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EXTREME PERFORMANCES OF PIEZO SYSTEM: HIGH STROKE, HIGH FREQUENCY, HIGH TEMPERATURE

Aleksander Kras, Olivier Sosnicki, Steven Rowe, Francesca Battistello, Frank Claeyssen

Cedrat Technologies
59 Chemin du Vieux Chêne, 38246 Meylan, France
E-mail: [aleksander.kras] [olivier.sosnicki] [steven.rowe] [francesca.battistello] [frank.claeyssen]@cedrat-tec.com,
Web page: www.cedrat-technologies.com

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Summary: *This paper presents research and development results of the high performances piezoelectric actuators. Performed studies were concentrated on the improvement of three major parameters: stroke, maximum driving frequency and operational temperature. Two, new actuators were presented and described in this paper. First presented actuator has increased maximum displacement. This actuator has doubled the stroke of standard, long stroke actuators. Improvement of the second actuator was concentrated on increase of constant driving frequency. Finally, special encapsulations designed for both actuators allow using them at high temperatures. Development of these two, new actuators was done simultaneously to the improvement of the electronics. High power amplifier presented in this paper provides sufficient current to drive both actuators at high frequencies.*

1 INTRODUCTION

Although the advantages of piezoelectric actuators are well know the number applications that these smart materials can be used for is still limited. The main drawbacks derive from stroke and frequency limitations, overheating of the ceramics, maximum operational temperature, power electronics, etc. Recently Cedrat Technologies has been investigating solutions in order to overcome these issues.

Up till now the piezo-actuators with the highest stroke that could be found on the market were limited to 1mm. To meet the needs of more demanding applications it was required to expand this boundary. The target was to double the stroke limitation while keeping a high resonant frequency.

Another limitation is ceramics self heating when using the actuators at high frequency for long time. This limits to minutes or even seconds depending on the driven frequency the time for constant use. Designed encapsulation with cooling systems overcome overheating limitation. Preliminary tests showed that encapsulated actuator constantly driven at 1000Hz at full strain keeps the ceramics temperature below 85ºC. Without the cooling system the standard actuator would have reach the Curie temperature in less than one minute at same frequency.

Power consumption of piezoelectric actuators increases proportionally to the driven frequency. Due to this correlation it is required to provide a high power supply that allows driving the actuators at high frequency. This paper presents recent development of switching amplifier portfolio and their capabilities in such demanding application.

Designed encapsulations for both actuators permits to use them in high temperature environment. With the protection body the actuators could be used in temperatures reaching 250°C. High temperature wire equipped with waterproof electrical connector provides power supply for the actuators even in the toughest environment.

This paper presents results of designing and testing new piezoelectric actuators that overcome usual limits in terms stroke, frequency and temperature.

2 HIGH STROKE ACTUATOR

Typically the multilayer piezoelectric actuators provide around 0.1% of displacement, which is insufficient in many applications. The simplest method to increase the elongation of the actuator is increase of the piezo stack length. Unfortunately this causes increase of the overall size, mass and volume of the actuator.

Second technique is to use mechanical amplification in order to improve the maximum stroke of the actuator. This technique allows obtaining high stroke actuators within compact size. Cedrat Technologies has long tradition of producing mechanically amplified actuators. This type of actuators is called APA® and stands for Amplified Piezoelectric Actuator (Figure 1). The whole mechanism is composed out of two major parts: piezoelectric ceramics that generates force and metal shell that mechanically amplifies displacement of the ceramics. The overall stroke of the actuator depends on the displacement of the ceramics and amplification ratio of the shell.

Commercially available actuators have free displacement between 0.5mm and 1mm [1]. The idea of this study was to increase maximum stroke up to 2mm. It was decided to design new APA® based on L series actuators. This series uses 6 ($10x10x20mm^3$) ceramics to generate displacement. Length and width is the same for each actuator in the series ($145x10mm^2$) while the height changes and has influence on the amplification ratio.

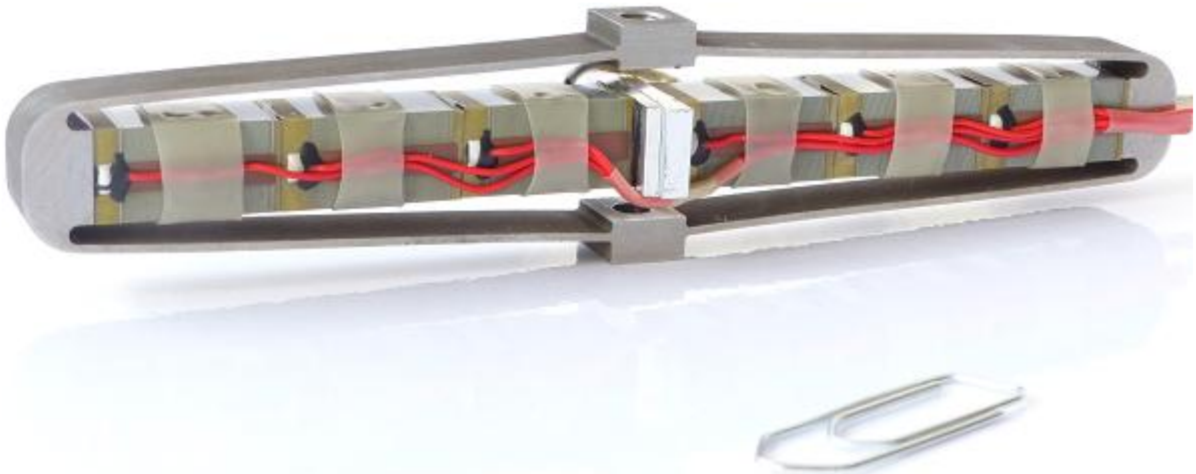

Figure 1: Amplified Piezoelectric Actuator APA® that provides 2mm of stroke.

Designed actuator obtained name APA2000L and provides 1968µm of stroke. The resonant frequency is 90Hz in with one extremity blocked and 487Hz with both extremities free. The blocked force of actuator is 60N. Based on free stroke and force the generated power of this actuator is 15J. The amplification ratio of the actuator is 15 times which is the highest value ever obtained before.

Designed actuator presents very good results in terms of resonant frequency and blocked force. It has the largest stroke from all typically available actuators on the market within the most compact size.

3 HIGH FREQUENCY ACTUATOR

It is well know that piezoelectric actuators are ideal solution for high dynamic applications. Unfortunately the ceramics self over-heating and low Curie temperature prohibits of using them at high frequency for long period of time. In order to cope with these drawbacks a cooling system for a piezoelectric actuator was investigated. For the prototype the parallel pre-stressed actuator (PPA) was chosen. A special encapsulation was designed and manufactured for this type of actuator. View of the actuator and designed encapsulation was presented in figure 2.

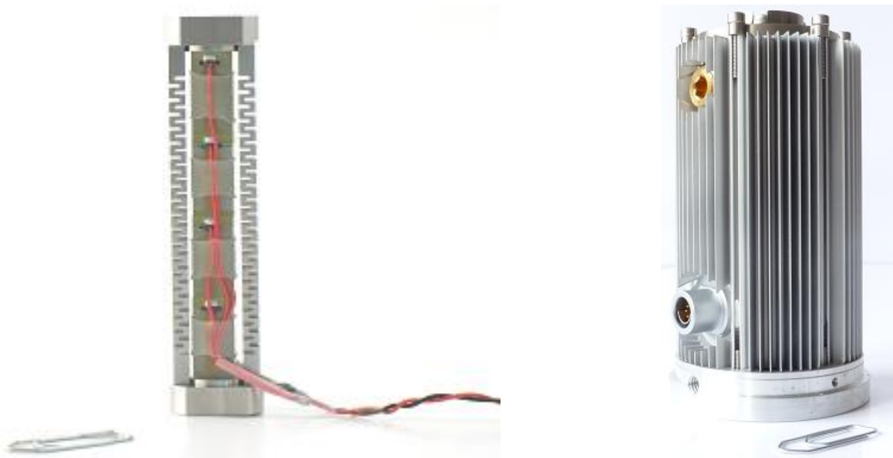

Figure 2: View of PPA80L actuator (to the left) and designed encapsulation for cooling system (to the right).

Proposed encapsulation was designed in order to use two types of cooling systems. First cooling system was based on special fluid that extracts heat directly from the ceramics. Second system uses fins and compressed air to extract heat from the fluid via encapsulation. The encapsulated PPA has obtained code PPA-E. Set of tests were performed on the actuators in order to characterise encapsulation and cooling systems.

First performed test showed capabilities of cooling systems. This test verified temperature increase of different actuators. First tested actuator was a regular PPA80L. This actuator is mounted with 4 piezoelectric ceramics that have overall dimensions of $80x10x10mm^3$. Second actuator was the encapsulated PPA80L that used only fluid as a cooling system. Final actuator used both cooling systems: fluid and compressed air.

All three actuators were driven with the same parameters of frequency (230Hz) and voltage (170Vpp). Temperature over the time of each actuator was registered and monitored. It was important to prevent the actuators from excessive overheating that could cause destruction of the ceramics. Temperature of the actuators had to stay below 85°C at the MLA surface [2]. For PPA80L the surface temperature was monitored using thermal camera. The same method could not be used for the encapsulated actuator, thus the thermocouple was installed on the ceramics surface for temperature measurement (Figure 3).

Figure 3: View of thermocouple attached to the piezoelectric ceramics used for temperature measurement.

Based on the tests, three heat up curves were obtained and plotted on the same graph (Figure 4). It can be observed that it takes around one minute for PPA80L to reach temperature that excides 80°C. The actuator had to be stopped in order to prevent from destruction.

The encapsulated actuator without air cooling system reached the same temperature of 80°C in 53 minutes after initiation of the amplifier. It was observed that in longer period of time the temperature of this actuator does not increases and stabilises at 82°C. In this configuration the actuator has performed more than 170 million cycles working constantly at 230Hz with full voltage signal.

Final tested actuator was the encapsulated version with air cooling system. The air cooling system in the actuator can be plugged to the facility compressed air network. For better air flow control a needle valve was installed just before actuator connector. Different air pressure values were evaluated. Naturally the increase of cooling efficiency was observed with increase of the air flow. Significant improvement was observed with the air pressure set to 0.25bar. Using this air pressure value it was observed that the temperature of the ceramics surface during constant work at 230Hz never exceeds 60°C. Based on the test results the proposed air pressure value improves cooling of the actuator and prevents excessive losses in the compressed air network.

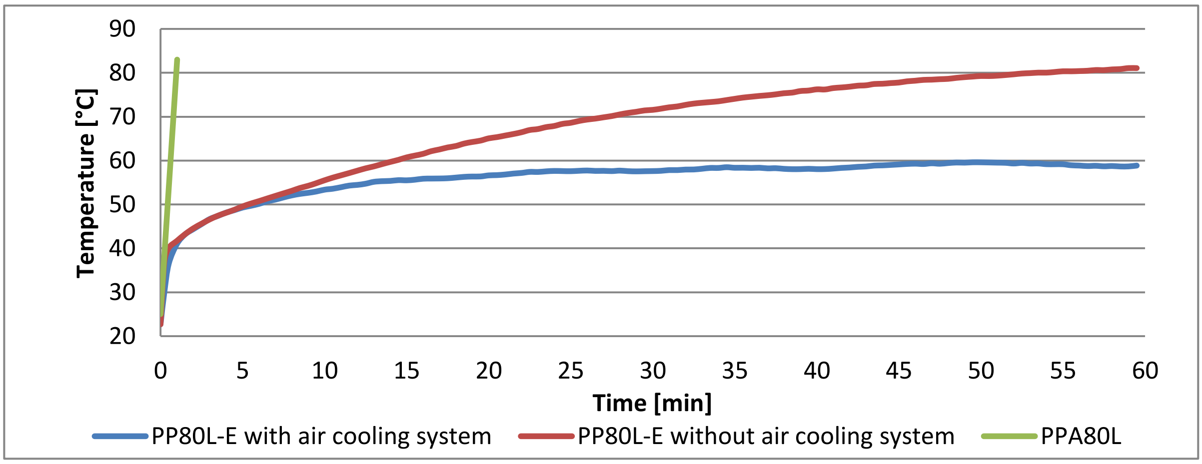

Figure 4: Heat up graph of the PPA80L and encapsulated actuator (PPA80L-E).

Benefits of the actuator cooling system based on compressed air were verified after turning off the power supply. The cooling graph of the ceramics surface was presented in figure 5. It was observed that using actuator with air cooling system it takes 15 minutes to reduce ceramics temperature from 82°C to an ambient temperature of 25°C. In the same period the ceramics of the encapsulated actuator without air cooling system cooled down to only 57°C.

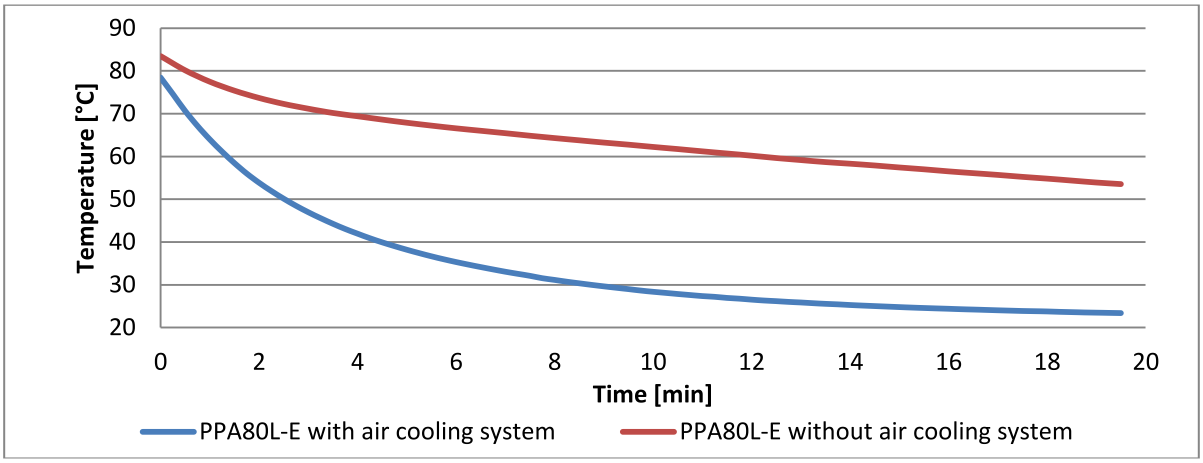

Figure 5: Cooling graph of the encapsulated actuator (PPA80L-E) with and without compressed air system.

High efficiency of the air cooling system allowed to increase driving frequency of the actuators. The air pressure was kept at the same level of 0.25bar while the frequency was increased. It was observed that the encapsulated actuator can be driven constantly even at 1000Hz. The same actuator without the encapsulation can be used only at 50Hz. Monitored temperature for both actuators confirmed that ceramics surface temperature never exceeded 90°C (Figure 6).

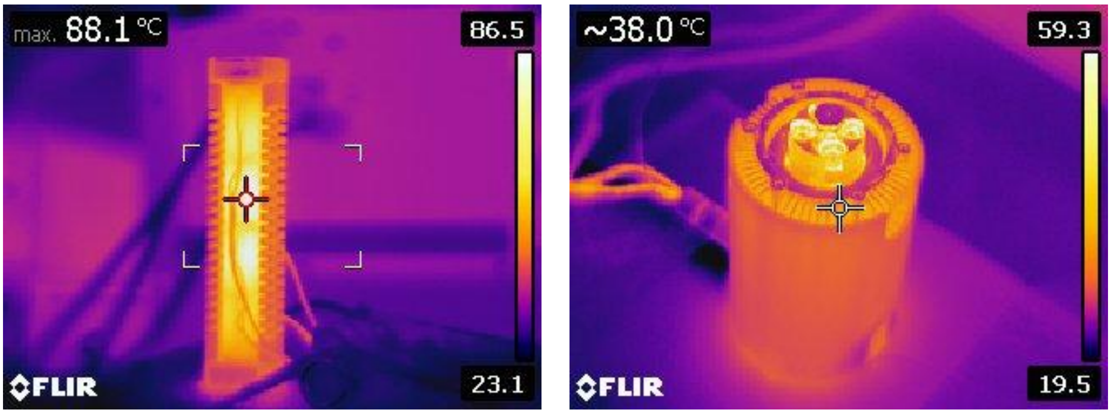

Figure 6: PPA80L (left) and PPA80L-E (right) working with differnet frequencies but at the same temperatures.

Presented configuration of the encapsulated actuator shows many advantages. Compared to regular version of the actuator the driving frequency has increased 20 times for encapsulated actuator with air cooling system (1000Hz). The encapsulated actuator without air cooling system can be used at frequency that is nearly 5 times higher (230Hz) compared to regular actuator (50Hz for PPA80L).

4 HIGH POWER ELECTRONICS

Ability to work at high frequencies of the encapsulated actuator equipped with air cooling system required to develop a sufficient power supply. To improve efficiency and reduce power losses an amplifier based on switching topology was developed. The amplifier had to be powerful enough to drive the encapsulated actuator (PPA80L-E) even at 1000Hz. Developed amplifier obtained name SA75 and is available in 3 configurations that depend on required current. The strongest configuration, the SA75D can provide up to 20A peak continuous current. Picture of the SA75D amplifier assembled in standard 19 inches rack is presented in figure 7. The switching amplifier was dedicated for low voltage piezoelectric ceramics and can provide supply from -20V to 150V [170Vpp].

Figure 7: SA75D assembled in standard 19 inches rack.

Developed switching amplifier was tested with encapsulated actuator (Figure 8). Preliminary the actuator was driven at 1000Hz using SA75D amplifier. The maximum current required to drive the actuator at this frequency was 17A peak. As the amplifier was designed to provide 20A the driving frequency of the actuator was increased to 1300Hz. At this frequency the current reached 19A peak. At the same time measurements of power consumption showed that real power requirement of the amplifier is 100W, thanks to an energy recovery function.

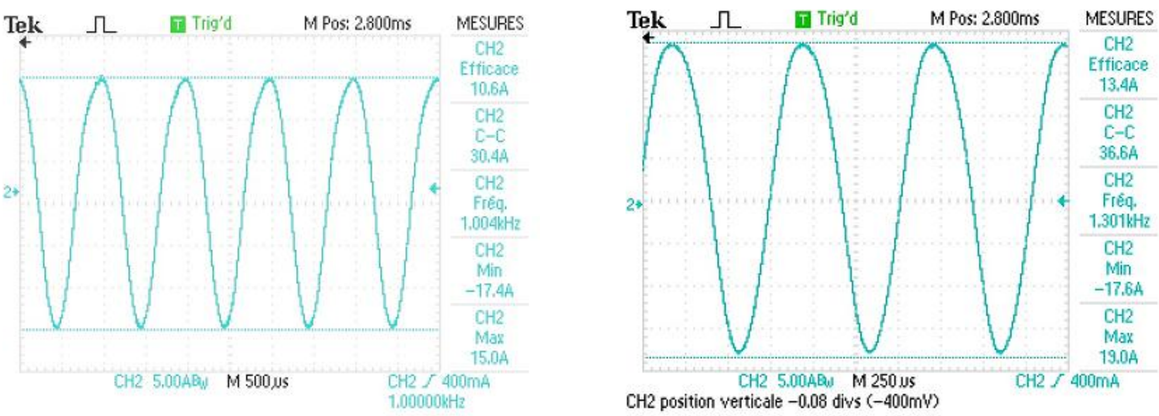

Figure 8: Tests of the SA75D at actuator driving frequency of 1kHz and 1.3kHz.

Additionally the switching topology allows to obtain a compact dimensions of 1dm³ with total mass of 850g for the driver part [3]. Presented specifications make this amplifier one of the most powerful currently available on the market while keeping small a volume in regard of the provided power.

6 HIGH TEMPERATURE ACTUATORS

Designed encapsulation for the piezoelectric actuators presents additional advantages. Besides using them as a cooling system they are used to protect the piezoelectric ceramics from harsh environment. In total two actuators were equipped with an encapsulation, the PPA80L and the APA2000L (Figure 9). Both actuators were prepared for high temperature and fluid environment.

The power supply connectors are perfectly sealed and water proof (IP68). The PTFE insulation of the wire allows to use them even at 250°C. High temperature ceramics developed by Noliac were mounted in actuators and can be used for operation up to 200°C. Scheduled future tests will show capabilities of using these actuators in harsh environment.

Figure 9: Encapsulated PPA80L and APA2000L.

8 CONCLUSIONS

The designed actuators presented in this article overcome typical limitations in terms of stroke, driven frequency and high temperature environment. Test results confirmed good capabilities of both actuators. Developed APA2000L doubled the stroke of typical amplified actuators. With 2mm stroke it has high bandwidths within most compact size.

The encapsulated PPA actuator increased maximum driving frequency. Using both cooling systems (fluid and air) this actuator can be driven constantly even at 1000Hz, which 20 times more compared to the regular actuator. Using just one cooling system this actuator can be driven constantly at 230Hz. Long life test did not show any loss of performance after 170 million cycles.

In order to drive the encapsulated actuator at high frequency a new power amplifier based on switching topology was developed. Tests showed that this amplifier can provide 20A peak current and allows driving the PPA80L-E actuator at 1300Hz. Measurements showed that thanks to switching topology and power recovery function this amplifier requires just 100W to drive the actuator at this frequency.

Encapsulations designed for both actuators protect ceramics form humid and high temperature environments. Future tests will show capabilities of using these actuators in harsh environment.

9 PROJECT OUTLINE

Development of actuators and amplifier presented in this article has been done in the framework of the European Union project FP7: AEROPZT. This project focuses on development of piezoelectric ceramics, actuators and encapsulations for advanced combustion fuel staging in the aircraft gas turbine engine. The designed actuation system has to be capable to operate at high temperature while being immersed in fluid.
There are four partners contributing in the AEROPZT project:
1 Plant integrity LTD
2 Politecnico di Torino
3 Cedrat technologies
4 Noliac A/S

10 ACNOWLAGEMENT

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