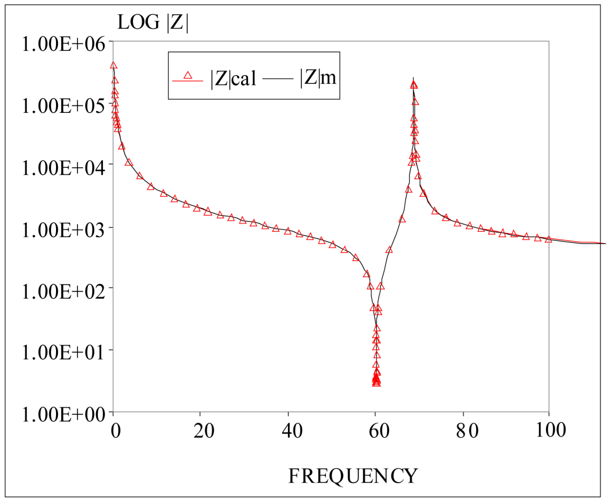


Figure 5. Gain impedance of PZT measurement at various frequency.

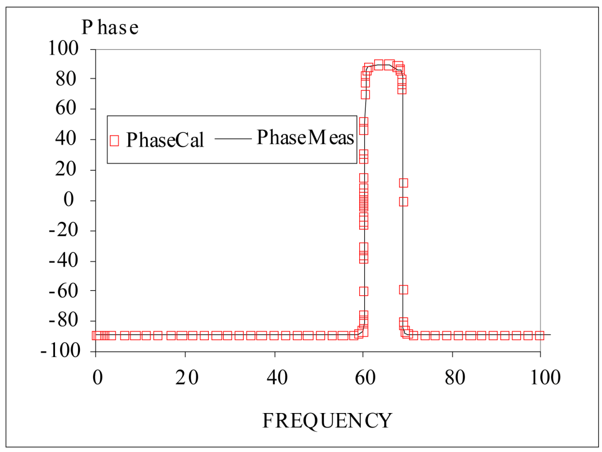


Figure 6. Phase impedance of PZT at various frequency.

the PZT experimental system connected with impedance analysis model HP4192A under temperature conditions.

Measuring the PZT impedance under room temperature was for assessing the influences of temperature on PZT impedance and comparing the results under room temperature and controlled temperature at various frequency. **Figures 9** and **10** illustrate the PZT impedance

Table 1. The PZT properties.

PZT properties	
Fundamental resonance frequency (f_r)	60.329 kHz
Fundamental anti-resonance frequency (f_a)	68.971 kHz
Impedance at f_r	2.847 Ω
Impedance at 1 kHz	41.040 kΩ
Impedance at 2 kHz	20.540 kΩ
Impedance at 3 kHz	11.245 kΩ
Impedance at 6 kHz	6.526 kΩ
Impedance at 14 kHz	2.863 kΩ

Table 2. Calculated parameters of BVD circuit at 100 Hz, 1 kHz, 2 kHz, 3 kHz, 6 kHz, and 14 kHz.

Parameters	Frequency					
	100 Hz	1 kHz	2 kHz	3 kHz	6 kHz	14 kHz
R_1 (Ω)	2.847	2.847	2.847	2.847	2.847	2.847
C_o (nF)	2.9715	2.9693	2.9697	3.019	3.037	3.172
C_1 (pF)	91.22	91.16	91.17	92.69	91.33	97.39
L_1 (mH)	7.63	7.64	7.64	7.51	7.47	7.15

Table 3. Physical and electrical characteristics of PZT (N01 and N04).

PZT	Density	d_{33} (10^{-12} C/N)	C_f (nF)	K (F/m)	k_t	Q_m
N01	7.38	275	4.7888	1040	0.48	846
N04	7.40	271	3.6474	1016	0.51	844

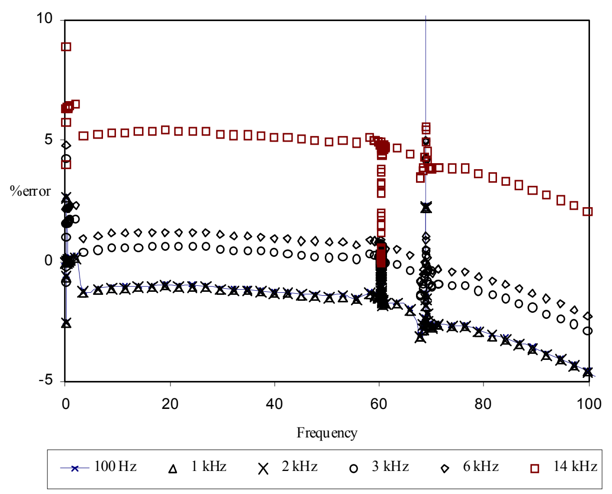


Figure 7. Error percentage of calculated impedance at various frequency.

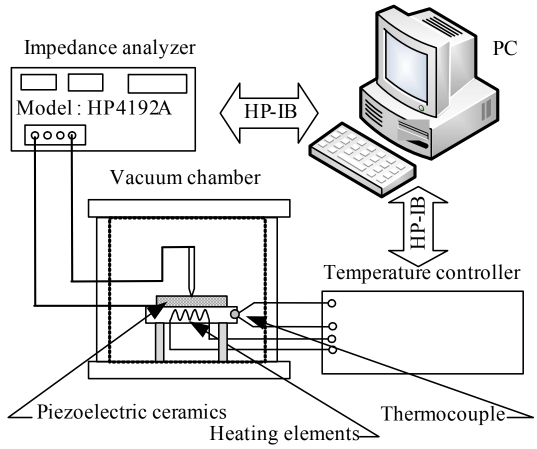


Figure 8. PZT experimental system and impedance analysis model HP4192A.

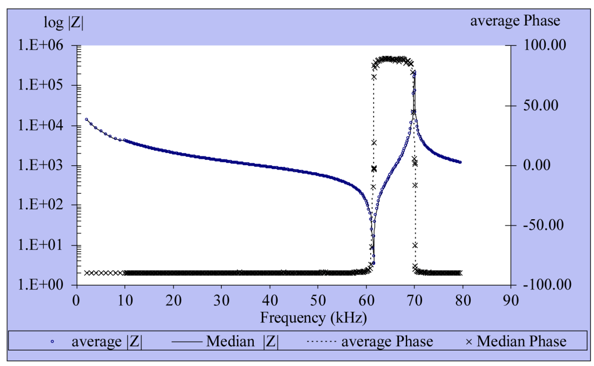


Figure 9. Impedance and phase at the frequency ranging from 100 Hz to 80 kHz of N01.

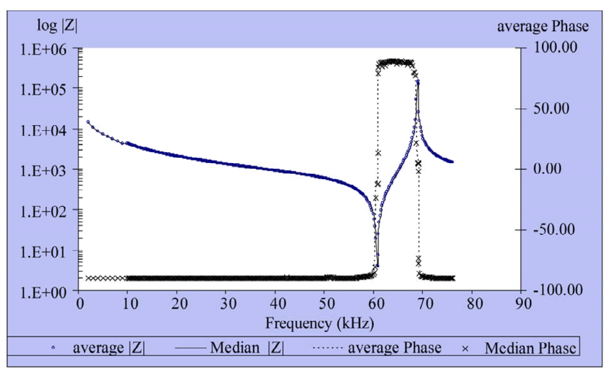


Figure 10. Impedance and phase at the frequency ranging from 100 Hz to 80 kHz of N04.

of N01 and N04 repeatedly measured 5 times by impedance analysis model HP4192A under room temperature at the frequency of 1 kHz to 80 kHz.

PZT was experimented by placing on heater plate in vacuum chamber under controlled temperature. The temperature can be controlled by a program developed on HP Vee via HP-IB port as shown in **Figure 11**. The temperature was varied from 25˚C to 230˚C with 20˚C

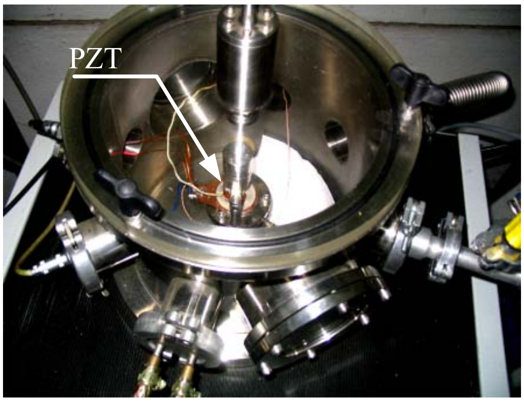


Figure 11. Position of PZT in temperature controlling chamber.

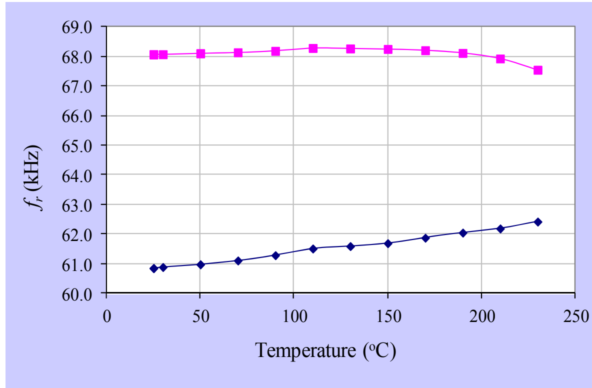


Figure 12. f_r of PZT at various temperatures.

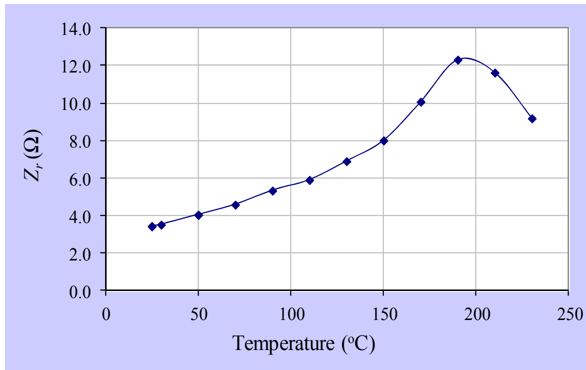


Figure 13. Impedance of PZT at f_r at various temperatures.

interval of measurement and the frequency was varied from 2 kHz to 80 kHz. Uncertainty of measurement and PZT was estimated by repeating 3 times of measurement.

4.1. Experimental Results under Temperature Conditions

The impedance of PZT in temperature controlled chamber (only N01) under specific temperature was similar to that under room temperature. However, it was observed that f_r and f_a were drifted. At 230˚C, f_r increased about ≈1.6 kHz while f_a decreased about ≈1 kHz. Therefore, the difference between f_r and f_a decreased about 2.6 kHz as shown in **Figure 12**. Moreover, when the temperature was increasing, the impedance at f_r was also increasing up until 190˚C and then starting to decrease as illustrated in **Figure 13**.

4.2. Analysis of Impedance Variation in the Range of 100 Hz to 10 kHz

Experiment of PZT in the range of 100 Hz to 10 kHz was to calculate the impedance of BVD circuit by repeatedly measuring 30 times. An average and standard deviation of impedance are given in **Figures 14** and **15**, respectively. It can be noted that the standard deviation would increase at low frequency range and decrease as the frequency is rising.

4.3. Calculation of BVD Circuit Using Impedance Method

To calculate BVD circuit, average experimental values of f_r, f_a, and Z_r at selected frequency ranging from 0.1 kHz to 10 kHz were used and then BVD parameters were obtained. The results were ranged as follows: L_1 ≈ 0.16 mH to 0.2 mH, C_1 ≈ 0.018 nF to 0.040 nF, C_o ≈ 0.06 nF to 0.18 nF. However, R_1 was uniform due to the identical impedance at f_r as shown in **Table 4**.

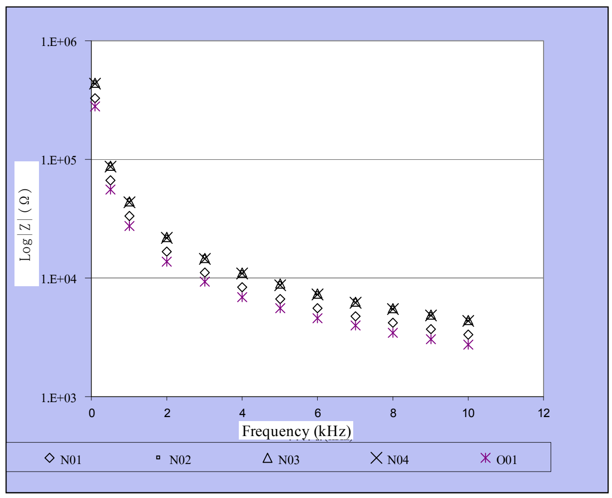


Figure 14. Average values at 100 Hz to 10 kHz of N01, N02, N03, N04, and O01.

4.4. Influences of Temperature Variation on BVD Parameters

When PZT was placed in the temperature controlling chamber at 23˚C, C_1 would be decrease by 72% or 0.726%/˚C that leads to 255% of increase in L_1. Therefore, the temperature would directly influence the char-

Table 4. BVD calculating parameters of N01 and N04 using impedance method.

PZT	BVD	Frequency (kHz)												
		0.1	0.5	1	2	3	4	5	6	7	8	9	10	σ
N01	C_o (nF)	3.870	3.850	3.850	3.840	3.840	3.850	3.860	3.870	3.880	3.890	3.910	3.930	0.090
	C_1 (nF)	0.947	0.941	0.940	0.940	0.940	0.941	0.943	0.946	0.948	0.952	0.956	0.961	0.021
	L_1 (mH)	7.146	7.190	7.199	7.203	7.202	7.192	7.179	7.159	7.142	7.112	7.079	7.044	0.159
	R_1 (Ω)	3.331	3.331	3.331	3.331	3.331	3.331	3.331	3.331	3.331	3.331	3.331	3.331	0.000
N04	C_o (nF)	2.840	2.840	2.840	2.840	2.840	2.840	2.850	2.850	2.860	2.870	2.890	2.900	0.060
	C_1 (nF)	0.804	0.806	0.805	0.804	0.805	0.806	0.808	0.809	0.811	0.814	0.818	0.822	0.018
	L_1 (mH)	8.449	8.429	8.439	8.441	8.439	8.429	8.403	8.396	8.373	8.337	8.298	8.258	0.191
	R_1 (Ω)	3.828	3.828	3.828	3.828	3.828	3.828	3.828	3.828	3.828	3.828	3.828	3.828	0.000

where σ is the standard deviation.

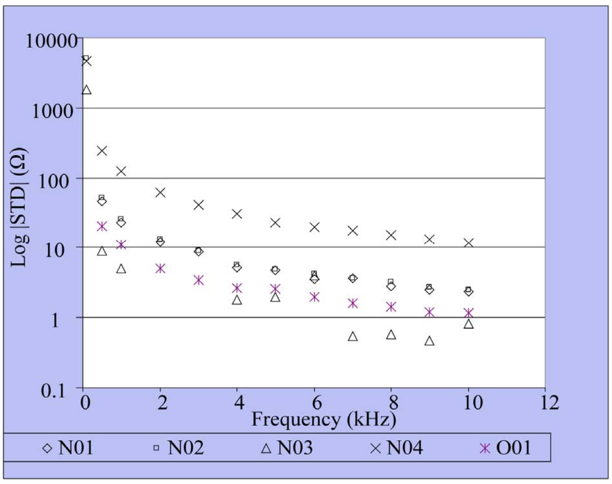


Figure 15. Standard deviation values at 100 Hz to 10 kHz of N01, N02, N03, N04, and O01.

acteristics of PZT as provided in **Table 5**.

5. Experiment of PZT under Mechanical Force

The parameters which was use in consideration of physical and electrical characteristics of PZT consists of ρ, d_{33}, k_t, and Q_m at 1 kHz. In this case, comparison of N02 and N03 is as shown in **Table 6**.

Measurement of Z_r under mechanical force was performed by using 0.5 lbs, 1.0 lbs, and 1.5 lbs of brass standard weights at room temperature. Each measurement was varied the frequency starting from 2 kHz to 80 kHz and repeated 30 times for calculating an average value. **Figures 16(a)** and **(b)** illustrate the experimental system and the brass standard weights, respectively.

Table 5. Percentage of BVD parameter changes as PZT temperature increasing by 230˚C.

Parameter of BVD	% Difference	% Difference/˚C
R_1	167.0	0.726
C_1	−72.0	−0.313
L_1	255.0	1.109
C_o	18.1	0.079

Table 6. Physical and electrical characteristics of PZT (N02 and N03).

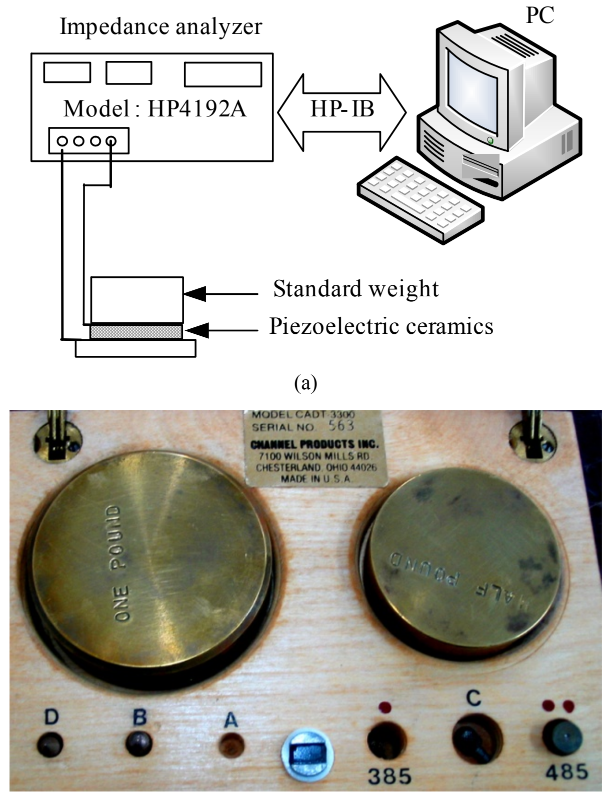
PZT	Density	d_{33} (10^{-12} C/N)	C_f (nF)	K (F/m)	k_t	Q_m
N02	7.42	256	3.5619	996	0.51	822
N03	7.40	262	3.5812	1002	0.51	919

5.1. Experiment of PZT at f_r

Standard weights (0.5 lbs, 1.0 lbs, and 1.5 lbs) were pressed to estimate f_r, f_a, and Z_r as shown in **Table 7** compared to weightless condition. The comparison was shown in **Table 8**. It can be noted that PZT pressed by 1.5 lbs standard weight would express higher f_r and f_a by ≈0.24 kHz and 2 kHz, respectively. However, Z_r would be varied by the weight pressing and become stable at ≈6.5 Ω.

5.2. Experiment of Z_r of PZT Connected Serially with Specific Capacitors

A capacitor (1.097 nF, 1.46 nF, 1.92 nF, 4.48 nF, 5.92 nF, 8.97 nF, and 33.016 nF) was connected serially with a given PZT (N02 and N03) and then, f_r, f_a, and Z_r were



(a)

(b)

Figure 16. Impedance measurement using Impedance analysis model HP4192A and standard weight pressing: (a) System diagram; (b) Brass standard weights.

Table 7. f_r, f_a, and Z_r of PZT under mechanical force loads.

PZT	Parameter	Under force load (lb)			
		0	0.5	1	1.5
	Z_r	3.601	8.770	7.536	10.553
N02	f_r	61.550	61.850	61.700	61.850
	f_a	69.800	69.650	69.950	79.099
	Z_r	3.964	5.575	10.587	5.506
N03	f_r	61.250	61.400	61.400	61.400
	f_a	69.350	69.500	69.350	69.350

Table 8. Variation of f_r, f_a, and Z_r of PZT under mechanical force loads.

Parameter	Under force load (lb)		
	0.5	1	1.5
ΔZ_r	2.602	5.380	6.560
Δf_r	0.180	0.180	0.240
Δf_a	0.210	0.300	2.130

measured. The relationships of $f_s/2$ (f_{sCL}-f_s) are as illustrated in **Figures 17-20** where f_s is the serial resonance frequency based on IEEE method [4,5]. The slope of linear relationship is $1/C_1$ as shown in **Table 9**.

5.3. Calculation of BVD Using Impedance Method

The average values of f_r, f_a, and Z_r at resonance frequency obtained from experiments of N02 and N03 were used for analyzing BVD. By selecting the frequency ranging from 0.1 kHz to 10 kHz, it can be observed that

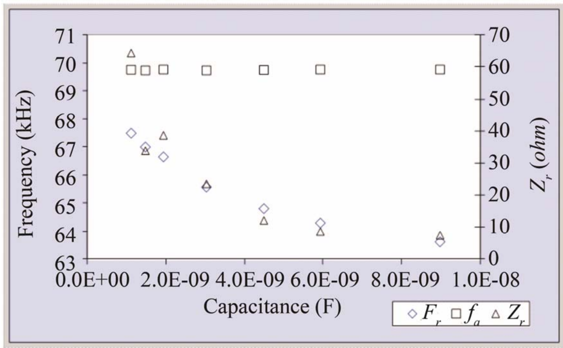


Figure 17. f_r, f_a, and Z_r of N02 connected serially with various capacitors.

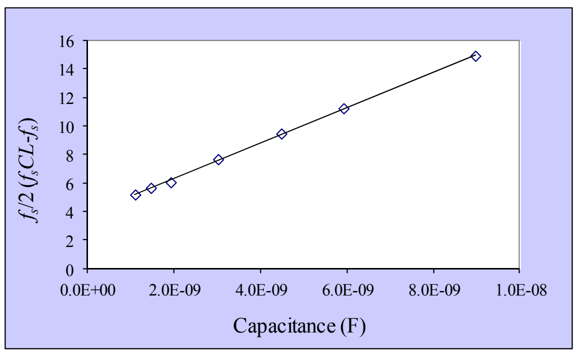


Figure 18. $f_s/2(f_{sCL}$-$f_s)$ of N02 connected serially with various capacitors.

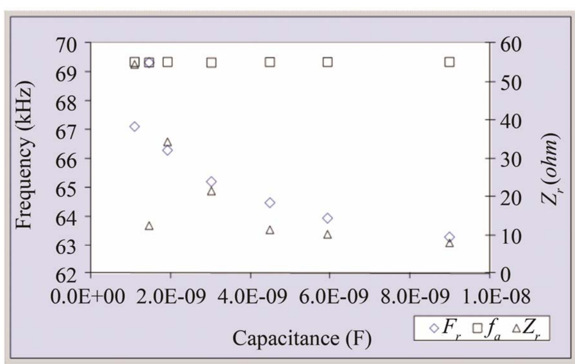


Figure 19. f_r, f_a, and Z_r of N03 connected serially with various capacitors.

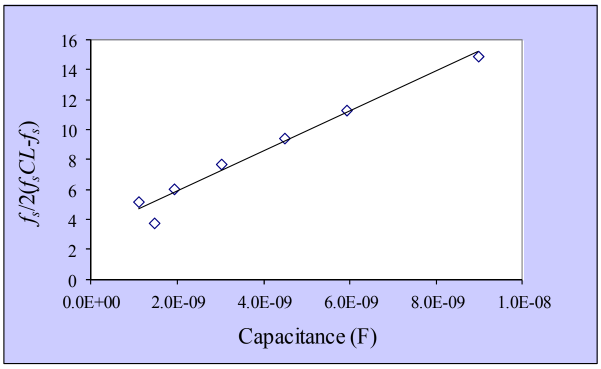


Figure 20. $f_s/2(f_{sCL}\text{-}f_s)$ **of N02 connected serially with various capacitors.**

Table 9. Slopes of $f_s/2(f_{sCL}\text{-}f_s)$**.**

PZT	Slope = $1/C_1$ (10^9)	C_1 (nF)
N02	1.237	0.808
N03	1.235	0.810

$C_o \approx 0.06$ nF, $C_1 \approx 0.018$ nF, $L_1 \approx 0.184$ mH to 0.190 mH while R_1 was identical due to the same impedance at f_r as given in **Table 10**. The **Table 11** shows the comparison of BVD parameters calculated by using impedance method, IEEE method, and HP4194 where IEEE method is the method of IEEE 176-1987, Δ_1 is the percentage of difference between values obtained from impedance and IEEE 176-1987 method, and Δ_2 is the percentage of difference between values obtained from impedance and HP4194 method.

5.4. Influences of Temperature on BVD Parameters under Mechanical Force

Variation of f_r, f_a, and Z_r when PZT was pressed by standard weights was calculated for C_o, C_1, and L_1 by impedance method. The differences are given in **Table 12**.

6. Conclusion

From calculation, it was observed that $|Z|$ and $Z(\theta)$ of the impedance ranging from low frequency to f_r and f_a tended to be equal to the impedance measured by impedance analysis model HP4192A. Selecting low frequency range (100 Hz, 1 kHz, and 2 kHz) for calculating C would cause the error of $|Z|$ by ≈−1%, On the other hand, selecting the impedance and frequency at 3 kHz the error would be exhibit less than 1%. However, the impedance and frequency at 14 kHz would exhibit the greater error by ≈5% because ωL can much influence the impedance while $1/\omega L$ decreases. Therefore, the impedance selected for calculating should have the frequency lower than f $f_a^2 - f_r^2$. Considering the percentage of impedance error, it can noted that the impedance at the frequency of 100 Hz, 1 kHz, and 2 kHz would provide the similar results with 20% - 25% of the maximum error of f_a. From experiment of the calculated impedance, the accuracy of f_r and f_a was ±0.0033 kHz with the standard deviation of 0.00129 kHz which would be reliable for calculating BVD circuit. From experiment of accuracy which was compared between Z_r of BVD equivalent circuit and Z_r from measurement, it can be noted that Z_r at f_r of BVD circuit calculated by impedance method and IEEE 176-1987 would exhibit the error by ≈2.37% which was lower than HP4194 method (≈4%). It would be because the impedance analysis using impedance analysis model HP4192A is applied the program to estimate f_r more accurately. However, R_1 was less different as it was a specific resistance at resonance frequency. Considering the influence of temperature on PZT characteristic, it was noted that the increase of temperature would contribute to less difference of f_r and f_a.

Table 10. Calculation of BVD parameters based on impedance method: a case of N02 and N03.

PZT	BVD	Frequency (kHz)											
		0.1	0.5	1	2	3	4	5	6	7	8	9	10	σ
N02	C_o (nF)	2.780	2.780	2.770	2.770	2.770	2.780	2.780	2.790	2.800	2.810	2.820	2.830	0.060
	C_1 (nF)	0.788	0.787	0.786	0.785	0.785	0.786	0.788	0.790	0.792	0.795	0.799	0.803	0.018
	L_1 (mH)	8.469	8.482	8.494	8.497	8.497	8.489	8.470	8.448	8.425	8.391	8.354	8.313	0.184
	R_1 (Ω)	4.035	4.035	4.035	4.035	4.035	4.035	4.035	4.035	4.035	4.035	4.035	4.035	0.000
N03	C_o (nF)	2.820	2.790	2.790	2.790	2.790	2.790	2.800	2.810	2.820	2.830	2.840	2.850	0.060
	C_1 (nF)	0.795	0.788	0.787	0.787	0.787	0.788	0.789	0.792	0.794	0.797	0.801	0.805	0.018
	L_1 (mH)	8.488	8.559	8.570	8.571	8.572	8.561	8.549	8.518	8.496	8.463	8.425	8.382	0.190
	R_1 (Ω)	3.590	3.590	3.590	3.590	3.590	3.590	3.590	3.590	3.590	3.590	3.590	3.590	0.000

Table 11. Comparison of average BVD parameters from each method.

PZT	BVD	Impedance method (1 kHz)	IEEE	HP4194	Δ_1	Δ_2
N02	C_o (nF)	2.770	2.852	2.707	2.96%	2.27%
	C_1 (nF)	0.786	0.808	0.791	2.80%	0.64%
	L_1 (mH)	8.494	8.258	8.483	2.78%	0.13%
	R_1 (Ω)	4.035	4.035	3.415	0.00%	15.37%
N03	C_o (nF)	2.790	2.872	2.719	2.94%	2.54%
	C_1 (nF)	0.787	0.810	0.791	2.92%	0.51%
	L_1 (mH)	8.570	8.328	8.572	2.82%	0.02%
	R_1 (Ω)	3.590	3.590	4.056	0.00%	12.98%

Table 12. Percentage of BVD parameter variation with 1.5 lbs standard weight pressing.

Parameter of BVD	% Difference	% Difference/°C
R_1	144.0	96
C_o	−4.96	−3.30667
C_1	21.22	14.14667
L_1	−18.14	−12.0933

However, the increase of Z_r would cause the variation of BVD calculated parameters such as decrease of C_1, increase of R_1, L_1, and C_o. On the other hand, the influences of mechanical force load on PZT parameters would cause f_r, f_a, and Z_r increase that also contribute to R_1 and C_1 increase while L_1 and C_o decrease.

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