Encapsulated Piezo Actuators for Use at High Power Levels and / or within Harsh Environmental Conditions.

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Abstract:
Traditionally piezo ceramic actuators have not been able to operate within harsh/humid environments. Furthermore, two temperature-related problems have limited the number of applications for piezo actuators. Firstly, internal heating of the ceramic from use at high frequency, for extended periods. Secondly, external environmental conditions. Encapsulation of the actuator offers an opportunity to overcome all of these problems by allowing the environment directly in contact with the ceramic to be controlled. This paper presents R&D work done on encapsulated actuators, design work, and thermal simulation calculations with an emphasis on experimental results.

Keywords: Actuator, Piezo, Encapsulation, Temperature, Cooling, Self-Heating

Introduction

In its simplest form encapsulation provides a physical barrier between the environment and the ceramic, restricting direct contact between the two. This form of encapsulation is ideal where the environmental conditions are either humid or harsh and contact between both the environment and the ceramic would limit the actuator life.

Furthermore traditionally two temperature-related problems have limited the number of applications for piezo actuators: firstly, internal heating of the ceramic from use at high frequency for extended periods; and secondly, external environmental conditions.

Self-heating is a new issue arising from the need for high power applications where actuators are expected to operate at high frequency, maximum stroke and for extended periods of continuous operation. These applications have become possible with the availability of new high power drivers.

At the same time, a range of applications are opening up where the thermal environmental conditions are elevated and above the Curie temperature of the ceramic, which requires the piezo ceramic to be protected by a physical barrier between the ceramic and the environment, however at the same time this barrier must not allow any major loss of performance of the actuator.

Encapsulation of the actuator offers an opportunity to overcome all of these problems by allowing the environment directly in contact with the ceramic to be controlled, either within a sealed actuator system, one with fluid cooling, or within a closed-loop fluid cooled system.

Some of the work presented here has been performed within the project AeroPZT, specifically funded under the Clean Sky Joint Technology Initiative (EUFP7). The project partners, Plant Integrity Ltd (UK), Cedrat Technologies (France), Noliac (Denmark) and Politecnico di Torino (Italy), are targeting the development of materials and processes for the application of piezoelectric actuators in aero engine controls, which implies harsh environmental conditions, particularly elevated temperature. Applications of such actuators could include valve control for fuel staging or clearance control.

Harsh/humid environments

As the applications for piezo actuators continue to expand especially into fields such as aerospace, oil/gas and science there is a requirement for the actuator to be immersed within increasingly harsh environmental conditions.

In the simplest form encapsulation systems, provides a single layer physical protection for the ceramic against the environmental conditions.

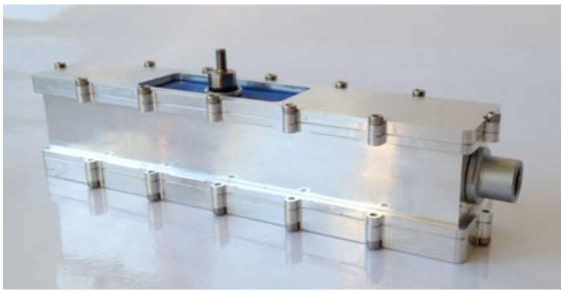

Fig. 1: *APA2000L-E*

The APA2000L-E developed with the AeroPZT project is able to reach 2mm of stroke and is hermetically sealed to IP68 for use in harsh environmental conditions, the overall size of the encapsulated actuator is 160mm long x 34mm wide x 38mm high, compared to the standard non encapsulated APA2000L of 140mm x 20mm x 20mm.

Encapsulated actuators have also been developed for use below ground level, here the temperature conditions remain fairly stable however the environment contains high levels of moisture and solid contaminates.

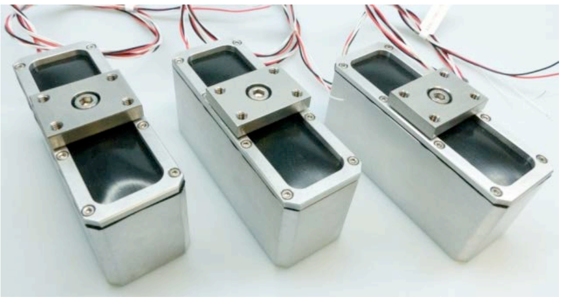

Fig. 2: *APA200ML-E*

These encapsulated actuators are based on the APA200ML, they have an average stroke of 225µm a blocked force of 804N, and a free/free resonance frequency of 3857Hz.

Self-heating

The availability of new high power drivers based on switching topology has allowed actuators to operate at high frequency, maximum stroke and for extended periods of continuous operation. However self-heating of the ceramic under high power loads has up to date restricted either the maximum operating frequency or the time of operation, where short bursts of high loading has had to be followed by extended periods of no operation in order to cool down the ceramic.

Fig. 3: *View of PPA80L actuator (to the left) and the encapsulation for cooling which includes the fluid (to the right).*

The next level of Encapsulation offers the option of incorporating a cooling fluid. By immersing the ceramic within a fluid any heat generated during operation of the actuator can be transferred to the body of the encapsulation and rapidly removed, either by natural convection or by the use of a secondary system.

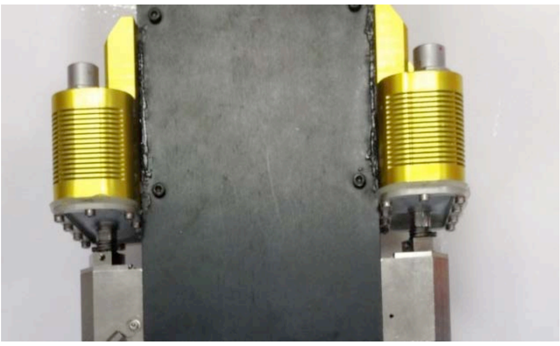

Fig. 4: *Twin encapsulated actuators for use on a machine tool within a water spray environment, furthermore the actuators are required to operate at 250Hz for 8 hour periods, successful trials show the ceramic temperature stabilises at 50°C – Note the air fins for improved heat dissipation.*

An encapsulation system was designed in order to test two types of cooling systems. The first cooling system was based on a cooling fluid that extracts heat directly from the ceramics. The second system uses radiator fins and compressed air to extract heat from the fluid via the encapsulation. A number of tests were performed on the actuator in order to characterise the encapsulation and the two cooling systems.

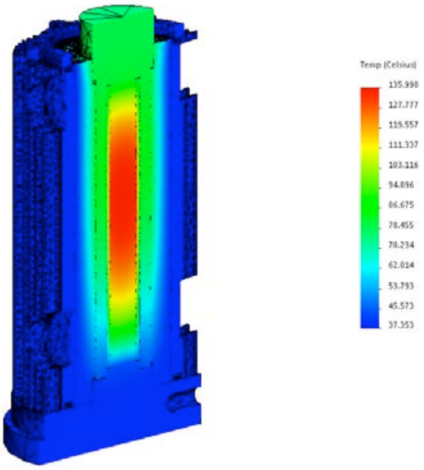

Fig. 5: *Thermal simulation showing the temperature difference between the ceramic and encapsulation*

The first test was on a standard PPA80L in order to gather baseline data. This actuator is mounted with four piezoelectric ceramics that each have dimensions of 20mm height x10mm wide x10mm deep.

The second test was on the encapsulated PPA80L-E which used only the fluid as a cooling system. The final test was on the encapsulated PPA80L-EA using both the cooling fluid and compressed air for cooling.

During the tests all three actuator versions were driven with the same parameters of frequency (230Hz) and voltage (170Vpp). Temperature over time for each actuator was registered. It was important to prevent the actuators from excessive overheating that could cause permeate damage of the ceramics. Therefore the maximum temperature of the actuator ceramic had to remain below 85°C on the ceramic surface, the actuators were thermally isolated to minimise conduction through any support and use only convection for heat loss.

For the standard PPA80L the surface temperature was monitored using a thermal camera. The same method could not be used for the encapsulated actuator, thus a thermocouple was installed on the ceramics surface for temperature measurement.

Fig. 6: *View of thermocouple attached to the piezoelectric ceramics.*

Based on the tests, three temperature gradient curves were obtained and plotted on the same graph. It can be seen that it takes around one minute for the PPA80L to reach a temperature in excess of 80°C. The actuator had to be stopped at this point in order to prevent damage to the ceramics.

The encapsulated actuator using only the cooling fluid system reached the same temperature of 80°C in 53 minutes. It was seen that in the long run 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 a full voltage signal.

The final test used the encapsulated actuator with both cooling fluid and forced air cooling PPA80L-EA. The air cooling system in the actuator can be plugged into a standard compressed air network. For a controlled air flow a needle valve was installed just before actuator connection this allowed different air pressure values to be evaluated.

An increase in cooling efficiency was observed with increase of the air flow. Significant improvement was observed with the air pressure set at 0.25bar. Using this air pressure value it was observed that the temperature of the ceramic 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.

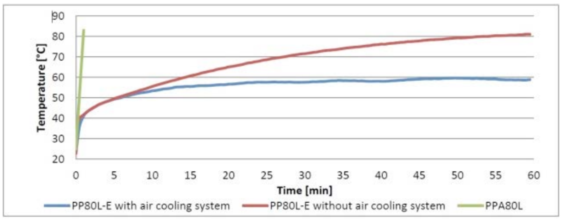

Fig. 7: *PPA80L/PPA80L-E and PPA80L-EA temperature stabilising time*

Further benefits of the compressed air actuator cooling system were verified after turning off the power supply. The time for cooling of the ceramic surface was measured. It was observed that the actuator with the air cooling system takes 15 minutes to reduce ceramics temperature from 82°C to an ambient temperature of 25°C. In the same time period the ceramics of the encapsulated actuator without air cooling system cooled down to 57°C.

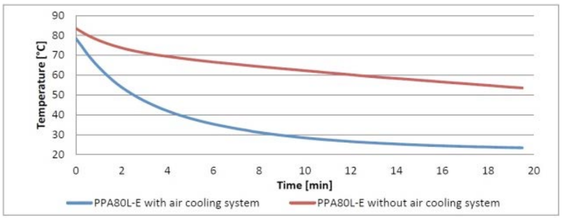

Fig. 8: *Ceramic cooling graph on the PPA80L encapsulated actuators with and without compressed air cooling*

The high efficiency of the air cooling system has allowed a drastic increase in driving frequency for the actuator. The air pressure was kept at the same level of 0.25bar while the frequency was increased. It was observed that the encapsulated air cooled actuator can be driven constantly even in excess of 1000Hz. The same actuator without the encapsulation can be used only up to 50Hz. The monitored temperature for both actuators confirmed that ceramics surface temperature never exceeded 90°C during both tests.

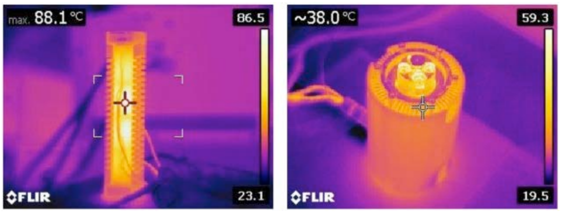

Fig. 9: *PPA80L (left) and PP80L-EA (right) working at the same ceramic surface temperature but different frequencies, note the encapsulation surface temperature*

The two configurations of an encapsulated actuator show many advantages, compared to the standard PPA80L version of the actuator, the driving frequency has increased 20 times for the encapsulated actuator fitted with the forced 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).

Note all tests were performed with the encapsulated isolated thermally, by fixing the actuator to a large thermally conductive mass allows even higher operating frequencies to be used.

Actuators operating within high temperature environments

Clearly when an encapsulated actuator is placed in a high temperature environment it will over time reach the same temperature as the environment. Two possible solutions exist either distant cooling of the fluid, or cooling the fluid locally.

Distant cooling of the encapsulated actuator includes circulating the cooling fluid within a closed loop system. With this type of system the cooling fluid is circulated between the actuator which can be within, for example, a high temperature environment and a heat exchanger positioned outside of the actuator environment, this ensures that the cooling fluid temperature keeps the ceramic cooled to a sufficient temperature so as not to damage the ceramic.

The advantage with this type of system is the possibility of maintaining a constant fluid/ceramic temperature even if the encapsulated actuator environment varies widely, for example actuators positioned within aircraft engines are required to operate between -40°C to 180°C and survive between -80°C to 250°C, with a reticulating fluid system it is perfectible possible for an actuator to operate within these conditions where the fluid is either heated or cooled depending on the current environment conditions.

Local cooling of the encapsulated actuator involves positioning a radiator system in contact with the encapsulation, while the fluid simple balances the heat difference between the self-heating ceramic, the environmental temperature and the radiator in order to maintain a suitable temperature for the ceramic.

Several options exist for suitable radiator systems, the use of compressed within the PPA80L-EA developed at Cedrat works perfectly allowing the actuator to achieve a constant operating frequency in excess of 1kHz within an ambient temperature environment. This actuator could be used within an environment where the temperature is greater than ambient, the ceramic temperature could be maintained at the same level by either increasing the air flow from the 0.25 bar used during the testing or decreasing the operating frequency of the actuator.

Other local radiator systems exist, including vortex cooling and Peltier Thermoelectric Cold Plates, both of these would allow a standalone encapsulated actuator to operate within an elevated temperature environment.

Conclusion

The actuators designed and presented in this article overcome typical limitations in terms of operating within harsh and or humid environments, working at very high frequency where self-heating of the ceramic has traditionally limited operating times, and working within an elevated temperature environment.

Several APA actuators have now been designed and delivered and are successfully operating within sever environmental conditions, at elevated driving frequencies.

An encapsulated PPA actuator has been tested in-house at extreme driving frequencies >1Khz. Using both cooling systems (fluid and air) this actuator can be driven constantly at this frequency, which is considerable greater compared to the standard actuator. Using just the fluid cooling and natural convection this actuator can be driven constantly at 230Hz. Long life tests 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-EA actuator at 1300Hz while maintain 90% of its stroke.

Encapsulations designed for both standard PPA and APA actuators protect ceramics form humid and high temperature environments.

Acknowledgement

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