Piezoelectric transformers for a high power module

T. Ezaki*, Taiheiyo Cement Corporation, Central Research and Development Center, Sakura-shi, Chiba, Japan;
S. Manuspiya, P. Moses, K. Uchino, Int'l Center for Actuators and Transducers, MRI, Penn State, University Park, PA;
A. Vazquez Carazo, Face Electronics, Norfolk, VA;

Abstract

Piezoelectric transformers are mainly commercialized for a LCD back light inverter module. With regard to laptop computers, the required output power for a piezoelectric transformer is around 5 W at present, and higher power will be needed for wider displays in the near future. In addition, modules such as AC-DC adaptors or fluorescent lamps may require a higher output power of more than 30 W. Here, in order to obtain compact and high-power AC-DC adaptors, we explored suitable designs for a multi-layered piezoelectric transformer, by taking into account the effect of the mechanical quality factor and the electromechanical coupling factor in the samples.

1. Introduction

In collaboration with ICAT at Penn State University and Face Electronics, Taiheiyo Cement Corporation is developing the piezoelectric transformers. This paper reports the AC/DC adaptors for laptop computers. This application requires piezoelectric transformers that can provide high output power, such as 30 W. Based on the design by Face Electronics, TRANSONER, Taiheiyo®Cement developed co-fired multi-layer transformers. We optimized the dimensions of TRANSONER® for this application, which were the diameter, thickness of the input or output side, and the layer number in the multi-layered part. In order to obtain the appropriate dimensions and the output of 30 W, we considered mechanical quality factor (Q_m) of an input side and electromechanical coupling factor (k_r) of an output side because these parameters seemed to influence the efficiency of piezoelectric transformers.

2. Samples

In this experiment, we used a hard type of piezoelectric material commercialized by Taiheiyo Cement Corporation, and the material properties measured at 1 Vrms and 1 kHz are shown in Table 1. We prepared disc type samples with a diameter of 27 mm as shown in Table 2 and Figure 1, which had single layered input and multi-layered output in order to adjust the step-up ratio.

Table 1. Low field characteristics of piezoelectric ceramics for high power applications commercialized by Taiheiyo-Cement Corporation. (measured at 1 Vrms)

ε_r	k_r	Q_m	d_{31}(m/V)	d_{33}(m/V)
1350	0.60	1800	-120×10^{-12}	315×10^{-12}

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
00 JUN 2003	**N/A**	**-**

4. TITLE AND SUBTITLE
Piezoelectric Transformers for a High Power Module

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Taiheiyo Cement Corporation, Central Research and Development Center, Sakura-shi, Chiba, Japan; Intl Center for Actuators and Transducers, MRI, Penn State, University Park, PA; Face Electronics, Norfolk, VA;Face Electronics, Norfolk, VA;

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001697, ARO-44924.1-EG-CF, International Conference on Intelligent Materials (5th) (Smart Systems & Nanotechnology)., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Table 2. Samples with single layered input and multi-layered output in order to obtain an acceptable step-up ratio for AC/DC adaptors.

Sample No.	Input thickness	Output thickness
1	2.0mm	0.45mm×5layers = 2.25mm
2	2.25mm	0.45mm×5layers = 2.25mm
3	2.30mm	0.26mm×5layers = 1.30mm

The samples were produced with the green sheet multi-layer technology. After printing Ag-Pd electrodes on a green sheet, green bodies were formed by means of a hot pressing process and sintered at around 1100 . Then Ag external electrodes were put on the sintered body and fired at 800 . After poled in silicon oil, the piezoelectric transformers were obtained.

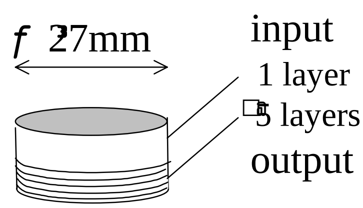

Figure 1. Down transformer sample with one layer of input and 5 layers of output using Ag-Pd electrodes.

3. Parameters in equivalent circuit of the samples

An equivalent circuit for a piezoelectric transformer is shown in Fig. 2 [1] and these parameters can be measured with an impedance analyzer such as HP4194A. The data in the equivalent circuit of the samples are shown in Table 3.

Due to the fact that the input side had a lower capacitance than the output side, these samples work as step-down transformers. In case of piezoelectric transformers a step-up ratio can be changed with a load resistance or a driving frequency. Regarding laptop computer applications, the range of the load is generally found between 10 ohm and 20 ohm. Here, we simulated the step-up ratio of these samples assuming a load of 15 ohm, and the results were shown in Fig. 3. On the other hand, we examined and found that many laptop computers needed DC 15 V in order to operate themselves. Roughly, the calculated step-up ratio indicated that AC/DC adaptors using these samples could transform AC 120 V to DC 15 V.

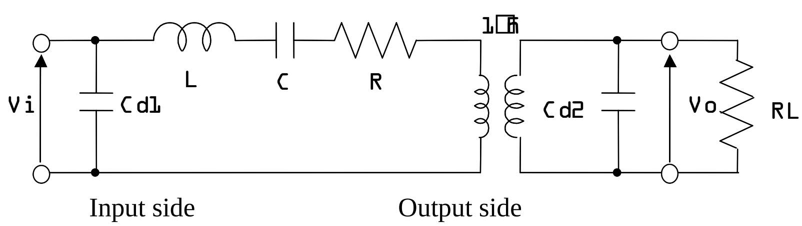

Figure 2. Equivalent circuit for a piezoelectric transformer.

Table 3. Parameters and the data of the samples measured with HP4194A.

Sample	Cd1(nF)	L(mH)	C(nF)	R(ohm)	Cd2(nF)	n	f_r(kHz)

1	2.7	9.7	0.4	12.4	56	0.19	80.8
2	2.2	10.7	0.3	9.8	54	0.19	83.2
3	3.3	7.2	0.5	9.7	121	0.18	81.3

From the equation of $R=1/(\omega Cd_2)$, we can obtain a load giving maximum efficiency to a piezoelectric transformer; this is called matching impedance. The samples No.1, No.2 and No.3 had the matching impedance of 35 ohm, 35 ohm and 16 ohm respectively, and the same value of the matching impedance was used as the load resistance in high power characteristic measurements.

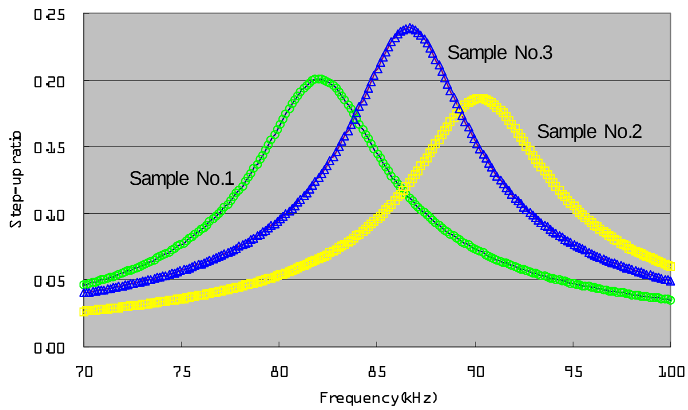

Figure 3. Calculated step-up ratio for the samples at 15ohm load.

4. Measurement of high power characteristics

4.1. Measurement system

The high power characteristics were measured with our automatic measurement system using a constant output current method. In this system, we can set output current and frequency range, and we can simultaneously record input voltage, input current, power factor, output current and temperature of the sample. The output voltage can be calculated from both the load resistance and the output current. The efficiency and the step-up ratio can be also obtained from the recorded or the calculated data.

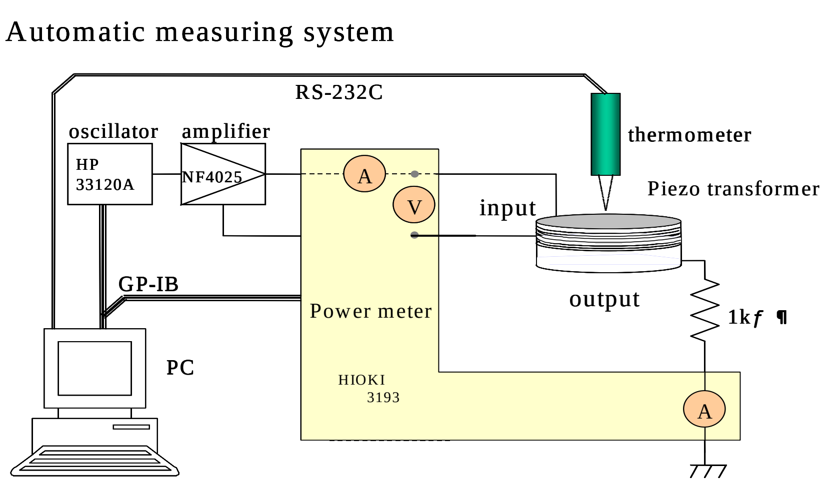

Figure 4. Measurement system on piezoelectric transformers.

4.2. Results

We measured the characteristics of the samples by using the same load as the matching impedance. After obtaining the data at a base input power, such as 1W, the input power was increased for each successional data point. Maximum efficiency and the temperature rise are shown in Figs. 5 and 6. Sample No.1 and No.2 had the efficiencies of 97-98 %, these were higher than Sample No.3. We defined a standard about the maximum output power of piezoelectric transformers as the output power at 20 temperature rise. The maximum output power reached 30 W for Sample No.2.

Using sample No.2, the relationship between the input voltage and output voltage at 90 kHz getting the maximum efficiency, is shown in Fig. 7, and the step-up ratio in case of changing frequency is shown in Fig. 8. Using the matching impedance of 35 ohm, the step-up ratio was from 0.15 to 0.25 and this range seemed to be acceptable for laptop computer applications, which needed DC 15 V.

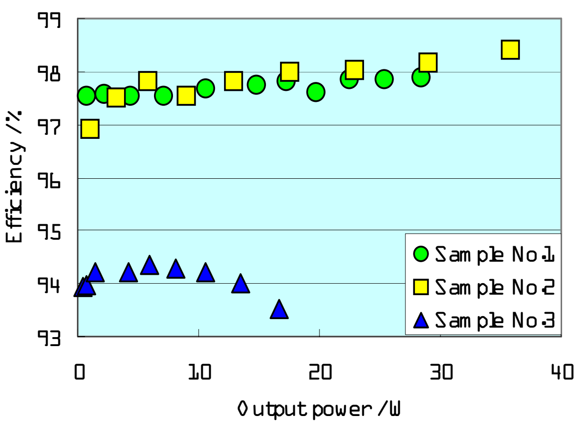

Figure 5. Efficiency vs. output power at the matching impedance of each sample.

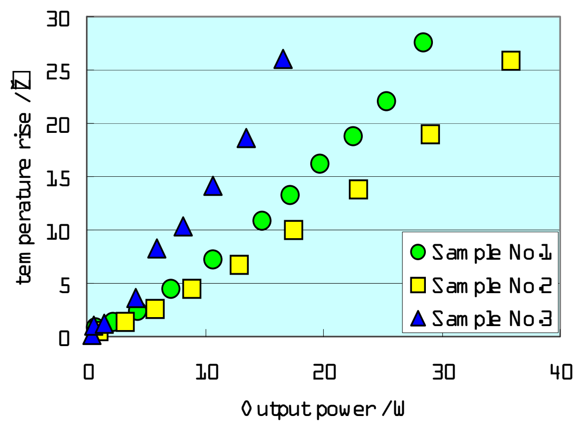

Figure 6. Temperature rise vs. output power at the matching impedance of each sample.

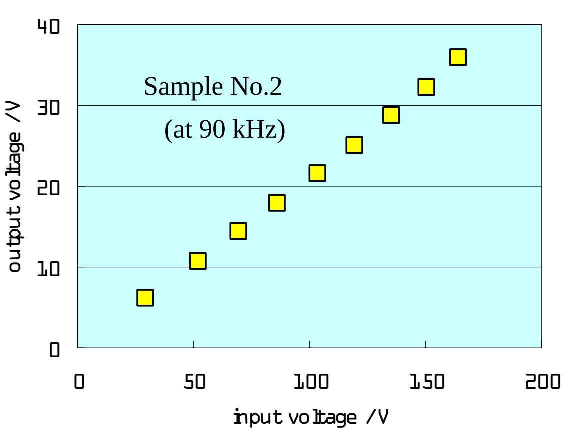

Figure 7. Input vs. output voltage of sample No.2.

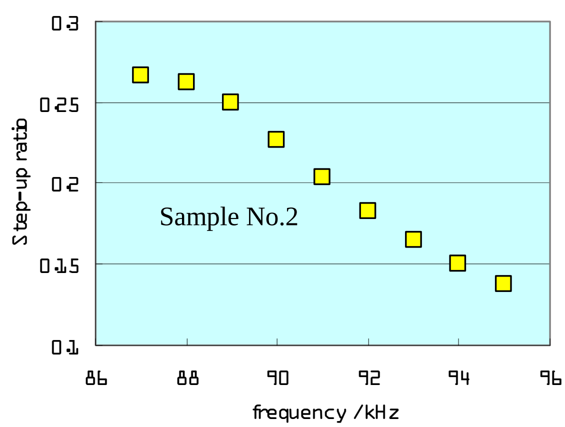

Figure 8. Frequency vs. step-up ratio of sample No.2.

5. Discussions

The efficiency of piezoelectric transformers can be calculated from the next equations using parameters in the equivalent circuit [2]. In the equation (1) the efficiency is expressed by "Q_m" and "k," mechanical quality factor and electromechanical coupling factor, respectively. Note that "Q_m" comes from the input side and "k" comes from the output side. Thus we can see that high Q_m in the input side and high k in the output side can generate high efficiency. In order to confirm this assumption, Q_m and k of the samples were measured with an impedance analyzer, HP4194A. These data are shown in Table 4.

<u>Calculation for efficiency of piezoelectric transformer</u>

$$\text{Efficiency} = \frac{1}{1+\frac{n^2R}{R_L}+(\omega Cd_2)^2 n^2 R R_L}$$

$$\text{Efficiency}_{(max)} = \frac{1}{1+(2\omega Cd_2 n^2 R)} \qquad \left(R_L = \frac{1}{\omega Cd_2}\right)$$

$$= \frac{1}{1+(2\omega Cd_2 RC/C_2)} \qquad \left(n^2 = C/C_2\right)$$

$$= \frac{1}{1+\left(\frac{2}{Q_m}\left(\frac{1}{k^2}-1\right)\right)} \qquad \left(Cd_2/C_2 = \left(\frac{1}{k^2}-1\right)\right) \quad \left(R = \frac{\omega L}{Q_m}\right) \qquad (1)$$

<u>Electromechanical coupling factor and parameters in equivalent circuit</u>

$$1-k^2 = \text{lost energy / input electric energy}$$

$$= \frac{1}{2}CdV^2 \Big/ \frac{1}{2}(Cd+C)V^2$$

$$\Downarrow$$

$$Cd/C = \frac{1}{k^2}-1$$

Table 4. Q_m and k_r measured with HP4194A and calculated efficiency from parameters of equivalent circuit.

Sample No.	Side	Q_m	k_r	Calculated efficiency	Actual efficiency
1	Input	<u>600</u>	0.41	97%	97.5-98%
	Output	420	<u>0.45</u>		
2	Input	<u>860</u>	0.41	98%	97-98.5%
	Output	590	<u>0.43</u>		
3	Input	<u>810</u>	0.36	96%	93.5-94.5%
	Output	310	<u>0.31</u>		

Roughly, sample No.1 and No.2 had the same Q_m, k_r and calculated efficiency, but sample No.3 showed much lower k_r and the lowest calculated efficiency. Comparing the calculated efficiency with the actual efficiency, it was found that these two needed to be close. Thus, Eq (1) seemed to be correct for explaining the efficiency of piezoelectric transformers.

In this experiment we changed the sample thickness in the input or output side. From these data we can see that if the output is thicker than the input, k_r in the output is larger than the input. Namely in this transformer's design with one input and one output, we don't know if this rule can be matched to other models, it seems that a thicker part has larger k_r. However since we have to consider not only k_r but also Q_m for high efficiency, we need to adjust the thickness in the input or output. Here is one example. Sample No.1, which had the thicker output and the largest k_r, but had the smallest Q_m, could not get the best efficiency in these samples. Finally, we were able to obtain the best efficiency from the sample No.2, which had the same thickness on both sides as well as well balanced Q_m and k_r.

As shown in the above results, when designing piezoelectric transformers, it is useful to consider Q_m and k to get high efficiency. Sample thickness influenced k in this experiment, but another design must have a different rule on these values. Once we have a relation between Q_m, k and the sample design, it would become much easier to design a good transformer. We know that there are a few software programs that can design samples or analyze the impedance dependency on the frequency or examine the vibration mode [3] [4]. However it is also important to find specific design rules from experimental data as we have done here.

6. Driving the laptop computer

6.1. Driving condition of laptop

The driving condition of the laptop computer “Toshiba DynaBook SS” was examined with using the original AC/DC adaptor with a coil type transformer. In the normal use condition, the current and voltage to the laptop were measured.

Table 5. Required condition for laptop computer “Toshiba DynaBook SS”

Input current	0.8A
Input voltage	DC15V
Power	12W
Load	18.8ohm

6.2. Measurement under driving conditions of laptop

We examined the sample No.2 at the load of 18.8 ohm, which was done to determine the possibility of using our sample as AC/DC adaptor for the laptop. In this measurement 0.8Arms was set as the output current and the data was recorded every 1kHz in the range from 80 kHz to 95 kHz. In order to check the temperature rise of the sample precisely, a time interval of 4 minutes was set to every 1 kHz.

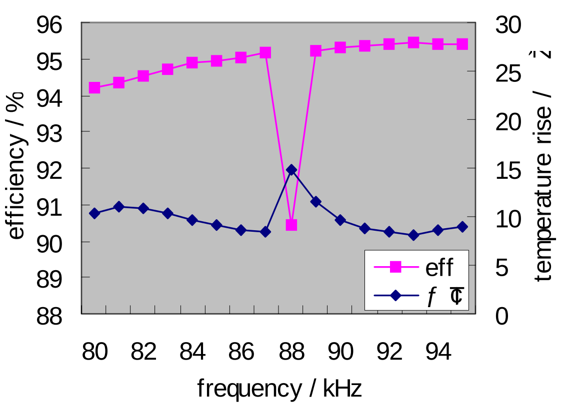

Figure 9. Efficiency and temperature rise under normal condition of laptop computer.

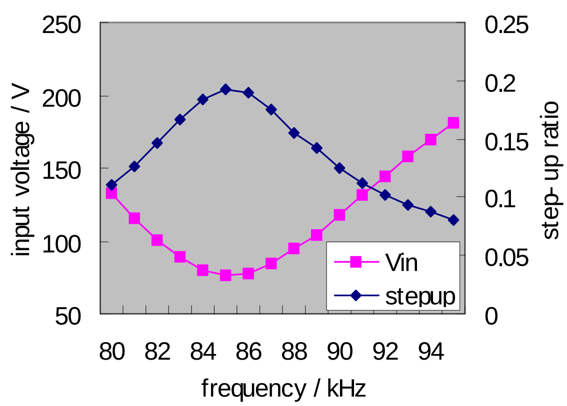

Figure 10. Input voltage and step-up ratio under normal use of laptop computer.

In the range from 80 kHz to 95 kHz the efficiency was shown to be more than 94 %, but at 88 kHz this sample seemed to have a spurious vibration and the efficiency went down to 90 %. It was desirable to get rid of this spurious vibration, however the temperature rise was always kept under 20 and even if at 88 kHz, the data didn’t reach 15 . The conclusion was that we could use this transformer in this frequency range without concern about temperature rise.

Figure 10. showed the required input voltage to make 15 Vrms. In this frequency range, the input voltage could be changed from 75 Vrms to 175 Vrms, which means we can use this transformer in both the U.S. and Japan where the outlet voltage ranges from 100 Vrms to 120 Vrms.

6.3. Driving circuit for AC/DC adaptor

This circuit is composed of an input rectifier, input regulator, inverter, piezoelectric transformer, output rectifier and output regulator. The input rectifier makes DC V from 100 Vrms or 120 Vrms and then on-off signals generated from DC 170 V drive the piezoelectric transformer. The AC voltage from the transformer is changed to DC voltage with the output rectifier and then the output regulator makes DC 15 V to drive the laptop properly. On the other hand, in order to drive inverter IC, the input regulator makes DC 15 V from 100 Vrms or 120 Vrms.

Here we tried to reduce the number of components and to make it as small as possible, and we obtained the prototype AC/DC adaptor that could drive the laptop computer in the U.S. or Japan.

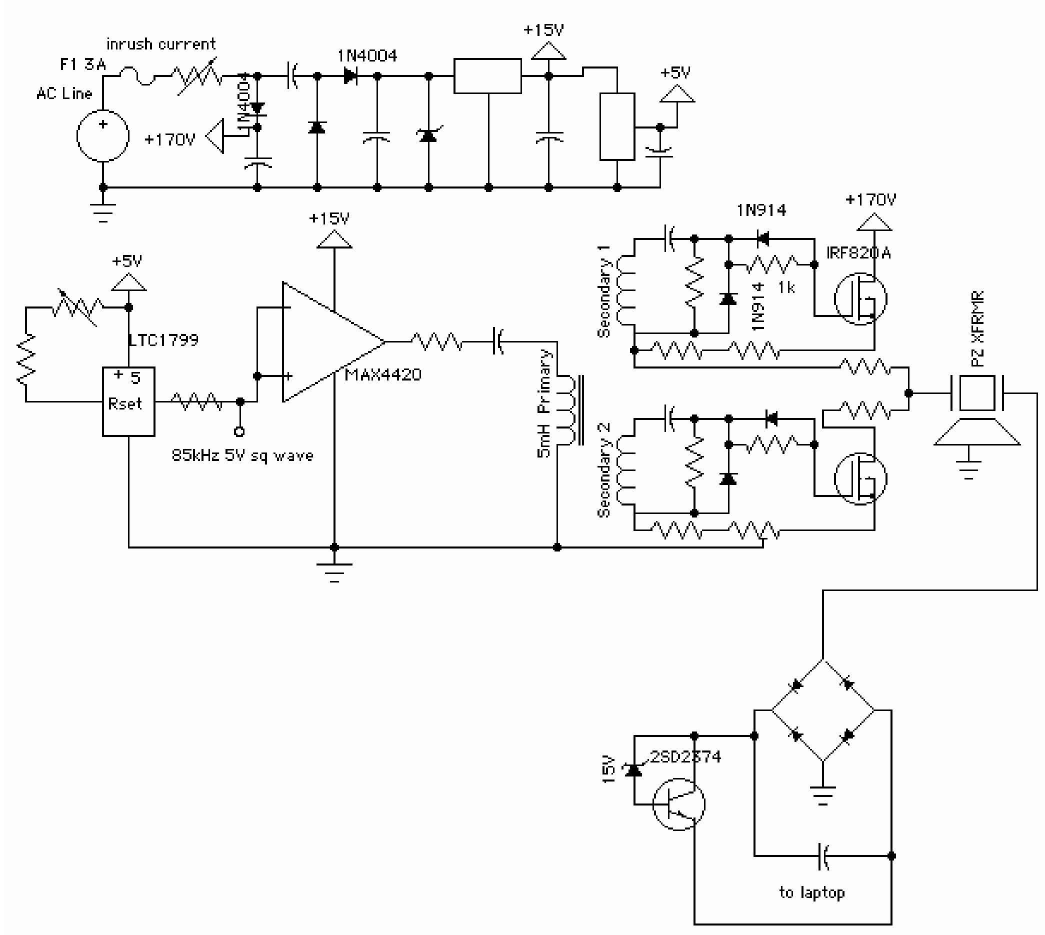

Figure 11. Circuit schematic of AC/DC adaptor for laptop computer

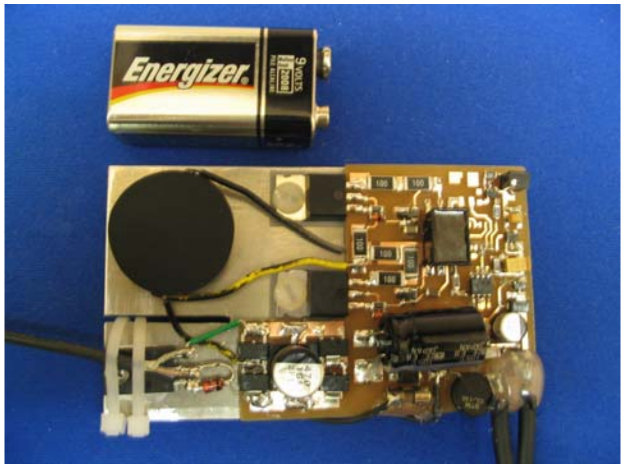

Figure 12. Photo of prototype AC/DC adaptor with piezoelectric transformer

The prototype is shown in Fig. 12. Here are the dimensions of this adaptor. As a result, we were able to reduce the volume to one-third of the original adaptor by using the piezoelectric transformer.

Prototype : Length 80mm×Width 54mm×Height 10mm = 43,200mm^3
(This assumes that there is a plastic case packing the circuit.)

Conventional : Length 105mm×Width 44mm×Height 28mm = 129,360mm^3

7. Conclusions

TRANSONER®, piezoelectric transformer designed by FACE electronics was optimized to high power applications. In the optimizing process, the sample thickness was considered in order to obtain high Q_m in the input side and high k in the output side, which were required for high efficiency or high power. As the result of this experiment we were able to get 30W from a 27 mm diameter sample that had the same thickness of 2.25 mm on the input and output side. The prototype AC/DC adaptor with TRANSONER® was developed in order to drive the "Toshiba DynaBook SS" laptop, and we verified that the adaptor would work under U.S. conditions of AC 120 V or Japanese conditions of AC 100 V. Furthermore this result indicated that TRANSONER® could reduce the volume of conventional AC/DC adaptors to one-third.

The possibility for the adaptor has been verified in this research. However, for the commercialization of adaptors many issues still remain and we will follow up on customer's request more closely in future work. One of these requests surely will be regarding low cost, and in order to respond to it we might have to change the dimensions, the piezoelectric materials, the electrode, the circuit design and so on.

8. References

[1] K. Sakurai, S. Shindou, K. Ohnishi, and Y. Tomikawa, IEEE, Ultrasonics Symposium, pp. 939-944, 1998.

[2] H. S. Jeong, B. C. Choi, J. H. Yoo, I. H. Im, and C. Y. Park, Jpn. J. Appl. Phys., Vol. 38, pp. 5166-5169, 1999.

[3] M. Yamamoto, Y. Sasaki, A. Ochi, T. Inoue, and S. Hamamura, Jpn. J. Appl. Phys., Vol. 40, pp. 3637-3642, 2001.

[4] B. Koc, S. Alkoy, and K. Uchino, IEEE, Ultrasonics Symposium, pp. 931-934, 1999.