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Relationship between performance of transducer and piezoelectricity at ultralow temperature

極低温環境における振動子の性能と圧電性の関係

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1. Introduction

Ultrasonic transducer is applied to several extreme environments, for example, in a high temperature, high vacuum, and a high magnetic field.[1-3)] An ultralow temperature is near a liquid helium temperature, 4.2 K. The temperature is an important extreme environment in the advanced scientific research area because a quantum-mechanical effects control physical phenomena in this temperature.

We have already reported a transducer for ultrasonic motor driven in ultralow temperature condition.[4)] Our ultrasonic motor had higher rotation speed than previous other types of actuators which have similar dimension.

In this paper, we discuss a relationship between the performance of the transducer and piezoelectric constant of ferroelectric material. The transducer's performance and piezoelectricity have different temperature dependency. The performance of the transducer is influenced by not only decreasing piezoelectricity but also decreasing vibration performance of metal structure at ultralow temperature.

2. Evaluation of piezoelectricity

Piezoelectric constant d_{31} was evaluated from room temperature to ultralow temperature. A resonance-antiresonance method was used for measuring d_{31} at ultralow temperature.[5)] PMN-PT single crystal and PZT ceramics were evaluated in this study. A relationship between the temperature and d_{31} is shown in **Fig. 1**.

PMN-PT has higher piezoelectricity than PZT at each temperature. The d_{31} of PMN-PT and PZT are 59.3 and 29.1 pC/N at 4.5 K.

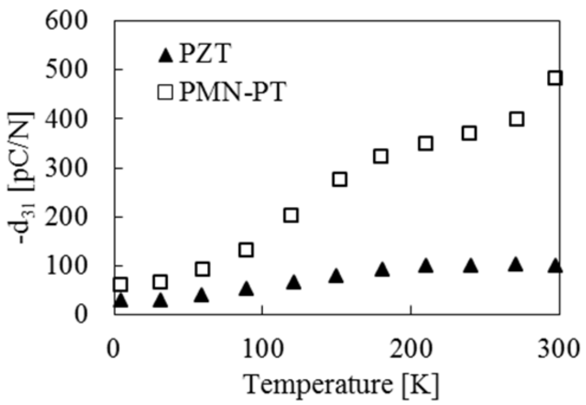

Fig. 1 Relationship between temperature and piezoelectric constant d_{31} [5)]

3. Structure and principle of transducer

A structure of the transducer is shown in **Fig. 2**. The transducer is composed a transducer body with flange, a bolt, a nut, two ring electrodes, quartered electrodes, and a two piezoelectric rings. The piezoelectric rings are cut out of a PZT ceramics plate or PMN-PT single crystals plate. The diameter and length of the transducer is 6 and 16 mm, respectively. The transducer has a flange at a node of vibration mode. The diameter of the flange is 20 mm.

The transducer vibrates in two flexural modes in each perpendicular direction when sinusoidal wave voltage which has phase difference at 90 deg was applied to quartered electrodes. The transducer is a bolt-clamped Langevin-type transducer (BLT). BLT can consist of suitable material in ultralow temperature environment. The thermal stress generated by temperature falling was simulated by finite element method.[6)] The transducer is assembled with applying the pre-load calculated by using the result of the simulation.

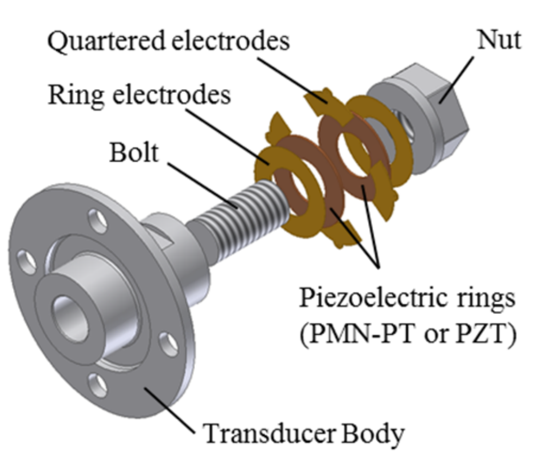

Fig. 2 Structure of transducer for ultrasonic motor

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3. Performance of transducer

A high power transducer has high conversion efficiency from input energy to mechanical energy and low inner loss. The performance index is defined.

An equivalent circuit model of a transducer is shown in **Fig. 3**. The model is described as a performance near a resonance frequency. C_d, C_m, L_m and R_m are parallel capacitance, series capacitance, series inductance, and series resistance, respectively. C_d is electrical component of transducer. C_m, L_m, and R_m are mechanical component. Input energy is divided electrical energy and mechanical energy. A ration between mechanical energy and electrical energy is expressed in the following equation.

$$\gamma=\frac{C_d}{C_m}. \quad (1)$$

The energy ratio is defined by capacitance ration γ. If γ is small, the performance of a transducer is large.

A transducer has internal loss including some loss in metal structure, piezoelectric material and composition surface. The loss is reciprocal number of mechanical quality factor Q_m. If Q_m is large, the loss of a transducer is small.

Therefore, a high power transducer has large Q_m and small γ. A performance factor of a transducer M is defined by a combination of γ and Q_m in following equation.[7)]

$$M=\frac{Q_m}{\gamma}. \quad (2)$$

4. Evaluation of transducer

The fabricated transducer was evaluated about vibration performance from room temperature to ultralow temperature. An ultralow temperature was obtained by liquid helium gas in a cryogenic evaluation system.[6)] The applied voltage was 10 $V_{p\text{-}p}$.

The M is shown in **Fig. 4**. The pre-load of the transducers is optimized at 4.5 K. At 120 K, the performance of the transducer using PMN-PT couldn't be measured because two resonance frequencies were measured. From this result, using PMN-PT realized high performance at ultralow temperature. The transducers have sharply decreasing of M from 210 to 300 K. This sharply decreasing wasn't shown in piezoelectric constant d_{31}. The decreasing is considered to be influenced by inner loss of the metal structures.

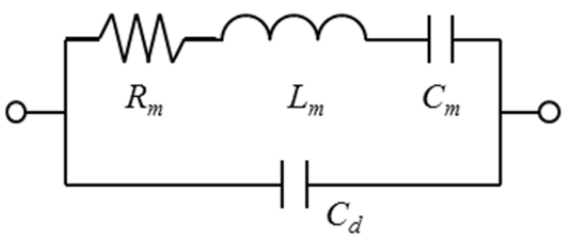

Fig. 3 Equivalent circuit model of transducer

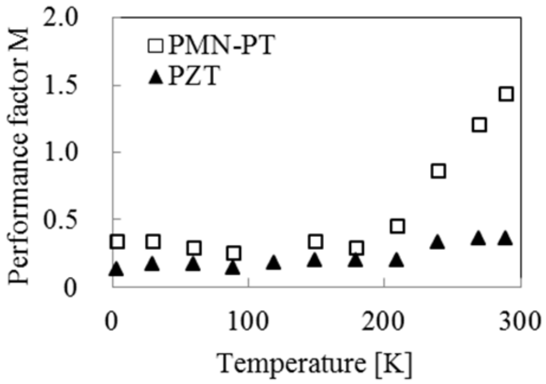

Fig. 4 Relationship between temperature and performance factor M

5. Conclusion

The performance of transducer and piezoelectric constant has different tendency with temperature. The difference was affected by changing mechanical loss of not only ferroelectric materials but also metals. Some decreasing of mechanical property is large factor at ultralow temperature.

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