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Jump phenomena of current in PZT-vibrators due to nonlinear damping of surrounding media

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Abstract

In some applications, surrounding media influence oscillating behavior of PZT vibrators by non-linear damping. This usually results in current jump phenomena of the supply. Such effects have been studied in detail under both atmospheric air pressure and vacuum. For a rate estimation about the influence of nonlinear crystal properties and of nonlinear damping the media influence has been minimized by driving the ceramic under low air pressure (1 Pa). Under these conditions the measurement showed a slightly higher current amplitude but no jump phenomena. This indicates that the velocity dependant damping of the air surrounding the actuator is the main reason for the jump phenomena.

Keywords: Actuators; Piezoelectric properties; PZT

1. Introduction

Piezoelectric actuators transfer electrical quantities like voltages or charges into mechanical displacements or forces. A special class of these actuators, known as ultrasonic transducers, are driven at resonant frequency. Depending on the direction of polarization and deflection piezoelectric actuators can be divided into three main groups:

- axial actuators (d_{33}-mode),
- transversal actuators (d_{31}),
- and flexural actuators (d_{31}).

In this paper, only investigation of transversal actuators will be presented, due to low resonant frequency and high forces attainable. High power transversal piezoelectric actuators are used for ultrasonic cleaners, piezoelectric vibrators and machining cutters. Besides heat generation and mechanical breakdown the jump phenomena effect stability of oscillation especially in high voltage applications. The significant change of the deflection amplitude at one frequency is called jump phenomenon. This "jump" frequency is different for measurement with increasing or decreasing frequencies (Fig. 8).

The influence of higher harmonics of current due to the ferroelectric hysteresis on the jump phenomenon was studied in Ref. 1. Previous investigations also focused on the influence of media surrounding the piezoelectric ceramic on the jump phenomena.[2] But so far, no work has been found excluding this influence by measuring under vacuum conditions. This approach enables exclusion of all media influences on crystal property measurement.

2. Experimental

The material chosen for the investigation was conventional PZT-ceramic (PIC 151) configured in rectangular bars coated with electrodes on top and bottom. For more detailed information about chemical composition and physical properties see Ref. 3. The ceramic had a high Young–modulus and a high mechanical quality factor.

Dimensions of the PZT-monomorphs were $(L\times W\times H)=(42\times 15\times 0.25)$ mm^3. The experimental setup is shown in Fig. 1. All measurements were carried out at room temperature.

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Two soldered wires connect the monomorph with the outside of the vacuum chamber. These connecting wires are the only mechanical contacts to the monomorph inside the chamber. The actuator is hanging on the top wire and is not pulled down by the bottom wire. The weight of wire and actuator can be neglected, so there is no extra tension through the wires.

The experimental setup made it possible to evacuate the chamber without any other change (e.g. resistivity of the wires). Measurements under vacuum and normal pressure were both possible.

The resonant frequency for deflection along the length L can be calculated by the use of the planar frequency constant (N_P^E) of the material and

$$f_s = \frac{N_P^E}{l} = \frac{1817\text{Hzm}}{42\text{mm}} \approx 43\text{kHz} \quad (1)$$

on the condition ($L \gg H$).

A resonant frequency f_w in direction of the width W of 120 kHz has been calculated by the use of Eq. (1).

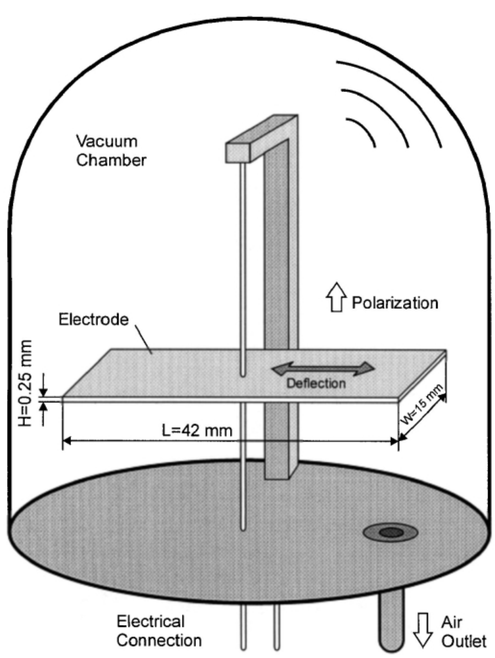

Fig. 1. Experimental setup.

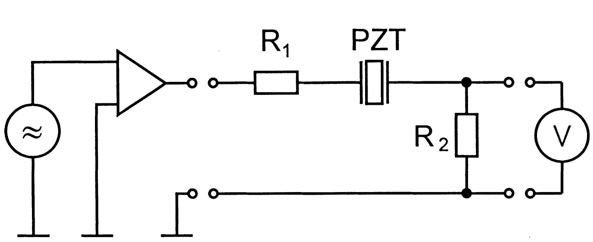

Fig. 2. Electrical setup.

For calculation of the resonant frequency of deflection in direction of polarization the axial frequency constant ($N_3^D = 1384$ Hz m) was used. It is 5.5 MHz.

It was shown that both other resonant frequencies are lying outside the investigated frequency range 35–50 kHz around the resonant frequency f_s for deflection along the length L.

The electrical setup is shown in Fig. 2. The voltage provided by a frequency generator was amplified by additional amplifier modules to an input voltage of 5 to 40 volts peak to peak. Resistor R_1 limited the current through the piezo monomorph, but also reduces the voltage over the ceramic.

3. Results

The dependence of the resonant frequency on different input voltages was checked first. Fig. 3 shows the current through the measuring resistor R_2. All measurements were done with increasing frequencies rising from 20 to 60 kHz. For basic statements, it was not necessary to repeat the measurement with decreasing frequencies. The mechanical resonant frequency in all three cases is located at the inversion (at 42.5 kHz). In Fig. 3, it is shown that there is no essential shift of the resonant frequency.

This measurement was done for classification of the following investigations and to verify the calculated resonant frequency. All other measurements were only done at 40 volts peak to peak, because the jump phenomenon especially appears at high power levels. The jump phenomenon may be recorded in both in deflection and in current. To clearly show the effect the curves of current were recorded with increasing and decreasing frequencies.

Fig. 4 shows the current through the PZT-monomorph measured in normal air pressure. Corresponding to Ref. 4, an obvious difference between both curves can be recorded. Additionally the abrupt slope change of the curve close to the upper inversion point can be seen. The measured current was derived by the frequency for determining the slope change (see Fig. 5).

Seen in electrical engineering the PZT-monomorph can be described as a capacitor.

$$U = \frac{1}{C}\int I \mathrm{d}t \quad (2)$$

From this follows:

$$\frac{\mathrm{d}U(t)}{\mathrm{d}t} = \frac{1}{C} I(t) \quad (3)$$

and in the frequency range:

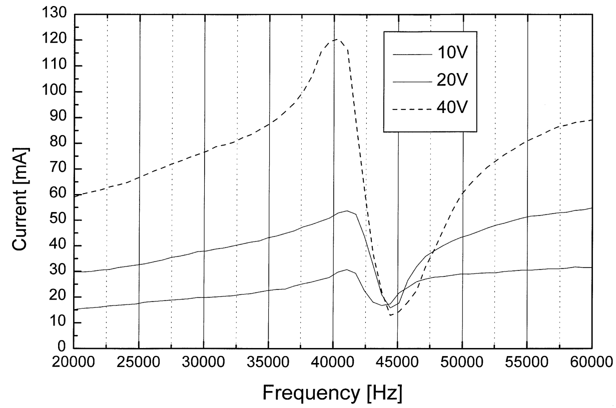

Fig. 3. Current through monomorph with different input voltages.

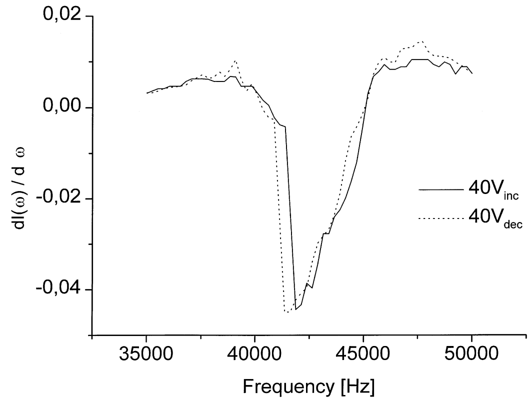

Fig. 5. $dI/d\omega$ for monomorph in air.

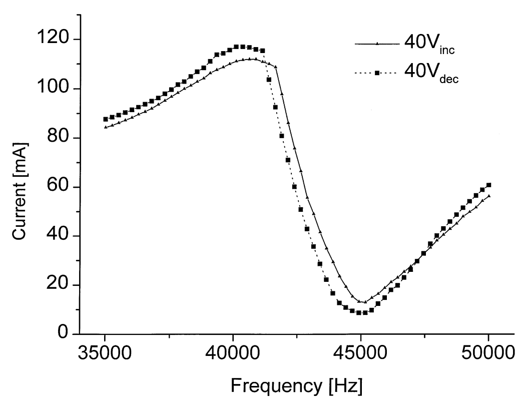

Fig. 4. Measured current (I) through monomorph in air.

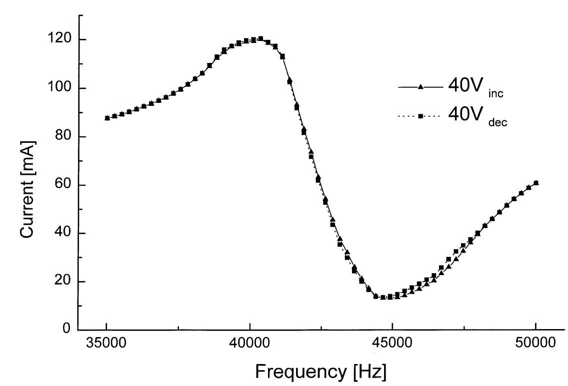

Fig. 6. Measured current (I) through monomorph in vacuum.

$$C \cdot U(\omega) = 2\pi \frac{dI(\omega)}{d\omega} \quad (4)$$

Under the condition that the deflection along the length (Δl) is directly proportional to the voltage, the curve in Fig. 5 is proportional to the charge output and to the deflection.[8]

$$\Delta l = d_{31} \frac{l}{h} U \quad (5)$$

(for PZT is $d_{31} = -2,14 \times 10^{-10}$ m/V)

To answer the question is the reason for the jump in deflection due to nonlinear damping of air or due to nonlinear ferroelectric properties of crystal, the measurement was repeated in vacuum.

Fig. 6 shows the measured current in vacuum (1 Pa). No significant difference between both curves can be recorded. No abrupt slope change of the curve can be seen in Fig. 6. The measured current was derived by the frequency for determining the slope change (see Fig. 7).

No jump phenomenon of deflection in vacuum could be detected with the measurement setup. The measurement was done under stable temperature and pressure conditions. The solution of measure-ment was not high enough to detect the influence of nonlinear material properties of PZT. It was shown that the influence of the nonlinear material properties of the actuator is small compared to the influence of nonlinear damping by air.

4. Discussion

The behavior of the jump phenomenon has been well known for a long time as the Duffing oscillator.[5,6] To explain this, the general equation of motion for an oscillating system is given by:

$$\ddot{x} + \delta^2 \dot{x} + \omega_0^2 x = \frac{F(t)}{m} \quad (6)$$

It is suitable for measurement in vacuum, where $\ddot{x}$ is the acceleration, $\dot{x}$ is the velocity, x is the deflection, δ^2 is the damping and ω_0 is the resonant frequency. This equation includes the driving force $F(t)$ and the moving mass m.

The influence of damping by surrounding air will be taken into account by the cubic term μx^3. The equation of motion for the oscillating monomorph in air is given by:

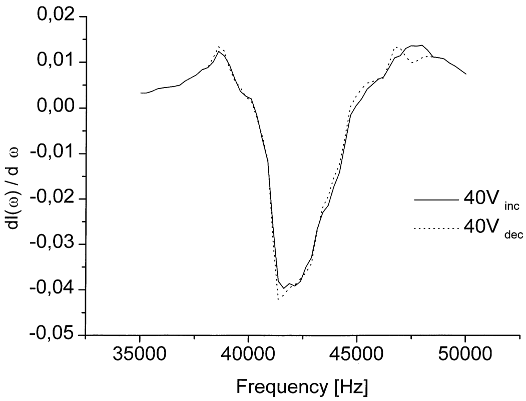

Fig. 7. $dI/d\omega$ for monomorph in vacuum.

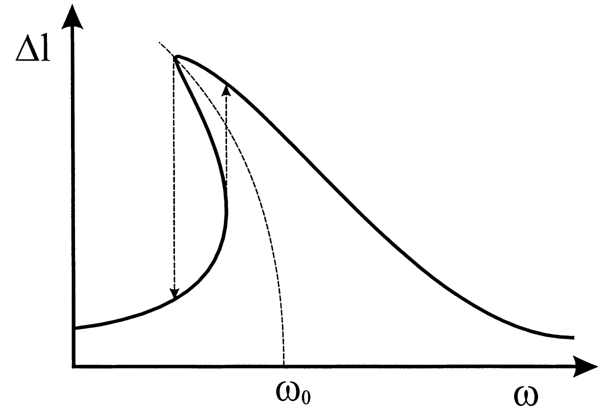

Fig. 8. Deflection of monomorph with $\mu/\omega_0^2 < 0$.

$$\ddot{x} + \delta^2\dot{x} + \omega_0^2 x + \mu x^3 = \frac{F(t)}{m} \quad (7)$$

The direction of the shift in resonant frequency depends on the sign of the fraction μ/ω_0^2. Measurement results indicate a negative μ. The value of the resonant frequency falls at larger input voltages. The measured deflection with decreasing frequencies reaches a higher value than the one for increasing frequencies.

In Fig. 8, a deflection of monomorph with $\mu/\omega_0^2 < 0$ is shown. It corresponds with an resonance diagram for a spring in which the stiffness decreases with the amplitude.[7]

5. Conclusion

The measurement in vacuum showed a slightly higher current amplitude due to less damping and larger deflection but no jump phenomena. This indicates that the velocity depending damping of the air surrounding the monomorph is the main reason for the jump phenomena.

It was shown that the jump phenomenon of current is not mainly due to higher harmonic voltages in the piezoelectric vibrator. Without any change in the ceramic or the electrical setup, the jump phenomenon disappears by removing the surrounding media. Even at higher amplitudes, no jump was recorded. The second and third harmonic voltages measured in Ref. 1 are effects and not causes of the phenomena.

Acknowledgements

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References

1. Ishii, K., Akimoto, N., Tashirio, S. and Igarashi, H., Jump phenomena of current in piezoelectric-ceramic vibrators under high power conditions. *Journal of the European Ceramic Society*, 1999, **19**, 1157–1160.
2. Ishii, K., Yamada, T., Tashirio, S. and Igarashi, H., Influence of media surrounding piezoelectric ceramics on current-jump phenomena. *Jpn. J. Appl. Phys.*, 1999, **38**, 5572–5575.
3. Anon. In Piezo-system. *Manufacturer Data Handbook*, Jena GmbH, 1999.
4. Nguyen, M. N., *Nichtlineares dynamisches Verhalten von Piezo-Balken-Systemen bei schwachem elektrischen Feld*. Forschen und Wissen-Mechatronik, GCA-Verl., 2000.
5. Hagedorn, P., *Non-linear Oscilations*, 2nd edn. Oxford University Press, New York, 1988.
6. Duffing, G., *Erzwungene Schwingungen bei veränderlicher Eigenfrequenz und ihre technische Bedeutung*. Druck und Verlag F. Vieweg & Sohn, 1918.
7. Den Hartog, J. P., *Mechanical Vibrations*. Dover Publications, New York, 1985.
8. Lee, C. et al., Self-exited piezoelectric PZT microcantilevers for dynamic SFM-with inherent sensing and actuating capabilities. *Sensors and Actuators*, 1999, **A72**, 179–188.