Pulse imaging in resonance frequency space

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Abstract. We applied some types of sequent pulses on ensembles of piezoelectric particles, with which some plastic deformations were introduced into particles. These traces were detected electrically and described with the absolute values of the Fourier components of applied pulses. The information of pulse width and pulse separation of multiple sequent pulses was left in the absorption spectrum. These experimental results enabled to explain the memory echo phenomena produced by double pulses with our deformation models.

1. Introduction
A piezoelectric plate has its own resonance frequencies, which are determined with particles dimensions, crystallographic angles and piezoelectric properties. Piezoelectric particles with different dimensions may have different resonance frequencies. When their dimensions in an ensemble of particles are slightly different from each other, their resonance or absorption frequencies spread wide and moderately [1]. When some large amplitude RF pulses are applied to them, some plastic deformation or crystal dislocations can be introduced [2] according to the absolute values of the Fourier components of applied pulses. Crystal dislocations contribute to change the characteristics of oscillation or elastic constants of crystals [3]. These traces are left in the absorption spectrum. We call them the deformation model for pulse imaging [3, 4, 5]. These phenomena can be called a hole burning in the electric field energy absorption by piezoelectric powders [6].

Memory echo phenomena, in which the time interval of applied double pulses is remembered by a third pulse, have been explained by the rotation models [7] or the broken model [8]. However, some contradictory results have been left [9]. We try to explain this phenomenon by our deformation models.

In this report, we showed that the resultant patterns left by application of some kinds of sequent pulses were detected in the absorption spectrum and could be described with our deformation models.

2. Experimental results and discussions
Commercial grade grains of Potassium Bromide KBrO₃ were ground with pestle and mortar. They were sorted with two standard meshes of 105 and 125 μm, whose resonance frequencies ranged from 10 to 40 MHz. We washed them in the ultrasonic bath filled with ethyl alcohol to wipe out electro-statically adhered small particles. After that, they were dried at temperature of 50 °C for about 24 hours. After sieved again, we packed them into a parallel plate condenser with surface of 8 x 12 cm² separated by 1 mm. The number of packed particles was about 10⁶. The shapes of the obtained particles were irregular and crystallographic angles were at random. The condenser was sealed with plastic plates and kept at a vacuum of about 0.1 Pa.
We used the timing circuit (EG&G 9650) and the RF pulse generator (Matec 7700+760V) to apply pulses. With these equipments, we could apply pulses that start at any time. As the instrument was the pulse generator in this case, the frequency had some ambiguity. And we used a combination of the time circuit of the gated amplifier (Matec 5100+515A) and the RF synthesizer (R&S SMX), where the frequencies of pulses are definite. However, as the pulses were cut out from the continuous RF sine wave supplied by the synthesizer, the starting time of sequent pulses are limited. Both systems provided pulses with pulse width up to 50 μs, repetition rate up to 50 Hz and pulse separation up to 50 μs. The maximum amplitude of electric field was about 400 Vpp/mm.

We detected the resultant spectra written by pulses by measuring impedance of the capacitor filled with the specimen particles. We used two methods. One was to measure the absolute complex impedance with the impedance meter (YHP 4193A). As its sensitivity was low, we could not detect the subtle spectrum change written by low amplitude pulses. The second measurement system was an electric magic-T, with which we could obtain the difference between before and after application of pulses. The magic-T had four terminals. The continuous RF sine waves introduced into the first terminal were divided between the second and third terminals. We connected the sample condenser to the second terminals and the reference load to the third ones, which is composed of a variable resistance and a variable condenser connected in parallel. When the balance of impedance of them was attained by tuning two variables, no output was brought to the fourth terminals. However, the matched frequency area was rather narrow and the output from the fourth terminal depended sometimes moderately or linearly upon the frequency. When the balance was broken by change of characteristics of particle oscillation, which were introduced by application of pulses, the output was obtained and showed the difference between before and after application of pulses. The output from fourth terminal was multiplied with reference RF waves and divided into the real and imaginary part of complex impedance of the condenser filled with specimen. Here, we showed only the real parts.

In Fig. 1, we show the spectrum attained by application of pulse sequence 2-5-2. We show pulse sequence as Δ-τ-Δ-..., with Δ of the pulse width and τ of the pulse interval. Here we mean the pulse interval is the time difference between the start positions of the sequent pulses. So in this case of 2-5-2, the pulse width was 2 μs and the pulse interval 5 μs. The frequency of the carrier wave $f_0$ was 20 MHz and total pulse number was in the range of $10^4$. The resultant spectrum is well described by our deformation model with the expression of the absolute values $F$ of the Fourier component of applied pulse sequence as:

$$F(f) \propto \left| \int_{\frac{\Delta - \tau}{2}}^{\frac{\Delta + \tau}{2}} \frac{\exp[i2\pi(f-f_0)\tau]}{2\pi(f-f_0)\Delta} \right|$$

$$= A \frac{\sin[2\pi(f-f_0)\Delta]}{2\pi(f-f_0)\Delta} \cos \left[ 2\pi(f-f_0)\frac{\tau}{2} \right]$$

(1)

Here, $A$ is a positive constant. The spectrum pattern contains information of the pulse width and the pulse separation. The gated amplified was used.

In Fig. 2, we show the resultant spectrum attained by three sequent pulses of 2-10-2-10-2. We used gated amplifier with carrier frequency $f_0$ 19.3 MHz. The calculated valued $F$ is expressed as:

$$F(f) \propto \frac{\sin[2\pi(f-f_0)\Delta]}{2\pi(f-f_0)\Delta} \left\{ 1 + \cos \left[ 2\pi(f-f_0)\frac{\tau}{2} \right] \right\}$$

(2)

This explains well the experimental results.
In Fig. 3, we show the results of four sequent pulses described by 2-5-2-5-2-5-2. The carrier frequency $f_0$ was 16 MHz and total pulse number was $10^4$. The calculated value $F$ of this case is expressed as

$$F(f) \propto \frac{\sin[2\pi(f-f_0)\frac{\Delta}{2}]}{2\pi(f-f_0)\frac{\Delta}{2}} \left\{ 4\cos^2\left[2\pi(f-f_0)\frac{\tau}{2}\right] - \cos\left[2\pi(f-f_0)\frac{\tau}{2}\right] \right\},$$

and describes the resultant spectrum very well.

**Figure 1.** The detected spectrum attained by 2-5-2 and calculated curve.

**Figure 2.** The detected spectrum attained by 2-10-2-10-2 and calculated curve.

In Fig. 4 we showed the obtained spectrum labeled as 1-10-1, which was introduced by applying two pulse sequence with the pulse width $\Delta$ of 1 $\mu$s and the pulse separation $\tau$ of 20 $\mu$s. We applied pulses with the pulse generator. The carrier frequency $f_0$ was set as 17.5 MHz and total number of pulses was about $10^3$. The calculated value as shown describes the experimental results very well. The data detected after 30 days are also shown and the height decreased and the figure became ambiguous, which means that the deformation could relax as the time passed and crystal dislocations moved and decreased. The rotation and broken model do not explain the decrease of memory echo height with time passing.

The specimens used to show results in Figs. 1 and 3 were rather fresh. And the obtained signals are scattered. On the contrary, the specimens used to show the results shown in Figs. 2 and 4 were applied with many pulses at many frequencies and the signals are steady. We explain these results with our deformation model as the deformation condition of particles were reflected on the spectrum.

The experimental results well described by our deformation model can be applied to describe the memory echo, in which the time interval of double pulses is memorized.
3. Conclusions
We described the resultant spectrum introduced by applied sequent pulses with the absolute values of the Fourier components of applied pulses, which based on the deformation model. The results that the spectrum became ambiguous or opaque as the time elapsed were also understood by the recovery of deformation of particles. We proposed to explain the memory echo phenomena by our deformation models.

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