Transducers considering Energy Saving

-Super-conductive and Electrostatic Loudspeaker driven by 1 bit Amplifier-

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Abstract

The widely used cone type dynamic loudspeakers have been devised and improved on their materials of magnets and cones, however, their basic structures have not been changed since 1925 when C. E. Rice and E. W. Kellog first introduced the prototypes. It is, in fact, an excellent transducer, and more than 500 million of various sizes is said to be running now in Japan. Yet, efficiency of a transducer, including the amplifier, is less than 0.1%, meaning more than 99.9% of the energy is wasted. This means the total wasted energy equals to the sum of energy produced by 2 of the heat-powered power plant.

This paper presents the test manufacture of the edgeless damper-less super-conductive loudspeaker and high efficiency electrostatic loudspeaker driven by 1bit switching amplifiers. The result being a 30% efficiency of speakers and 80% efficiency of amplifiers, thus, we could gain 24% total efficiency.

1. Introduction

Since April, 1999, Committee for the Next Generation Audio Equipments, established in JAS (Japan Audio Society), has been working hard to improve the efficiency of transducer to the level of solar cells or electric motors, and to conquer the many problems concerning speakers itself. It introduced the floating magnet-typed super-conductive speaker at Spring conference of ASJ(Acoustic Society of Japan) in March, 2001, and underwent demonstrations in the acoustic educational exhibition.

Also in October, 2001, it introduced and presented an edgeless damper-less super-conductive loudspeaker at the Audio-Expo held in the Tokyo Big Site.

2. Challenges in Dynamic Speakers

The construction of a cone dynamic speaker is shown in Fig.1. There are 2 types of resistances: electrical resistance in the voice coil, and mechanical resistance in the edge and damper which holds the cone. Because of them, a big proportion of the given energy is wasted. The efficiency (input electric power to output acoustic power), which had it's height of a few% during the "tube age", is now less than 1% due to the widely popularized transistors and size minimization of

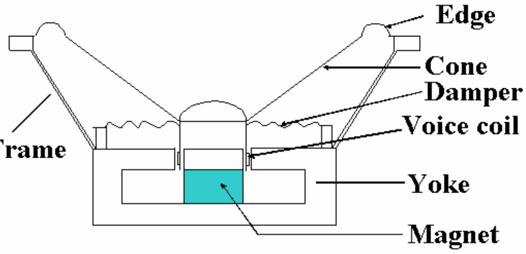


Fig.1 Dynamic Speaker

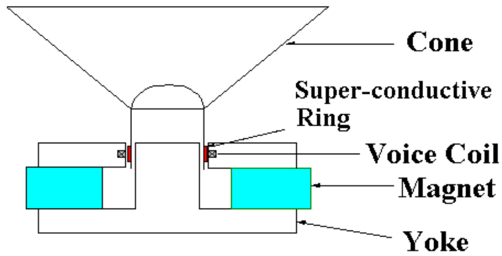


Fig.2 Super-conductive loudspeaker

speakers. Moreover, the efficiency of the amplifiers, however was improved by the introduction of semi-conductors, are still about 10% meaning the total efficiency is less than 0.1%.

In order to improve the efficiency of these cone dynamic speakers, there are needs of minimizing the resistance, reinforcing the magnetic circuit, enlarging the diaphragm, and improving the algorism. Also, the edge and the damper are the cause of distortions. Especially, the edge's restless movement causes the deterioration and destruction over time, thus, shortening the speaker's lifespan.

3. Super-conductive Loudspeaker

3.1. Peculiarity of a Super-conductive State

The super-conductivity has following qualities:

1) the electric resistance becomes 0 and current keeps flowing forever,

2) perfect diamagnetism （Meissner Effect） ,

3) flux quantization where magnetic field is trapped and it magnetically floats,

4) Josephson effect where current flows with 0 voltage. It’s special qualities has been used widely in devices like SFQ device, SQUID device and Josephson device, in recent years.

A super-conductive state had been known to be the special phenomenon within the metals and alloys like mercury and Niobium at a temperature of a liquid-helium(4 K = -269 ℃), meaning very close to absolute zero or lower. However, due to the recent experiments and further investigations by great experimentalists, super-conductive state is now known to be achieved at a relatively easily reached temperature of liquid nitrogen (77 K = -196 ℃).

3.2. Composition of Super-conductive Loudspeakers

By introducing the super-conductive materials into the dynamic speakers, we could expect a strong magnetic circuit, high efficiency due to the deletion of electrical resistance within the voice coil, achievement of edgeless, damper-less speaker by the pinning effect. Plus, the accomplishment of great energy saving can be expected by connecting this with the switching amplifier.

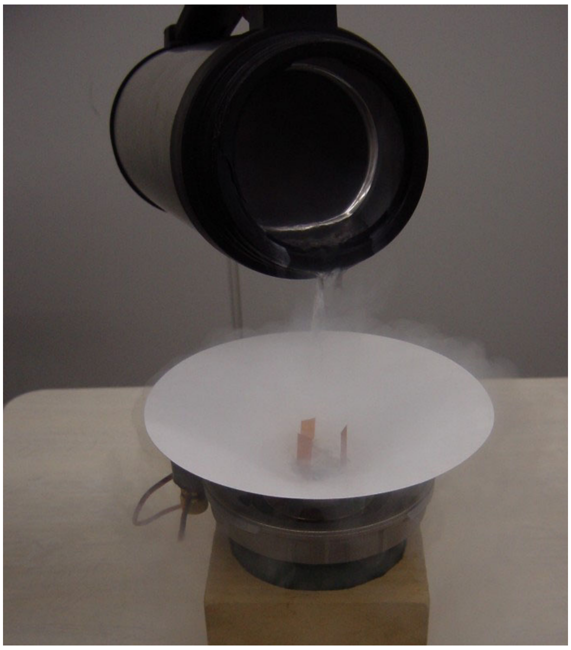
Figure 2 shows the composition of an edgeless damper-less inductive super-conductive loudspeaker we have trial manufactured. By using induction as opposed to the direct connecting of the voice coil, we could make the cone free from electric lines, take out the edge and damper, and float the cone in the air while in use. We used a simple piece of apparatus to hold it until it became super-conductive and let it go after the cooling is done.

In super-conductors, Y-Ba-Cu-O rare earth single crystal super-conductive bulk material QMG (manufactured by Nippon Steal Corporation) was processed into a ring form of 25.6 mm inner and 29.6 mm outer diameters and height of 3.0 mm, and used as 1-turn voice coils.

3.3. Equivalent Circuit

The equivalent circuit of the inductive speaker under super-conductive state is shown in fig. 3. The speaker constants are as follows:

primary voice coil resistance :R_{c1}= 0~5(Ω)
primary voice coil inductance:L_1 =0~1(mH)
secondary coil inductance:L_2=0.01(mH)
coupling coefficient :k =0.5~1
resonance frequency: F_0=153.5(Hz)
resonance Q factor :Q_{mo} =3.60
mass of movement :M_d =2.1 (g)
force coefficient :B_l =0.08 (Tm)
radius of the cone: a =22.5(mm)



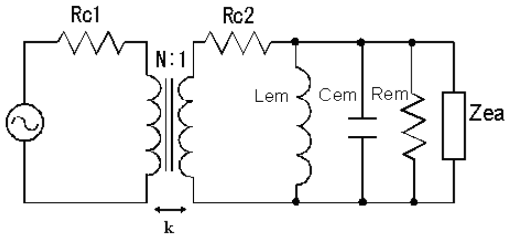
And the relationship between output sound pressure level and the coupling coefficient between the primary and secondary coil under the condition above with driving wattage of 1 W, with the infinite baffle and with the distance 1 m is shown in Fig. 4. . Figure. 5 shows the relationship between resistance value of the primary coil and output sound pressure level. In doing so, we supposed that the coupling coefficient does not change due to the frequency.

As you may see by the equivalent circuit, when the primary coil is also super-conductive and coupling coefficient *k* between primary and secondary is 1, then all of the electrical input becomes a load, thus, as shown in fig. 5, the output sound pressure level rises drastically compared to a conventional speakers, and it should keep on rising according to the frequency rise without concerning the requirement of the movement.

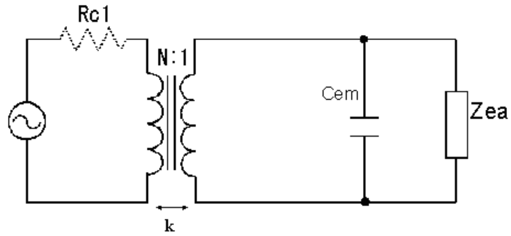
Figure. 6(a) shows the super-conductive speaker's frequency characteristics of the electrical impedance and output sound pressure level taken at the distance of 1m under the input level of 1 W. Figure. 6(b) shows the frequency characteristics under the normal temperature when the secondary voice coil is 1turn of aluminum.

No more than 6 dB/oct of rise rate shown in Fig.5 was able to see because of the primary coil being copper and coupling coefficient not being 1, however, in the middle sound range with 1 W input observed at 1m distance, 110 dB of output sound pressure level was obtained. This is a very high efficiency exceeding more than 20 dB compared to the same-sized cone-type speaker.

The super-conductive loudspeaker driven by a 1bit switching amplifier reaches the efficiency of about 20% in the middle-range sound frequencies.



(a) Normal temperature



(b) Super-conductive temperature

N : turns of primary voice coil
Lem : compliance of movement
Cem : mass of movement
Rem : mechanical resistance
Zea : radiation impedance

Fig.3 Equivalent circuit

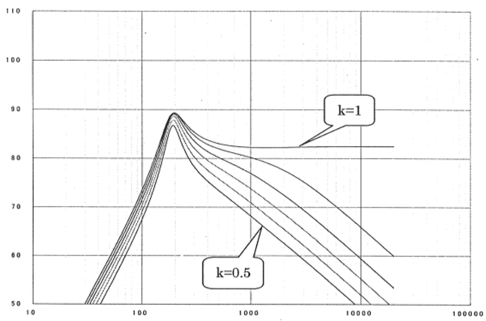


Fig.4 SPL vs *k*

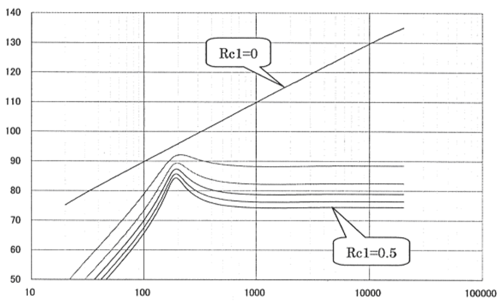
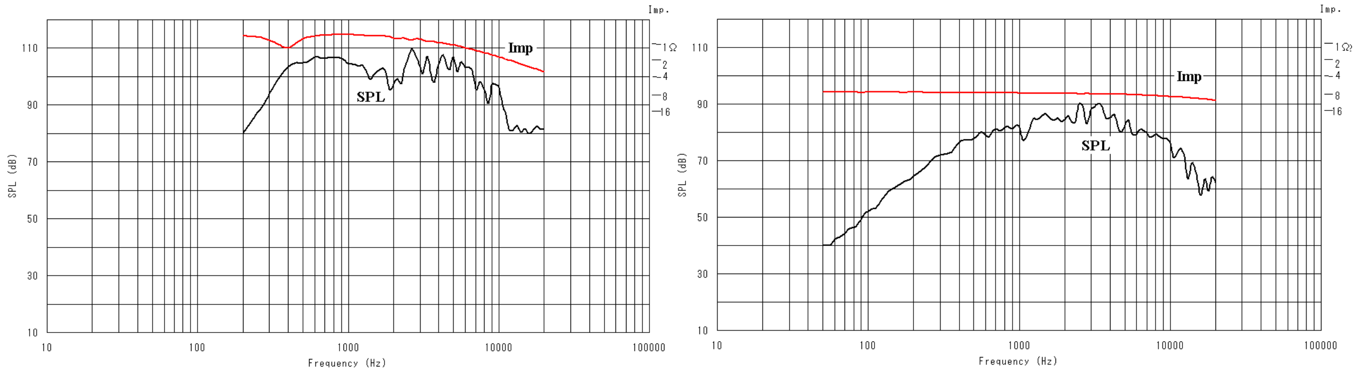


Fig.5 SPL vs R_{c1}



(a) Super-conductive speaker (b) Normal temperature

Fig. 6 Frequency characteristics

4. Electrostatic Loudspeakers

4.1. Composition of Electrostatic Loudspeakers

Electrostatic loudspeakers produce sound by applying a bias voltage between the two parallel electrodes facing each other and adding the input signal to change the aspiration force between the electrodes (see fig. 7). The changes in aspiration force between the two electrodes f [N] is expressed by the following.

$$f \approx \frac{\varepsilon_0 SE}{g^2} e = \frac{CE}{g} e = Ke \qquad (1)$$

C is a capacitance between electrodes and K is a force coefficient. Therefore the aspiration force is proportionate to the area of the electrodes S and bias voltage E, and is in inverse proportion to the square of distance between the electrodes g.

The electrostatic speaker we have test manufactured is a push-pull type like shown in fig. 8 and the exterior looks like this in fig. 9, the parameters are shown in table 1. The diaphragms for both speakers are composed of aluminum deposited polyester which is 50 μm thick.

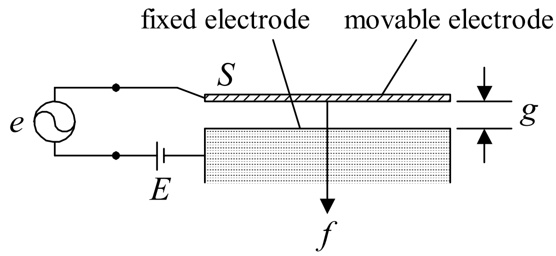


Fig.7 Single ended electrostatic loudspeaker

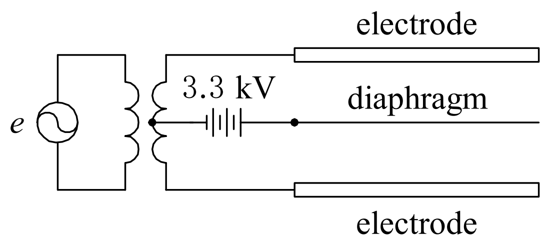


Fig.8 Push-pull type electrostatic loudspeaker

Table 1 : Two prototype electrostatic loudspeakers

	diaphragm area [mm^2]	gap of diaphragm and electrode [mm]	electrode	frame
Speaker 1 (fig.9 left)	560×500	4	punched aluminum	wood
Speaker 2 (fig.9 right)	270×270	5	punched steel	acrylic resin

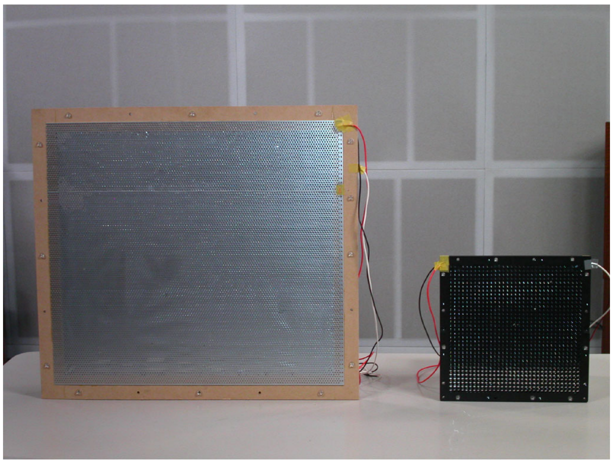


Fig.9 Prototype electrostatic loudspeakers

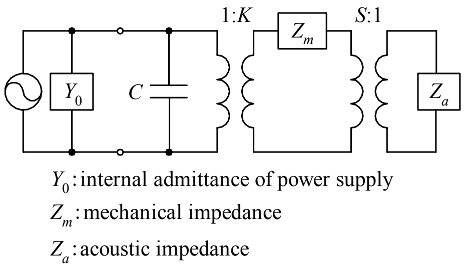


Fig.10 Equivalent circuit

4.2. Transducer Efficiency

Electrostatic speakers are normally said to be an inefficient transducer. However, as one can see by the equivalent circuit in fig. 10, there is no DC resistance in the voice coil, and it is equivalent to that of super-conductive speaker, thus theoretically it has got to be efficient. Then, we gained $v(t)$, and $i(t)$ by organizing a measuring system shown in fig. 11, and found the active power consumption P[W] of the electrostatic speaker.

$$P = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T v(t)i(t)dt \qquad (2)$$

Using the speaker 1, and setting the input signal to a sine wave of 400 Hz, and assuming that the sound pressure at 1 m in front of the speaker is 80 dB, the values of $v(t)$, $i(t)$ is shown in fig. 12. In this state, P became 15 mW. As similar operation was undergone for the speaker 2, the P was 37 mW. Thus, the electric power is not consumed in electrostatic speakers, and most of it becomes reactive power. In conclusion, by connecting the electrostatic speaker with a negative-feedback constant current 1 bit amplifier we could expect to achieve a very highly efficient speaker.

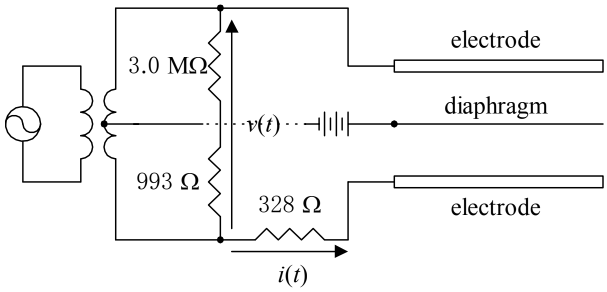


Fig.11 Power measurement

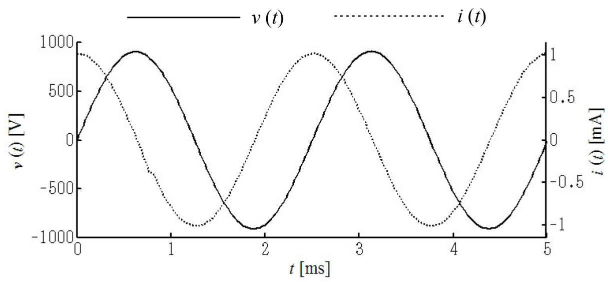


Fig.12 Driving voltage v and current i

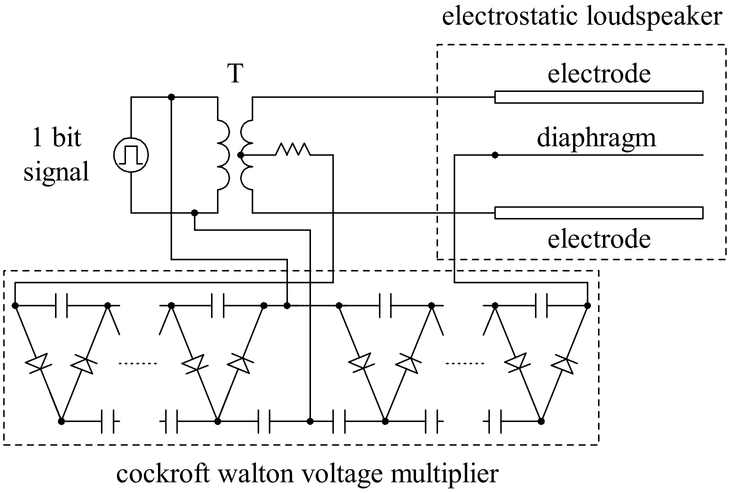
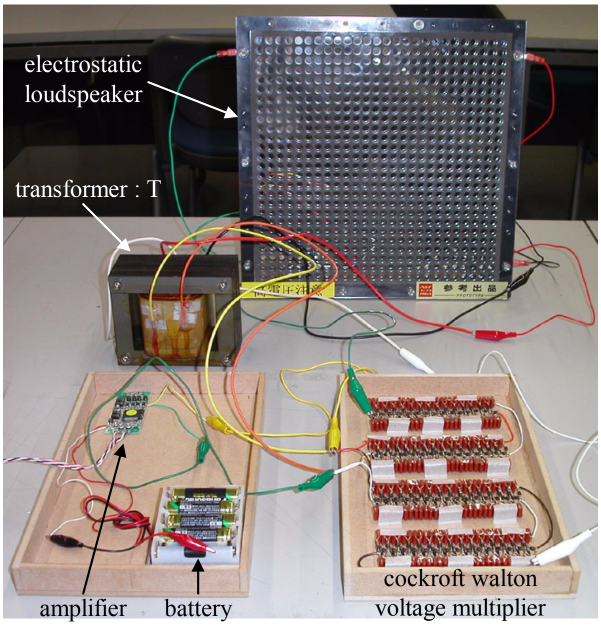
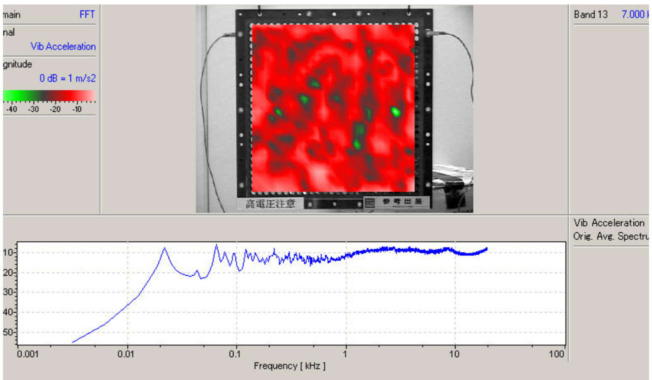


Fig.13 Electrostatic loudspeaker driven by 1 bit signal



System

Polytec Scanning Vibrometer



Vibration and acceleration of diaphragm by Vibrometer

5. 1 bit Driving

It is effective to induce the switching circuit to make amplifiers high in efficiency. The power loss of the switching amplifier is mainly caused by the internal resistance and the switching loss occurred by the gate capacitance and the response delay. Therefore, it is possible to reduce power loss by reducing the number of the switching times as well as by the improvement of the power device. We tried to make a high-S/N amplifier using the usual switching device by inducing "Run Length Limited Coding" in sigma-delta modulator so that high resolution in time domain should be acquired in conditional pulse width. As the result, it is shown by simulation, that a switching amplifier over 100 dB S/N in audible band is available under the condition of more than 1 μs pulse width.

6. Conclusion

The widely used small cone dynamic loudspeakers have a surprisingly low efficiency of electric-to-acoustic transducers, reaching only about 0.1% in pair with amplifiers. Opposingly, the test manufactured edgeless, damper-less super-conductive loudspeaker with a 1bit switching amplifier reaches the efficiency of about 20% in the middle-range sound frequencies. Also the electrostatic loudspeaker with a 1bit switching amplifier accomplishes 30% efficiency.

The electrostatic speaker, shown in photo(left above), runs on 8 AAA batteries and can withstand a continuous drive for 3 days.

We should give a sincere thanking to the members of the Committee for Next-Generation Audio Apparatus of JAS, Nippon Steal Corporation for the manufacturing and offering of the super-conductive materials, North-East Pioneer for their help in test manufacturing the speakers, and the rest of the men who were more than happy to lend their helpful hands for us.

7. References

[1] Heitaro Nakajima, Yoshio Yamasaki, "Edgeless damper-less super-conductive loudspeaker", *J.Acoust.Soc.Japan.*, vol.59,no.10,pp.634-638, 2003.

[2] Yoshio Yamasaki , Heitaro Nakajima, "Prototype edgeless loudspeaker by pinning of superconductor", *In Proc. Meeting JAS.*,pp.517-518, March, 2001

[3] Heitaro Nakajima, Ikuo Chatani, Kouichi Kitazawa, "Super-conductive speaker", *Documents of 50th anniversary seminar of Jpn Audio Soc.*, pp.1-8, Oct.2001

[4] Masanori Okazaki, Yasuhiro Oikawa, Yoshio Yamasaki, "Distance Learning and Conference System using Electrostatic Loudspeakers", *In Proc. Meeting JAS,* pp.571-572, Sep, 2003