論 文 の 内 容 の 要 旨

論文題目　Nonlinear Modeling of Piezoelectric Transducers under High-power Operation
（ハイパワー駆動時における圧電振動子の非線形モデルに関する研究）

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Lead-free piezoelectric material potassium sodium niobate (K,Na)NbO_3 (KNN) has proved to be a promising substitute for lead-based piezoelectrics. In this thesis, CuO-doped KNN ceramics were synthesized using the hydrothermal method; and a method was proposed to enhance the quality factor Q_m on the basis of acceptor doping. To estimate the high power properties of the CuO-KNN ceramics, the phenomena and mechanism at high power conditions were systematically studied. A nonlinear model on the basis of burst mode results was proposed and proved to be efficient in estimating the high power characteristics. Simulations were given to help the comprehension of the exhibited phenomena and the initial mechanism. The main conclusions are as follows:

In chapter 1, the principle, categories, constitutive equations, applications, and the lead-free tendency of the piezoelectrics were introduced. Niobate piezoelectrics (especially potassium niobate $KNbO_3$ and sodium niobate $NaNbO_3$, as one family of the most promising lead-free substitutes for PZT, and hydrothermal methods adopted in this study were then introduced. The serious limitation of high power characteristics and thus developed evaluation methods were presented at last.

In chapter 2, the hydrothermal synthesis processes of $KNbO_3$ and $NaNbO_3$ powders and the ensuing solid state reaction of $(K_{0.48}Na_{0.52})NbO_3$ ceramics were listed first. Then we explained the experimental details of the burst mode method, the estimation of various properties, and their calculation methods.

In chapter 3, pure and CuO-doped KNN ceramics were prepared on the basis of $KNbO_3$ and $NaNbO_3$ powders fabrication. CuO-KNN ceramics was fabricated via a hydrothermal method and solid state sintering. The crystal structure of CuO-KNN was similar to that of pure KNN and corresponds to an orthorhombic single phase without impurities. In the experiments, we found that the extra post-annealing process did not change the phase of the CuO-KNN ceramics; however, the intense transitions of the domains in the ceramics that occurred after post-annealing caused a change in Q_m. Q_m was decreased to a small value by the post-annealing process and recovered gradually over several hours. We believe that this phenomenon can be attributed to the rearrangement of oxygen vacancies in the domains. The validity of a new method to enhance the Q_m of CuO-KNN ceramics was then investigated and discussed. A post-annealing process in an oxygen-deficient atmosphere was used to increase the amount of oxygen vacancies, which could impede the movement of the domain structures, and thus increased Q_m. In the case of annealing in argon, Q_m was increased to approximately 1500 from 950, whereas post-annealing in oxygen resulted in a decrease of Q_m.

In chapter 4, prior to the estimation of the high power characteristics for CuO-KNN ceramics, the investigation on nonlinear behavior in PZT transducers was carried out. Nonlinearity in high voltage admittance curves and burst mode method were presented and discussed consecutively. The burst mode method was used at first to measure the vibration velocity of the transducers after excitation by a burst voltage. The equivalent mechanical loss and equivalent spring constant were determined by the decay rate of the vibration velocity and the resonant frequency. Both of them were found to be functions of velocity amplitude, suggesting that nonlinearity should be considered when the transducers are driven at high power. Admittance curves at high voltages corroborated the presence of nonlinearity in PZT transducers. In the admittance curves of the hard-type transducer, a jumping phenomenon and an admittance hysteresis between different sweep directions appeared. A model taking into account the nonlinearity was proposed and adopted to fit the admittance curves. It was demonstrated to be effective in describing the admittance hysteresis and jumping observed in the case of the hard-type PZT transducer and the deformation admittance curve for both PZT transducers. The curve fitting yielded the nonlinear coefficients and force factor. In the ensuing discussion, we concluded that in the admittance curve, the mechanical nonlinearity was the main source instead of the dielectric and piezoelectric nonlinearities. At last, through theoretical derivation of the piezoelectric constitutive equations, dimensionless coefficients were suggested for the comparison of samples with different sizes.

In chapter 5, using the proposed nonlinear model in chapter 4, the estimation of fabricated CuO-KNN transducers were carried out. The comparison of nonlinear levels between PZT and CuO-KNN transducers was then given and discussed. Similar to the hard-type PZT, the admittance curves of the CuO-KNN transducers at high voltages also have serious deformation, significant jumping, and admittance hysteresis. The proposed nonlinear model enabled the determination of nonlinear coefficients; using which the prediction of admittance curves at other voltages was realized. In the burst-mode method, the nonlinearity at high voltages was confirmed. The results obtained from the burst mode results were found to be consistent with the admittance curve measurements. Combining the velocity-time and current-time curves, it was found to be possible to determine the piezoelectric coefficients. Compared with the PZT transducers, lead-free CuO-KNN transducers were less dependent on high-velocity condition. Along with the high Q_m, CuO-KNN is a promising material for high-power applications. This method can be used to analyze the nonlinearity in piezoelectrics, and the two nonlinear coefficients can be regarded as criteria for assessing piezoelectric transducers driven at high voltage. The comparable results of admittance curve measurement and burst mode method suggest that the two methods can be substitutes for each other in estimating the nonlinearity level. The feasibility of the model without considering the dielectric nonlinearity and piezoelectric nonlinearity also indicates that the jumping and admittance hysteresis in the admittance curve results from the mechanical nonlinearity.

In chapter 6, we carried out the simulations of nonlinear circuits for better understanding of the appeared nonlinear phenomena. The nonlinear behaviors were further investigated in this chapter; *G*-*B* circles of PZT transducers were depicted to illustrate the jumping behavior. Using the proposed nonlinear model, the simulations of current jumping in frequency response and voltage response were realized. All of the parameters: two nonlinear coefficients ξ, η, and voltage amplitude can affect the jumping phenomena (resonance frequency shift, half bandwidth change, appearing and disappearing of the jumping) separately and together. For practical usage, a simplified method for estimating the nonlinear level was proposed. The nonlinear coefficients can be obtained via simple calculation from the feature points in low voltage and high voltage admittance curves. The definition and calculation of quality factor under high power operation were discussed; based on the nonlinear coefficients it is also possible to determine Q_m at high power condition. We also presented the comparison of nonlinearities between the present studies and other conditions; simulations of *P*-*E* hysteresis loops and strain-field loops were realized. The results supported our discussion that the admittance hysteresis and *P*-*E* hysteresis were different in essence.