ADVANTAGES OF LARGE PIEZOELECTRIC ACTUATORS AND HIGH POWER DRIVERS FOR FATIGUE AND FRETTING TEST

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Abstract: Constant expansion of new materials requires fretting or fatigue machines in order to test their failure. In many cases tests must be performed in severe conditions and at high frequency. These requirements come from the use of the materials in highly demanding applications. At the same time it is expected to reduce the time required to characterise such materials. Piezoelectric actuators are more and more common in testing machines, but they still reach limitations in terms of maximum displacement, cycling frequency or power. In order to cope with these issues, Cedrat Technologies has been investigating solutions. In this paper long stroke and high frequency actuators, coupled with powerful driving control are introduced. These actuators are based on piezoelectric materials and can be easily integrated into the fatigue machines. In order to improve precision of these tests, two of the most common displacement sensors used in smart actuators are also presented in this paper.

Keywords: Piezoelectric actuator; ECS sensor; Switching amplifier; Heat management

1 INTRODUCTION

Most common systems used these days for fatigue machines are based on servohydraulics actuators. Although these systems provide high force and long stroke they are limited in terms of frequency, speed or acceleration. Due to these limitations fatigue machines based on smart actuators have the advantage over the hydraulic systems in terms of response time and cost. Especially piezoelectric actuators are good candidates [1, 2]. This type of propulsion presents many advantages over the conventional systems. It can provide good accelerations with high amounts of force. At the same time integrated displacement sensors allow precise measurement for closed loop control system. Recently, Cedrat Technologies has developed new actuators and a dedicated high power supply that are adapted to testing machines.

First development was concentrated on improving the actuator maximum displacement. Typically available piezoelectric actuators reach stroke limitation above 1mm. In order to extend this boundary Cedrat Technologies has developed a new actuator that doubles this limitation. A second development concerned increasing the actuator maximum driving frequency. The frequency limitation derives from self overheating of the piezoelectric ceramics, which is a huge problem. Sufficient cooling systems allow increasing the driving frequency and at the same time prevent overheating. However a higher driving frequency requires sufficient power supply for the piezoelectric components. The current need increases linearly with the driven frequency. Development of the power supply for piezoelectric actuators is presented in this paper. Final improvement was concentrated on the displacement sensors used for precise control and possible closed loop systems. Current position measurement is based on strain gauges. A new option for displacement measurement is an eddy current sensor integrated in the actuator. Both systems are presented and described in this paper.

2 LONG STROKE ACTUATOR

Maximum stroke increase of piezoelectric actuators is subject to extensive research. Typically the maximum displacement generated by piezoelectric ceramics is limited to a 0.1% elongation. This value depends on the type of the ceramics. With mechanical amplification this value can be increased 10 times. For many years Cedrat Technologies has been producing mechanically amplified actuators within the most compact volume. This patented mechanism used with piezoelectric ceramics is called amplified piezoelectric actuator (APA®). Up till now the maximum displacement of these actuators was 1mm.

Over the last year intensive research was performed in order to double the available stroke of an APA®. The research was based on the standard actuator APA1000L, which provides nearly a 1mm stroke and uses stack of 6 (10x10x20mm^3) piezoelectric ceramics to generate displacement. The idea was to keep the same number of the ceramics and to increase the amplification ratio of the mechanism.

Based on simulations work an increase of amplification ratio was shown to be possible, in order to reach the required displacement. First measurements with standard ceramics showed that the displacement of the actuator was doubled compared to previews products. The new actuator provides a 1967µm stroke. The amplification ratio is now multiplied by 15. It is the biggest amplification ratio obtained so far with this type of an actuator. Furthermore the maximum force obtained with this actuator is 60N. Based on blocked force value and displacement measurements this actuator generates 15mJ of energy. The developed actuator was named APA2000L (**Fig. 1**). A derivate called the APA1500L has also been design, which produces a stroke of 1480µm and a blocked force of 121N. When more force is needed, two identical actuators may be set up in parallel to double the available force, with the same stroke.

Maximum speed and acceleration of the actuator depends on the driven frequency. With piezoelectric actuators, there are two configurations in which they can be used. The first configuration is called Blocked – Free. In this condition one extremity of the actuator is attached to a rigid base while the other one is free. The second configuration called Free – Free is when both actuator extremities are not rigidly fixed. Due to these two configurations the resonance frequency varies and changes the maximum driving frequency. The APA2000L can be driven up to 30Hz in Blocked – Free condition and up to 150Hz in Free – Free condition. The generated acceleration is quite huge regarding to the offered displacement. For the Blocked – Free condition the actuator can reach acceleration of 37m/s² and in Free – Free condition it can reach 1740m/s².

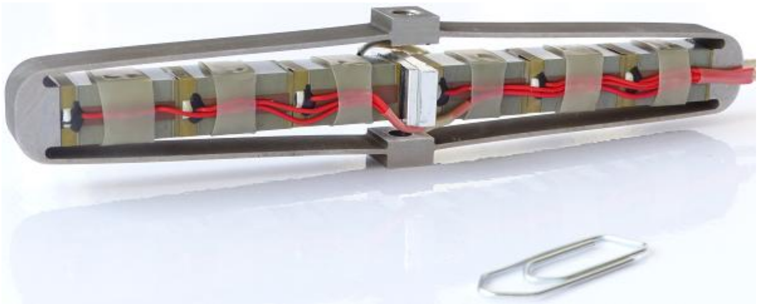


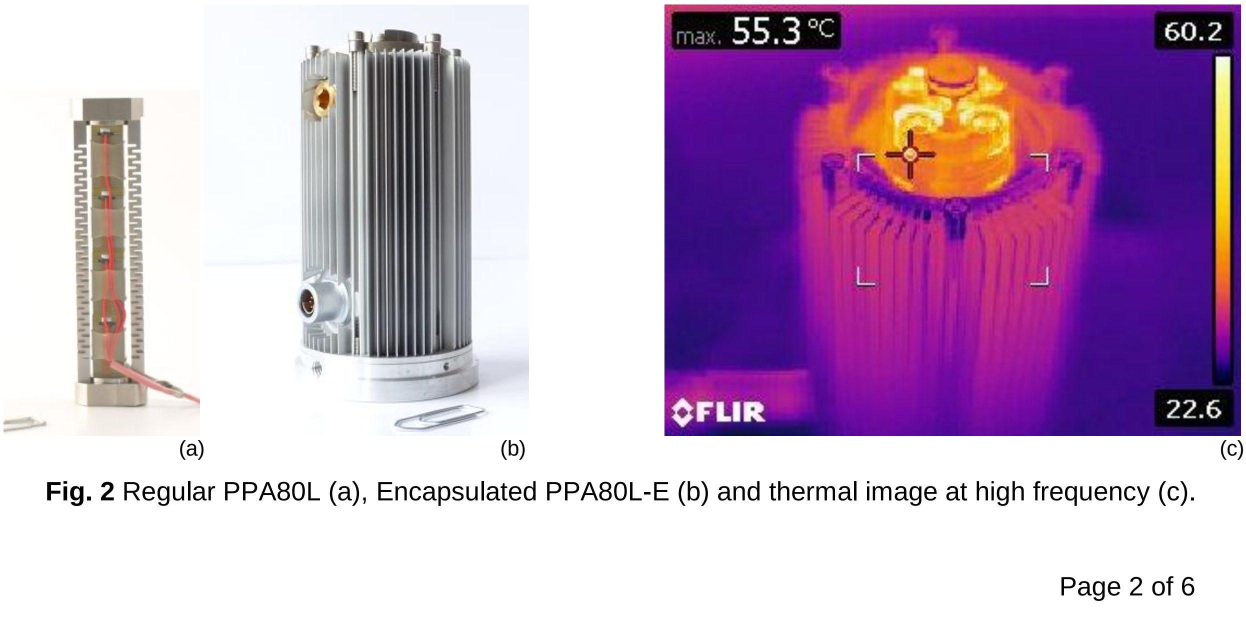
Fig. 1 Long stroke amplified piezoelectric actuator APA2000L.

The developed actuator, has a compact dimensions of 140x10x28mm³ (length x width x height), and can be easily integrated in fatigue mechanisms. The increase of maximum displacement, improved performance and doubled the stroke of typical actuators, together with high generated energy can be sufficient in fatigue of fretting testing.

3 HIGH FREQUENCY ACTUATOR

Due to excessive overheating of the piezoelectric ceramics, the use of piezoelectric actuators in high dynamic conditions is limited. In many cases the maximum operating temperature is limited to 85°C. With this limitation the actuators can be used only for a few moments at maximum frequency, typically one or two minutes, depending on the driven frequency. In order to overcome this issue it was decided to develop an actuator that could work at high frequency for a long period of time.

Development of an actuator with a sufficient cooling system was investigated at Cedrat Technologies. Some precautions are needed: A piezo actuator has to be encapsulated in order to use a cooling system and the cooling fluid must be compatible with piezo ceramics.



(a) (b) (c)

Fig. 2 Regular PPA80L (a), Encapsulated PPA80L-E (b) and thermal image at high frequency (c).

Two-stage architecture was made with internal cooling system that is used to extract the heat from the ceramic to the encapsulation, and an external system that employs compressed air and radiator fins in the encapsulation to improve heat extraction. A developed prototype was based on a standard parallel pre-stressed actuator PPA80L, renamed PPA80L-E for identifying the encapsulation (**Fig. 2**). This actuator has been tested in order to verify both cooling systems. Significant improvement of the actuator in terms of maximum driving frequency has been observed.

In the first test the internal cooling system was tested alone. Based on this test it was observed that the PPA80L-E can be driven at 230Hz constantly. Monitored temperature of the ceramics stayed below the critical temperature value. During long cycling test the actuator has performed 170 million cycles during 8 days. During this period the actuator was turned off and on couple of times. These activities allowed to obtain heat up and cooling graphs of the actuator. The heats up curves of the regular and encapsulated actuators were compared (**Fig. 3**). Working at 230Hz, regular actuator reaches 81°C in 1:07minute and should then been stopped to prevent damages. At the same time the encapsulated actuator can work constantly at that frequency.

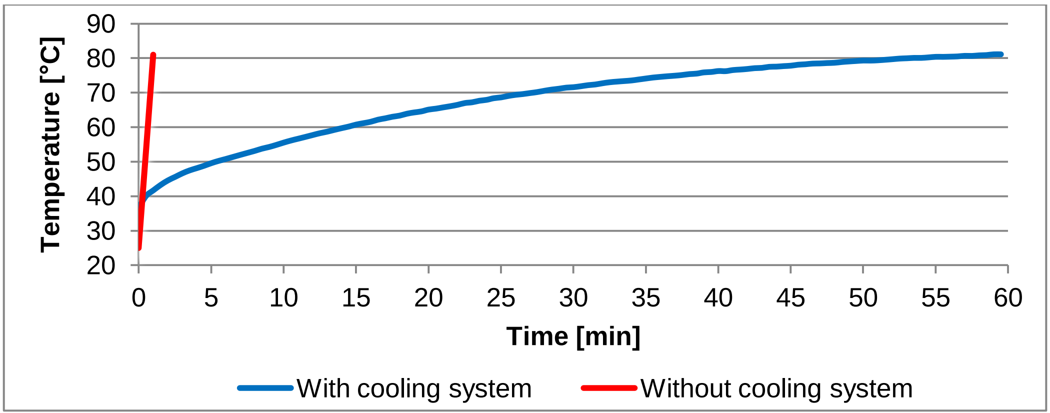


Fig. 3 Heat up curves of the PPA actuators with and without cooling system driven at 230Hz.

Promising results led to testing the external cooling system, this just requires plugging the actuator into a compressed air supply. The air pressure was set to 0.25bar. With both cooling systems working, the maximum driving frequency was increased up to 1000Hz in continuous running. The external system, based on optimised flow of compressed air, allows an increase in the driving frequency by a factor of 4 compared to using the cooling fluid only.

The developed actuator with cooling system can be used at high frequency in many different applications. One of these applications can be integration in the fatigue mechanism, where using higher frequencies reduces testing time and increases efficiency of the machines.

4 SENSOR INTEGRATION

The most common sensors integrated in the piezoelectric actuators are strain gauges. This type of sensor presents many advantages which include good reliability, conditioning and accuracy. The strain gauge is directly glued to the ceramics and measures strains on the piezoelectric component, which is then converted by the conditioner into a standard ±10V signal. Calibrated output signal is proportional to the displacement of the whole actuator with a specific gain value.

Although this sensor presents many advantages, the measured displacement in APA® actuator is indirect due to mechanical amplification. This means that displacement of the actuator is measured on the base of the ceramics displacement. This solution works well, as long as the actuator is not subject to dominant external forces. Unfortunately, it is often the case in fatigue or wear test benches.

The possibility of a direct measurement of the displacement in APA® has been investigated. A solution was developed with an eddy current technology probe. This sensor allows for a contactless and direct measurement of the actuator displacement.

Promising results of the prototype introduced in previous publications [3, 4] induced further investigation of ECS sensor integration in standard actuators. The integration of the sensor in the APA® actuators was initiated by designing support that could be integrated in the actuator. Three supports were manufactured and tested in order to choose the best configuration. First two supports were measuring displacement of the actuator between two extremities. Third version was attached at ceramics level and measured displacement of the actuator extremity relatively to the position of the ceramics.

Evaluation of designed supports was based on thermal testing and measurements at low and high frequencies. Measurements at different frequencies showed which support type gives the best sensitivity with narrow hysteresis. Thermal tests clarified the actuator stroke measurement error caused by temperature variation. It was observed that one of the supports extinguish with good results from two others (**Fig. 4**). This type of support due to small dimensions provides the best sensitivity at different frequencies with small signal error coming from temperature variation.

The ECS probe mounted inside the APA® shape allows direct measurement of the actuator extremity displacement. The compact dimensions of the probe and the fixing method do not increase the total volume of the actuator. At the same time the hysteresis correction and thermal behaviour presented the best conditions with the selected support.

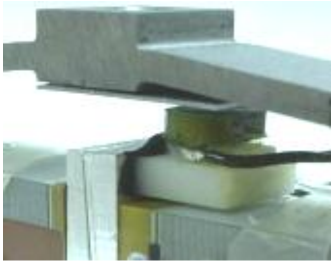


Fig. 4 ECS with special support integrated in the APA.

Both presented sensors can be easily used and integrated in fatigue test benches. Signals coming from the sensor can be used for monitoring and controlling the actuator. Displacement measurement can provide information about fatigue or fracture propagation in the tested samples. Based on this data the closed loop control system can adjust testing parameters in real time.

5 HIGH POWER AMPLIFIER

One advantage of piezoelectric actuator for fatigue testing machines is the opportunity to work at high frequency. But with big actuators, this requires high power amplifier, as the current need is proportional to the frequency. The most common amplifiers used for driving capacitive loads are linear amplifiers. Although this type of amplifier provides smooth supply signals with low output noise (THD), their configuration causes huge power losses. At the same time power and current values require large components and heat sinks that make this amplifier massive. Due to this disadvantage the maximum current value is limited (**Fig. 5)**.

It became necessary to develop a new amplifier for overtaking the limitation in current. In order to get an amplifier capable to generate more power, a new configuration based on switching topology was investigated. This configuration enables to obtain much more power with negligible losses that makes this amplifier very efficient. Developed portfolio of switching amplifiers obtained the name SA75.

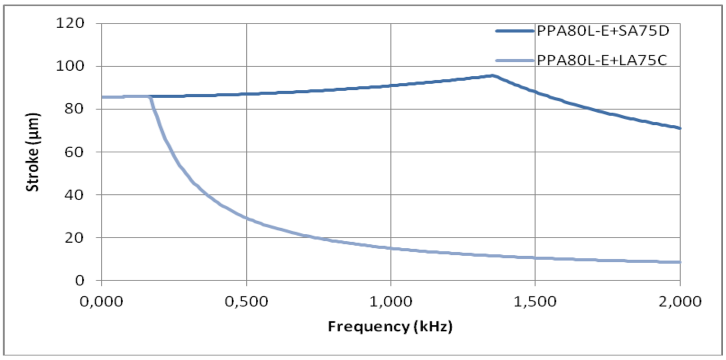


Fig. 5 Power capabilities comparison of a switching amplifier (SA) and linear amplifier (LA) on a PPA80L actuator

The design of the amplifier has concentrated on driving capacitive loads, particularly piezoelectric actuators. The low voltage piezoelectric materials require a driving range between -20 and 150V (170Vpp). At the same time, driving these actuators at high frequency requires high current values. Following the requirements, the developed amplifier can provide up to 20A continuously, in the SA75D version. This value is sufficient enough to drive one large actuator (like actuators from the L or XL range from Cedrat Technologies) at high frequency or couple actuators in parallel.

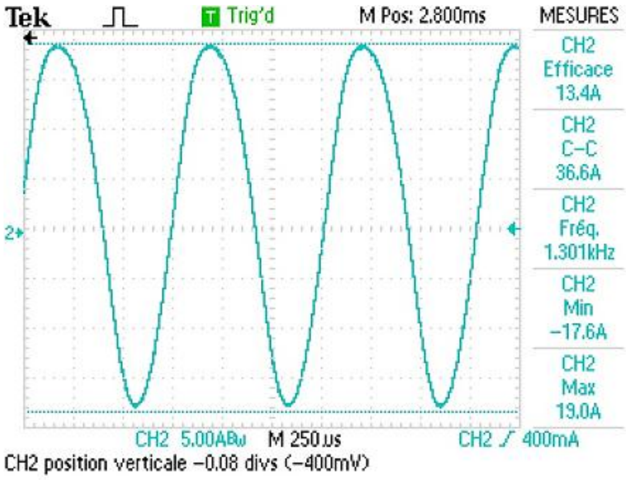


Fig. 6 Current measurement of the PPA80L-E driven with SA75D at 1300Hz.

Tests with the SA75D and PPA80L-E showed that this amplifier can easily provide 18.3A peak value while driving the actuator at 1300Hz (**Fig. 6**). In these conditions, the PPA80L provides 3500N and a stroke of 94µm. At 1300Hz, the mechanical reactive power stored in the actuator is 1.3kVA, whereas the maximum electric reactive power provided by the amplifier is 1.5kVA [5]. Power consumption gets a benefit from the low losses of switching technology. Moreover, an energy recovery system has been included for driving capacitive loads. Finally, at maximum driving parameters (20A and 170Vpp) the required active power is less than 100W.

Low power consumption and recovery system allowed using smaller and less massive components. The mass of the core amplifier is less than 850g with total volume of 100x100x100mm³. The power ratio of the amplifier is 1.75kVA/kg.

6 APPLICATION NOTES

Piezo actuators are easily controllable, this makes them versatile for test machines or for particular methodologies. Due to the proportional relation between voltage order and actuator displacement the fatigue excitation or fretting stroke on the sample can be easily set up. Additionally the signal shape can be adjusted to the requirements. A large variety of signals can be applied to the actuators: from the most common continuous sin, square, sawtooth, triangle signals to a personally-created signal that can vary in amplitude or over time.

In fretting test benches, which are used to produce the wear of two surfaces, the amplitude of the relative sliding motion is in the order of magnitude of a few microns to millimeters. Piezoelectric actuators are a good choice for this application, offering easy control and high speeds. Their intrinsic mechanical stiffness is an additional advantage for the application.

For fatigue machines a piezoelectric actuator may be coupled with a hydraulic actuator to get the benefit of both technologies. This is the choice that Fraunhofer LBF (DE) has made. They developed a hybrid high cycle fatigue (HCF) testing machine used to investigate the high frequency properties of different materials, with a low-frequency hydraulic actuator for a frequency band between static to 50 Hz and a high frequency piezo actuator system for frequencies up to 1000Hz (**Fig. 7**).

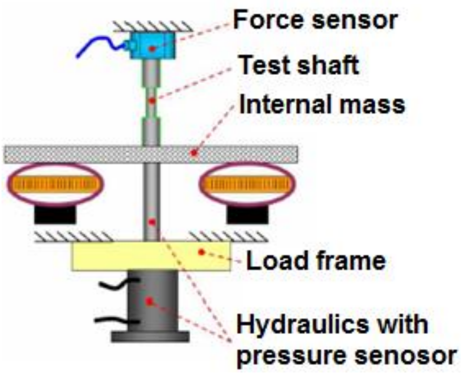
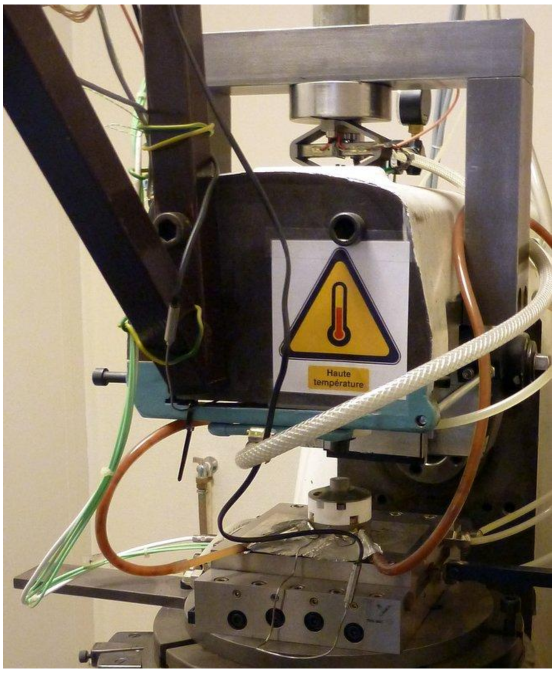


Fig. 7 Hybrid high cycle fatigue (HCF) testing machine using 4 APA230L (Courtesy of Fraunhofer LBF)

Since the introduction of our devices in that field, laboratories such as LAMCOS (**Fig. 8**) or LMT and industrial such as AIRBUS or EPT (Electronics Precision Technology) have tested and approved our technology for fretting.



Application: Impact or sliding testing

Temperature: up to 500°C

Horizontal mouvement:
- Shaker Gearing Watson V 100 SS 600
- Sinusoidal Force peak 778N
- Maximum Acceleration Peak 981m/s²
- Maximum Velocity Peak 1.65m/s
- Maximum Displacement pk-pk 12.7mm

Vertical Mouvement:
- Piezoelectric actuator APA 120 ML
- Sinusoidal stroke 0 to 70µm
- Bloqued force 1400N
- Maximum frequencu Blocked-free 1750Hz

Forces sensor
- KISTLER 9251A
- Measurement of impact forces and tangential rubbing forces

Fig. 8 IMPACT II: APA120ML actuator for impact or normal force control (Courtesy of LAMCOS)

7 CONCLUSIONS

Presented development of the new piezoelectric actuators can bring advantages in fatigue and fretting testing machines. Encapsulated actuator with integrated cooling systems (PPA80L-E) allows performing tests at high frequency, up to 1000Hz. This parameter reduces time and/or improves efficiency of testing machines. The switching amplifier range SA75 provides sufficient power to drive big piezoelectric actuators at high frequency. Presented test results shows that this amplifier can drive the encapsulated actuator at up to 1300Hz. At the same time real power consumption stays below 100W. Long stroke actuators (APA2000L) generate two times larger displacement compared to standard actuators, with maintained dynamic capacities. For complete mechanism, a displacement sensor can be integrated in the piezoelectric actuators. Displacement sensor based on the eddy current effect (ECS) can be used for monitoring and controlling the actuator.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

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