Self Heating of Piezoelectric Actuators: Measurement and Compensation

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***Abstract*–This paper introduces the effect of self heating on the displacement of piezoelectric actuators and a novel method to quantify self heating. Issues influencing self heating include; the frequency and the amplitude of the driving voltage, and the size, or more specifically the volume-area ratio of the actuator and they are also discussed. The effect of a load on the heat generation is studied. According to the experiments, the peak-to-peak value of the consumed current is a good indication of the temperature rise of the actuator. This can be used for the protection of the actuator from overheating, or as the authors will propose in the paper, it can be used to compensate for the changes in the displacement induced by the self heating. The displacement error of the heated actuator reduces in average down to one part in three when the proposed compensation is used.**

1. INTRODUCTION

Piezoelectric actuators are widely used in applications requiring high resolution and accuracy. Their favorable dynamic properties extend the application areas into high speed areas such as vibration control. However, large hysteresis, drift, self heating and load effects decrease the open-loop positioning accuracy. If a high accuracy is required, these non-linearities have to be compensated for. The compensation is usually accomplished by means of four different control principles: *feedforward voltage control*, where non-linear models are typically used [1], [2], [3]; *feedback voltage control*, where various sensors are used; *feedforward charge control*, where the operating current is controlled [4], [5] and *feedback charge control*, where charge is measured and controlled [6], [7], [8].

Driving piezoelectric actuators with fast periodic control signals causes intrinsic heat generation in the piezoelectric elements. The increased temperature causes inaccuracy in operation of the piezoelectric actuators due to heat expansion and variation of the characteristics of the element as a function of the temperature, and it can even cause destruction of the element itself.

When a piezoelectric actuator is under a varying electric field, the actuator heats until a steady-state is reached. In the steady-state, the heat generation and the radiation are at the same level [9], [10], [11], [12].

It is suggested that dielectric losses are the main reason for self heating [10], [11], [12], [13]. The heat generation appears to be proportional to the driving frequency and to the square of the amplitude of the driving voltage [12], [13]. Since the actuator produces heat in the entire volume and dissipates it through the surface area, it seems quite obvious that the heat generation is proportional to the volume/area of the actuator [10].

Temperature has an influence on the output of piezoelectric actuators [14]. The outside temperature is rather simple to measure, but intrinsic heat generation requires a sensor attached to the actuator. In some applications, this might be difficult to accomplish.

The goals of this paper are to (i) experimentally study the different aspects affecting self heating; (ii) demonstrate the effect of self heating on the displacement; (iii) provide a novel method for determining the state of self heating in the actuator without temperature measurement and (iv) to provide a method for the compensation of the displacement error of the actuator caused by the heat generation.

Previously issues influencing self heating of piezoelectric actuators have been studied. The contribution of this paper is to provide methods for the quantification of self heating and the compensation of its effects.

A detailed description of the stack actuators used in the paper will be given in the end of the paper in Table 3 and they will be referred in the text as Piezo 1, Piezo 2 and Piezo 3.

The rest of the paper is organized as follows. Section 2 presents the effect of the driving frequency on self heating. In Section 3, the relationship between the driving voltage and self heating is introduced. Section 4 presents the effect of a load on the heat generation. Section 5 discusses the influence of the actuator size on self heating. In Section 6, the effect of self heating on the displacement is studied. Section 7 introduces the relationship between self heating and driving current. Advantage of this is taken in Section 8, where a compensation method for the displacement variations is presented. Section 9 presents some application areas for the proposed methods. Conclusions are drawn at the end of the paper.

2. Effect of Driving Frequency

The effect of the driving frequency was determined by driving the actuators with different frequencies and a constant amplitude of 200 V. In the experiments, the temperature of the actuators was measured. Figure 1 shows the rise in the temperature as a function of the driving frequency.

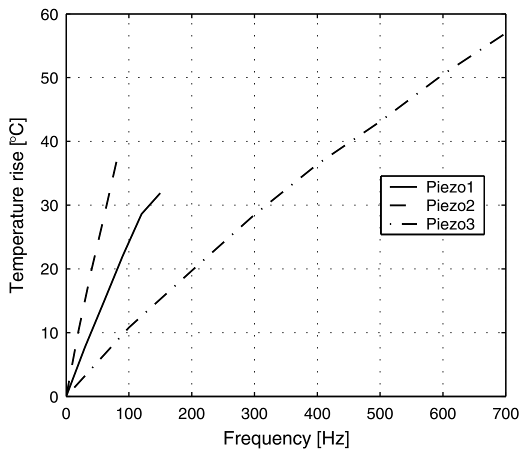

Figure 1: The effect of the driving frequency on self heating.

The heating is proportional to the frequency in all three piezos, as was demonstrated in [12] and [13]. The small decay with Piezo 1 at 150 Hz is caused by the lack of the current driving capability of the piezo amplifier in use.

3. Effect of Driving Voltage

The effect of the amplitude of the driving voltage was evaluated similarly to the frequency test. Now the three actuators were driven with different amplitudes and the actuator temperatures were measured. The frequencies for the actuators were 120 Hz for Piezo 1, 80 Hz for Piezo 2 and 700 Hz for Piezo 3. Figure 2 presents the temperature increase as a function of the driving voltage.

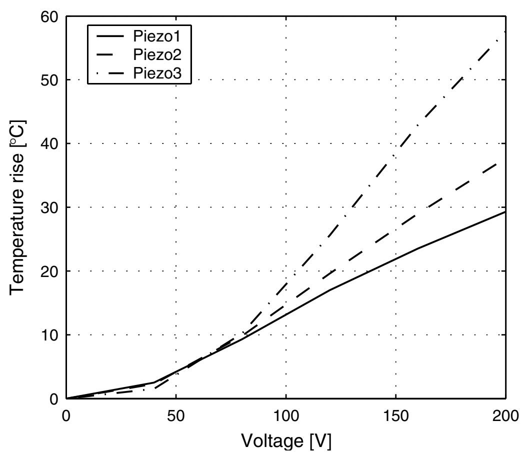

Figure 2: The effect of the driving voltage on self heating.

The results of Piezo 3 resemble most the earlier results presented in [10] and [11], where the heat generation is proportional to the square of the driving voltage. Piezo 1 and Piezo 2, however do not follow the relationship as precisely, and their temperatures remain lower at high voltages than would be expected.

4. Effect of Load

The effect of a load on self heating was tested by measuring the heat generation of Piezo 1 with and without a 100 N spring load (the blocking force of the actuator is stated to be 1500 N). The driving conditions were 200 V / 100 Hz. Figure 3 presents self heating with (dotted lines) and without (dashed lines) the load.

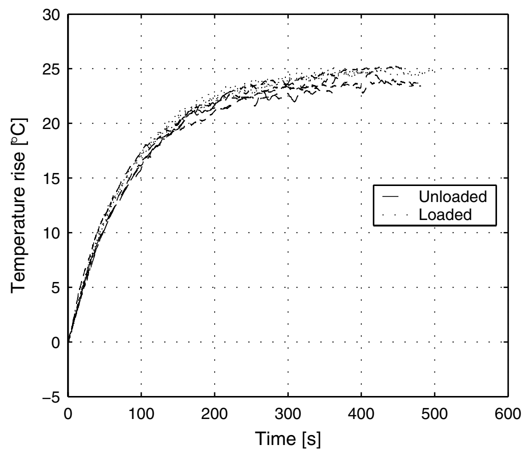

Figure 3: The effect of a load on self heating.

There is a small difference in the steady-state temperature. The temperature rises slightly higher with the load, but the difference is very small. The test was repeated with a 150 N spring load and the result was the opposite: the unloaded actuator heated slightly more than the loaded.

These tests indicate that at least a light loading of the actuator does not increase self heating remarkably. The loads were quite small in comparison to the blocking force of the actuator, and the results might be different with larger loads. It is also noticeable that no feedback was used in the testing. Therefore, the displacement under a load was smaller because of the load. If the displacements were kept constant, the electric field should have been higher in the load cases leading to a greater heat generation.

5. Effect of Size

The three actuators, two (Piezo 1 and Piezo 2) of which are made out of the same material, were driven with the same frequency and voltage (200 V / 80 Hz). Figure 4 presents the results.

The continuous line presents the temperature rise of Piezo 1, the dashed line Piezo 2 and the dash-dot line Piezo 3. Piezo 3 is composed of different material (even though it is soft and it has high dielectric constant similar to the material of Piezo 1 and Piezo 2, see the end of the paper) and its layer thickness can differ from the other two and therefore, its results cannot be directly compared with the others. It is, however, clear that a large actuator gets more heated than a small one. Due to the scaling effect, the volume/area ratio decreases, when the dimensions are scaled down.

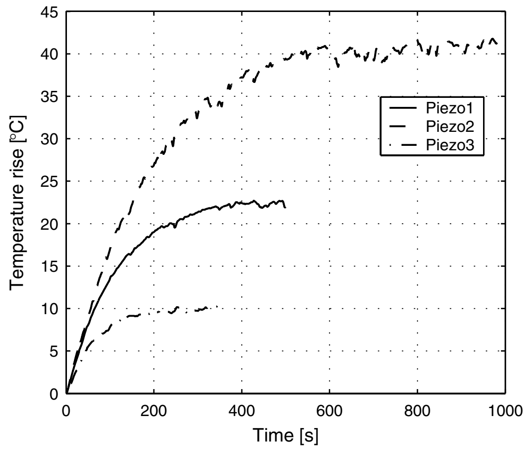

Figure 4: Effect of size on self heating.

Figure 5 presents the increase in the temperature as a function of the actuators' volume/area ratio.

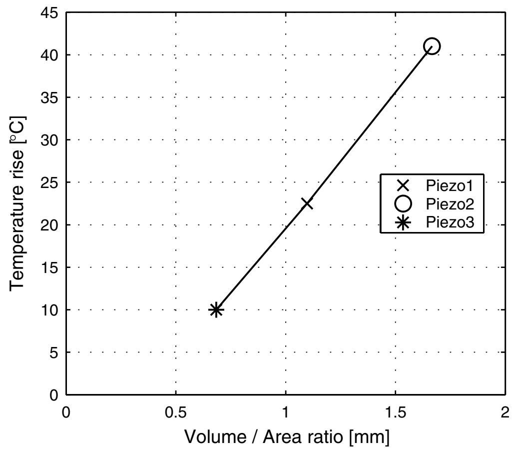

Figure 5: Self heating with respect to the volume/area ratio.

In Figure 5, a linear relation can be observed. The relationship is linear, although one actuator differs from the others. Theoretically, the line should intersect the origin [10].

6. Effect of Self Heating on Displacement

Until this point, the discussion has focused on the issues that influence self heating of piezoelectric actuators. From now on, the emphasis will be on issues, which are affected by the heat generation. Naturally, the damage in the actuator or the destruction of its periphery are the most severe effects. Some milder effects are e.g. thermal expansion of the actuator and changes in its displacement which can, however, be of high significance, too.

The effect of self heating on the displacement was studied using Piezo 1 by driving it with a sine wave (200 V / 100 Hz).

Figure 6 presents the results, the black line presenting the temperature and the grey line the displacement. The thermal expansion of the actuator, being slightly over 5 µm and approximately 0.03 % of the actuator length, can be seen quite nicely in the figure.

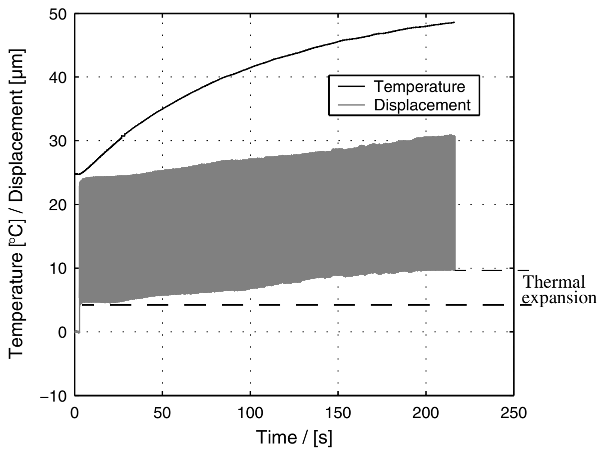

Figure 6: Influence of self heating on the displacement.

In addition to the thermal expansion of the actuator, the amplitude of the displacement changes, increasing from 19.0 µm to 20.5 µm. The change corresponds to 8 % of the original amplitude (taken from the averages of the first and the last 1000 displacement cycles).

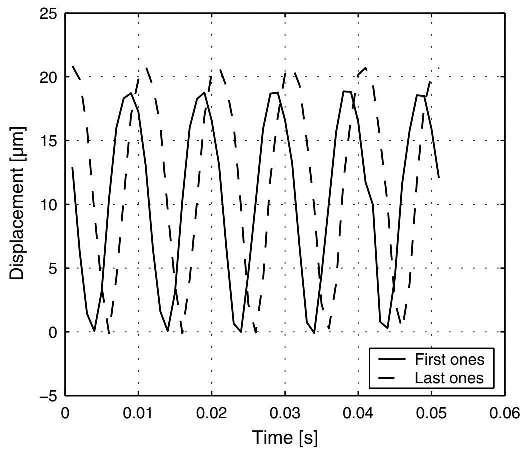

Figure 7: Five displacement cycles from the beginning (continuous) and in the end (dashed) of the test.

The amplitude increase is illustrated in Figure 7, where few displacement cycles from the beginning and in the end of the experiment have been captured to the same figure. The offset has been removed to show the difference in the amplitude more clearly.

7. Effect of Self Heating on Current Consumption

When the actuator is controlled by a voltage and is heating up, it is noticeable that the current consumption is increasing along the temperature rise. Figure 8 presents the current (grey line) and temperature (black line) values from the test presented in Section 6 (Piezo 1, 200 V / 100 Hz).

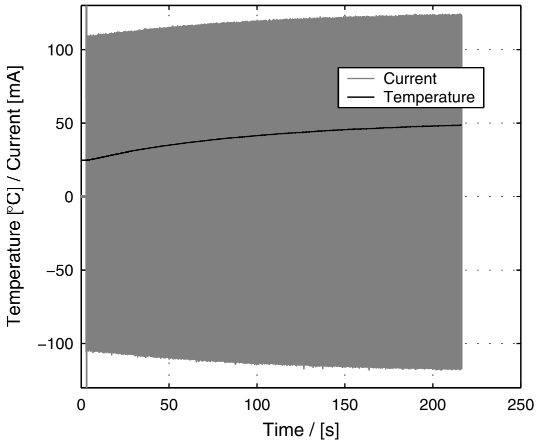

Figure 8: Influence of self heating on the current.

The connection of the current consumption with the actuator temperature is depicted more clearly in Figure 9, where the temperature and the peak-to-peak values of the current are shown. The offset value of the peak-to-peak current is removed. In the beginning, the peak-to-peak current value was 205 mA (at 25 °C), and it increased over 10 %, while the temperature increased approximately 25 degrees.

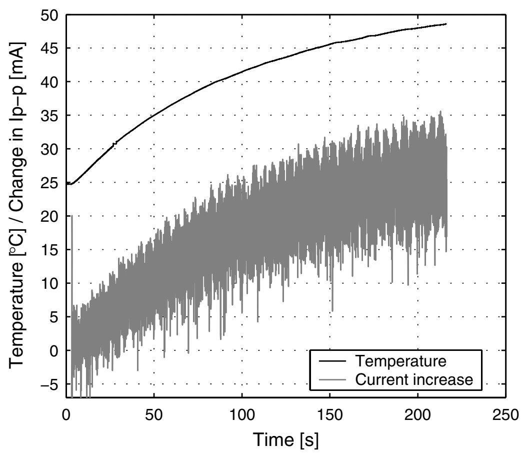

Figure 9: Temperature and change in peak-to-peak current value.

To quantify the relation between the current increase and the temperature rise, more measurements were carried out with two actuators; Piezo 1 and Piezo 3. Piezo 1 was tested with three frequencies; 100 Hz, 120 Hz and 180 Hz, and Piezo 3 with two frequencies; 500 Hz and 700 Hz. 200 V triangular driving signal is used in the measurements. Each test was repeated five times. Table 1 presents the results. Current increase is presented as percents of the original peak to peak current. According to the results the average current increase per degree is 0.5 %/°C, and a standard deviation 0.03 %/°C in these 25 tests. The measured temperature rise varied from 15 °C up to 44 °C. According to these results, the current consumption can be utilized in the measurement of the actuator temperature change.

Table 1: Average results from the measurements.

Stack no.	Freq.	Tempe-rature increase	Current increase in %	Current increase per °C
Piezo 1	100 Hz	16 °C	8 %	0.49 %/°C
Piezo 1	120 Hz	19 °C	10 %	0.50 %/°C
Piezo 1	180 Hz	29 °C	15 %	0.52 %/°C
Piezo 3	500 Hz	27 °C	13 %	0.46 %/°C
Piezo 3	700 Hz	43 °C	21 %	0.48 %/°C
			Average	0.49 %/°C

8. Compensation

Section 7 showed that self heating is possible to measure without a temperature sensor using the current consumed. In this section, the emphasis will be on the compensation of the increase in the displacement amplitude induced by self heating using information on the current consumption of the actuator.

The compensation approach is to keep the peak to peak current constant when the actuator is driven by a reciprocating signal resulting in self heating.

Figure 10 presents the block diagram of the proposed control method; an actuator current i is measured, and converted into a peak to peak current I_{pp}. A controller adjusts the amplitude A in order to maintain the current I_{pp} at a set point current I_{sp}. The set point current equals to the peak to peak current at the beginning, $I_{sp} = I_{pp\ at\ t\ zero}$. In the block diagram f presents the frequency, v the voltage and d the displacement.

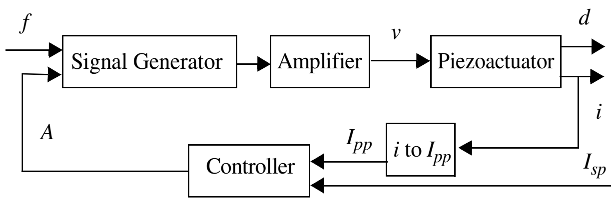

Figure 10: The block diagram of the proposed control method.

The devices utilized in the experiment are a current meter, a PC with data acquisition, a laser displacement sensor, a signal generator and a piezo amplifier. A manual control is utilized in these first experiments.

The proposed method is experimented with two actuators in the same conditions as in previous section; (triangular wave, Piezo 1: 100 Hz, 120 Hz, 180 Hz; Piezo 3: 500 Hz, 700 Hz). Each test was repeated five times. For a reference, the same experiments were done also without the compensation.

Table 2 presents the results; Error is the relative difference between the original displacement amplitude and the final displacement amplitude. It is noticeable that the difference in the displacement amplitudes might have been slightly greater than this during the process. The temperature increase is the average value in the tests; in the compensated case the temperature is typically couple of degrees less, and in the uncompensated couple of degrees more than the average.

Table 2: Average results from the experiments.

Stack no.	Freq.	Tempe-rature increase	Error without compen-sation	Error with compen-sation
Piezo 1	100 Hz	16 °C	3 %	0.7 %
Piezo 1	120 Hz	19 °C	4 %	0.7 %
Piezo 1	180 Hz	28 °C	6 %	3 %
Piezo 3	500 Hz	25 °C	4 %	1.1 %
Piezo 3	700 Hz	39 °C	9 %	3 %
		Average	5.2 %	1.7 %

As can be seen, the results are far better when the compensation is used; the differences between the displacement amplitudes in the beginning and at the end are in average three times smaller with compensation than without compensation.

Figure 11 presents typical results from the first tests (Piezo 1, 100 Hz): the displacement amplitude of the uncompensated case increases until a certain point, while the displacement amplitude of the compensated case remains quite constant. The difference in the origin of the compensated and uncompensated cases is probably due to some remaining heat in the uncompensated case after the previous measurement. The actuator was cooled down between measurements with an air fan and even though the surface of the actuator was at the room temperature, the temperature of the inner body of the actuator could have been slightly higher. This decreases the displacement error of the uncompensated case and by eliminating this remaining heat the results would appear to be even better than presented now.

In the experiments, where the compensated result differed significantly from the original and was as great as 3 %, (Piezo 1 180 Hz and Piezo 3 700 Hz), the compensation decreased the displacement amplitude and the final amplitude was smaller than in the beginning. It therefore seems that in some cases the proposed compensation method too effectively decreases the increased displacement amplitude due to self heating.

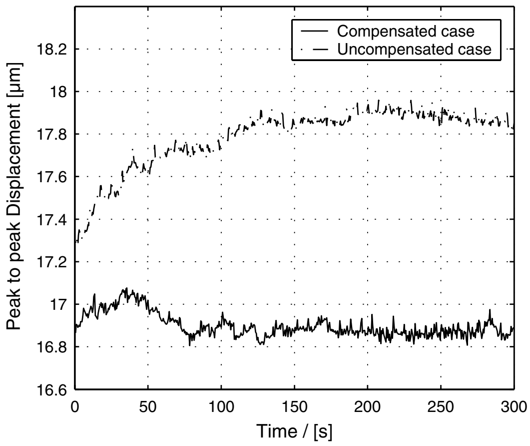

Figure 11: Typical results from the first test (Piezo 1, 100Hz), the uncompensated case with a dash-dot line and the compensated case with a continuous line.

9. Application Areas

The temperature measurement by measuring the peak to peak current could be used as a safety feature preventing overheating, or as a trigger to start an additional cooler. An interesting application could also be piezoelectric pumps, where it might be possible to detect the media inside the pump due to their different cooling capability.

The proposed compensation method can be utilized in applications, which use a periodic control signal, and where the overall performance can be increased by controlling the actuator amplitude more precisely. They include different piezoelectric pumps, liquid dispensers and motors, for example.

Piezoelectric stepper motors could benefit in open loop accuracy by using the compensation method. Then the step size would be more constant and dependency on the temperature would be decreased. Naturally load would remain as the main source of inaccuracy in piezo motors. In robotic applications where high accuracy is required, feedback sensors are naturally used, but a current measurement could give valuable information of the temperature of the motor.

Piezoelectric pumps can easily be thought to be used in applications where constant flow is required, but an implementation of a flow sensor would be impossible due to size / price requirements. Such application would benefit from the proposed compensation.

10. CONCLUSION

This paper presented issues concerning self heating of piezoelectric actuators. Besides the effects of the frequency and amplitude of the driving voltage, a load and the size of the actuator on the self heating, a novel method was presented for determining the state of self heating in a piezoelectric actuator without temperature measurement. Furthermore, a compensation method for the reduction of the self heating induced displacement variations was proposed. The displacement error of an actuator driven by a high-frequency reciprocating signal reduces in average down to one part in three when the proposed compensation is used.

The future work will include the application of the proposed control method to a practical device, such as a reciprocating piezoelectric pump or motor, and to develop the control system such that the peak-to-peak current can be utilized more efficiently in the control.

MATERIALS AND METHODS

Three piezoelectric actuators were used in the experiments of the paper. The manufacturers, sizes and the materials of the actuators are presented in Table 3.

Table 3: Actuator properties.

Stack no.	Manuf.	Size mm^3	Mat.
Piezo 1	Noliac	5*5*18	S2
Piezo 2	Noliac	10*10*10	S2
Piezo 3	Marco	3*3*18	FPM231

S2 is a soft doped PZT material with a high strain performance and a high dielectric constant [15].

FPM 231 is a soft material with a high deformation, a low mechanical quality factor and a relatively high dielectric constant [16].

Thermistors are glued with thermally conductive glue on to the actuators to measure the actuator temperatures.

Other devices used in the experiments are a current meter, a PC with data acquisition, a laser displacement sensor, a signal generator and a piezo amplifier.

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