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Nonlinear modeling of Bolt-clamped Langevin transducer and measurement of nonlinear elastic coefficients
ボルト締めランジュバン振動子の非線形モデル化および非線形弾性係数の測定

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1. Introduction

Bolt-clamped Langevin transducers (BLT) are widely used for high-power applications such as sonar, surgical knife, wire bonding machines and so on.[1)] High-power drive is possible by applying compressive preload because piezoelectric material degrades its performance because of tensile stress. However, the optimum preload design has not been established. It is known that some properties of piezoelectric material depend on the preload.[2)] Paying attention to the fact that the vibration velocity is saturated because of the nonlinear effect of the piezoelectric material [3)], design guidelines can be considered by elucidating the relationship between preload and nonlinear effects.

In this study, introduced the nonlinear elastic coefficients in the transfer matrix method, the nonlinearity of the BLT were analyzed, and nonlinear coefficients were calculated from admittance curve.

2. Nonlinear model

In the previous study, in order to express the nonlinear effect of the piezoelectric material, we introduced third order teams of *C* and *R* into the *LCR* equivalent circuit of piezoelectric material.[4)]

Further, a third order term of strain was put into the relationship between stress T and strain S as shown in equation (1). This stiffness $\overline{c^E}$ is complex stiffness, and the real part expresses elasticity and the imaginary part does mechanical damping. In order to apply the nonlinear elastic coefficient to the transfer matrix method, equation (1) is transformed to (2). S' is amplitude of strain.[5)]

$$T = \overline{c_{(1)}^E} S + \overline{c_{(3)}^E} S^3 \qquad (1)$$

$$T = \overline{c^E}' S, \quad \overline{c^E}' = \overline{c_{(1)}^E} + \frac{3}{4}\overline{c_{(3)}^E} S'^2 \qquad (2)$$

Transfer matrix parameters for piezoelectric material depend on material constants and dimensions.[6)] By setting the stiffness for obtaining sound velocity to $\overline{c^E}'$, nonlinear vibration can be expressed.

The $\overline{c^E}'$ is nonlinear parameter which is a function of strain. Therefore, even if you calculate the strain distribution with certain $\overline{c^E}'$, $\overline{c^E}'$ itself is modified from initial value by obtained distribution. Therefore, the loop calculation is indispensable to satisfy consistent $\overline{c^E}'$ and strain distributions.

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Table I 33mode nonlinear coefficients of C203 (measurement by *LCR* equivalent circuit)

Real part	$\overline{c_{33(3r)}^E}$	-6.2×10^{16} [N/m^2]
Imag part	$\overline{c_{33(3i)}^E}$	5.1×10^{15} [N/m^2]

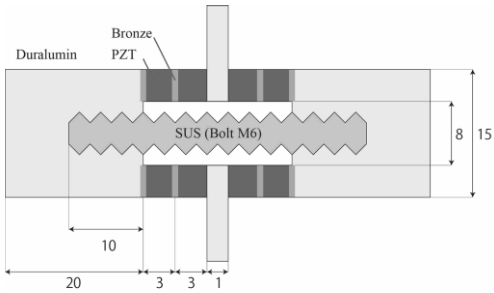

Fig. 1 Sectional view of BLT model

3. Simulation without clamping bolt

Simulation was carried out with the model shown in **Fig. 1**. Material parameters for C203 (Fuji Ceramics Corp.) were used as the material constants for PZT part. **Table I**, which is measured by the equivalent circuit using plate-shaped transducer, was adopted as the nonlinear coefficients.

In general, the mechanical loss is difficult to be modeled because it is composed inner friction, holding mechanical loss, air damping and so on. Therefore, Q factor for each materials is determined from actual measurement. In the simulation, Q factor of duralumin parts was settled as 1000.

In advance of experiments, studied with a simple model that does not include the clamping bolt inside the transducer. Nonlinear effect such as decrease of Q factor and of resonance frequency, hysteresis and jumping phenomenon were confirmed

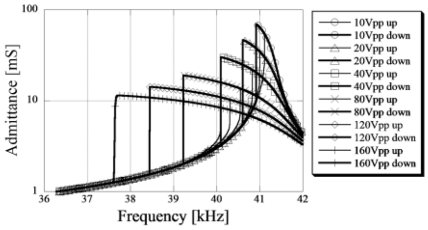

Fig. 2 Simulated admittance and velocity curve

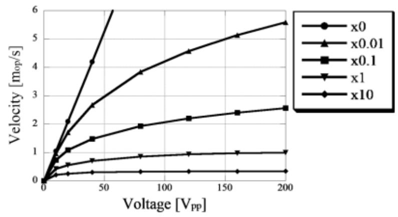

Fig. 3 Vibration velocity calculated by changing nonlinear coefficients

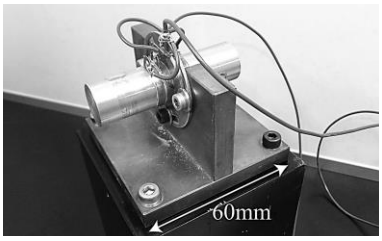

Fig. 4 BLT produced

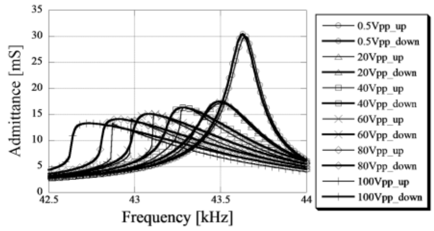

Fig. 5 Admittance curve of experiment

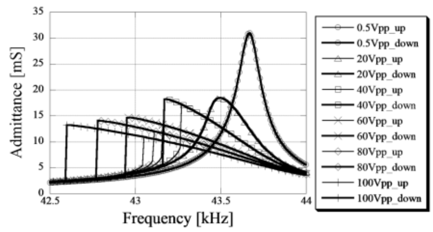

Fig. 6 Admittance curve of simulation

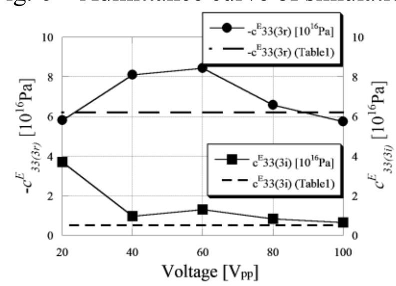

Fig. 7 Calculated nonlinear coefficients

in frequency response of admittance as shown in **Fig. 2**. **Fig. 3** shows the relation between driving voltage and vibration velocity. The calculation was conducted with various nonlinear coefficients from 0 times (linear model) to 10 times to the parameters shown in Table I. This result shows that it is suggested that the nonlinear coefficients dominantly contribute to the saturation of the vibration velocity.

4. Experiment and simulation

A BLT having the same shape as the simulation model was fabricated as shown in **Fig. 4**. Tightening torque was set to 10 [N·m] using a torque wrench.

Fig. 5 shows the measured admittance curve. The linear parameters for modeling was calculated from the admittance with 0.5 V_{pp} input voltage. By increasing the applied voltage amplitude, the nonlinear effect became remarkable. Then, the nonlinear parameters were calculated by curve fitting for each voltage using the obtained linear parameters. The admittance curve was calculated as shown in **Fig. 6**. The overall nonlinear effect could be reproduced.

The nonlinear coefficients obtained as a fitting parameters are shown in **Fig. 7**. Not as expected, nonlinear parameters were not constant and depended on the driving voltage. However, at the same time, they are not far from the expected values indicated in Table I as shown by the broken line. At present detail consideration is going on.

5. Summary

By introducing nonlinear elastic coefficients into the transfer matrix method, it became possible to analyze the nonlinear effect appearing in admittance and vibration velocity of BLT. It was confirmed that nonlinear elastic coefficients can be obtained from admittance measurement.

References

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