Compact, Lightweight, and Efficient Piezo-Actuation Chain for Aeronautical Applications

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Abstract:
Many past and on-going studies are focusing on the use of piezo-actuators for aeronautical applications. One of the trendiest topics is the use of such devices for active flow control in aircraft, in order to reduce fuel consumption and noise. However, the implementation of such systems in aircraft suffer a lack of maturity with respect to aeronautical constraints, which are: high efficiency, compactness, and lightweight. In general, the actuators are composed of ceramics integrated in a metallic shell, which makes them heavy. For driving the actuators, the power amplifiers employed are usually linear amplifiers, which have a poor efficiency, leading to bulky designs due to large heatsinks. This paper presents recent developments that have been made to cope with these issues in order to obtain a piezo-actuation chain suitable for aeronautical applications.

Keywords: Actuator, Piezoelectric, Composite, CFRP, Switching, Amplifier

Introduction

Global tendency of using more electrical systems in aircraft opens the opportunity to replace the standard hydraulic or pneumatic cylinders with piezoelectric actuation units [1]. However, those units are usually quite bulky, heavy, and with low power efficiency, which are serious drawbacks for aeronautical applications. In order to cope with these issues, CEDRAT Technologies has been working on the development of new actuators which can be driven with more efficient amplifiers.
Growing influence of composite materials in the aeronautical industry encourages implementing these materials for piezoelectric actuators. Currently, the mechanical structure of the actuators, the “shell”, is made of metal. By replacing the metal structure with a composite material, it is possible to obtain a lighter actuator. The objective of this study is to verify that the change of the material does not reduce functionality of the actuator.
The piezo-actuator requires high power amplifiers, which are usually a linear type. The drawback of the linear topology is poor efficiency. Switching power amplifiers are very common for driving inductive loads such as magnetic motors. These amplifiers have a very high efficiency, which makes them very appealing for piezo-actuation solutions. However, it is more complex to design switching power amplifiers for piezo-actuators, since they have a capacitive behavior. CEDRAT Technologies has sucesfully developed compact and efficient switching power amplifiers for piezo-actuators.

Design of composite piezo-actuators

The new amplified piezoelectric actuator (APA®) with composite shell was designed by ONERA based on the standard metal-shell actuator APA500L [2]. As a consequence, the dimensions are roughly the same as in regular version. As there is a close similarity to the standard actuator the test results of the new APA® were compared between both types. The new shell was made out of T300 carbon fiber with a high glass transition temperature epoxy resin (Fig. 1).
Change of material used for manufacturing the shell presents many advantages. Since the shell is not metallic, the actuator is non-magnetic, and thus has the ability to be used in strong magnetic fields or in applications where the magnetic field should not be perturbated.

Fig. 1: Amplified piezoelectric actuator APA® with composite shell.

Tests of the composite actuator

After manufacturing, the mass of the composite APA® is 32.5% lower (with better dynamic behavior) than the regular actuator, thus the main objective is achieved. At the same time the mechanical parameters stayed the same as for the metal actuator. The stroke generated by the actuator is the same as for the regular one. The total displacement of the actuator is 500µm.
From the dynamic point of view, the new actuator was tested under two conditions. In the blocked condition, the resonance frequency increases by 8% compared to the regular actuator, while in the free condition it increases by 93%, i.e. it almost doubled. The resonance frequency is a crucial parameter, as it

is related to the mechanical bandwidth. With the higher resonance frequency the actuator can be used within a wider stable operating range.
On a dedicated test bench a maximum force was measured. While applying maximum voltage the APA® generates a maximum force which is measured with the sensor. The values of the force generated by the composite and standard actuator are the same at 570N.

Life time tests of the composite APA®

As the mechanical parameters of the composite may change in time the stability of a new shell had to be verified. This reliability was verified with life time testing. The actuator was driven at high frequency (290Hz) with full stroke in the blocked – free condition. To make the test more severe for the composite shell an additional mass was attached to the actuator. Three metal discs were attached with total mass of 330g. The APA® has run over $4*10^{9}$ cycles, and no delamination, cracks, or any frying of the composite was observed. During periodical verifications the stroke and resonance frequency of the actuator were measured. Both parameters were stable during whole life time testing.

Thermal tests of the composite APA®

Two thermal tests were performed on the new actuator. In the first test mechanical parameters of the composite actuator were measured. In the second test the shell was verified during a long cycling test. The temperature range for both tests was based on the AIMS (Airbus Industry Material Specification) specification. According to those specifications composite material has to sustain long exposure to low temperature (-55°C) and high temperature (90°C).
For testing mechanical parameters in different temperatures, stroke and, resonance frequency were measured. It was observed that the stroke of the APA® changes with the change in temperature.

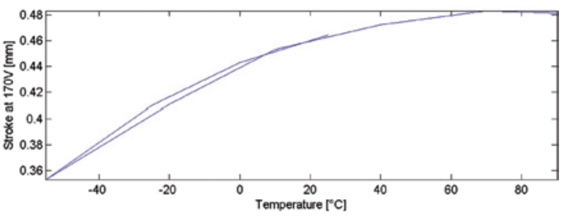

Fig. 2: Maximum stroke of the actuator in change of the temperature.

This change is normal and it is caused by the thermal behavior of the piezoelectric ceramics. With an increase of the temperature the maximum displacement increases. In low temperatures the displacement of the ceramics decreases by 30%. This decrease can be also observed for the whole actuator (Fig. 2). Measurements of the resonance frequency showed that this parameter also changes with the change of the temperature. With a decrease of temperature the resonance frequency increases. In the measured range the resonance frequency has changed by ±2%.
In the second thermal test the long cycling measurement was verified on the composite actuator. The APA® run for more than one million cycles at low temperature (-55°C). The test was divided into three stages in which the actuator was driven with different frequencies. A slight delamination was observed on the shell after the test. To verify the performance, sets of experiments were performed on the actuator. Based on the obtained results from all the tests the occurrence of delamination did not caused any loss in performances of the APA®.
For the long cycle test at high temperature (90°C) no deformation of the shell was observed. Long cycling test in low and high temperatures showed that the mechanical parameters of the APA stayed the same as before the performed thermal test.

ECS displacement sensor integration

The new composite actuator was designed to meet the requirements for high precision applications. To fulfill these demands a displacement sensor was integrated in to the actuator (Fig. 3). With an additional sensor the actuator can be easily used in a closed loop control system. An eddy current sensor (ECS) was used for displacement measurements down to nanometers. With this contactless sensor the actuator can be controlled. At all times it verifies position of the actuator mechanical interfaces. To integrate the sensor probe in the composite actuator a special support was designed. The compact size of the designed support does not increase the total size of the actuator. Performed tests showed that the thermal influence on the support is negligible. This allows using the actuator with the closed loop control in a wide temperature range.

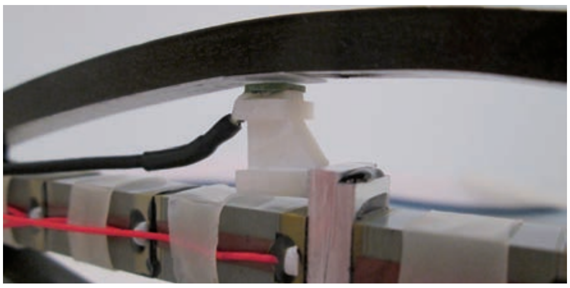

Fig. 3: ECS integrated in composite APA.

Design and performance of the SA75X

The SA75X is a portfolio of switching power amplifiers that has been developed to drive piezo-actuators between -20V and +150V, with a voltage gain of 20V/V, and with an output current up to 20A for the SA75D. In order to optimize the resolution, the amplifiers are designed to switch at very high frequency (typically few 100 kHz at the PWM signal level). The amplifier operates in closed-loop to ensure that the output voltage is equal to what is commanded. From the performance point of view, the output power of the SA75D is up to 1.5kVA. The OEM version has a weight of approximately 850g, and dimensions of 100x100x100mm, i.e. 1 liter. The power ratio of the solution is thus of 1.5kVA/L, and 1.75kVA/kg.

Proposed topology

The synoptic of the power supply chain for piezoelectric actuators in such applications is described in figure 4. It consists of a half bridge DC-DC converter to handle the stabilized supply voltage to the SA75 (200Vdc).
From the DC-DC converter point of view, it should provide an active power close to 300W to take into account the dielectric loss of the piezo load (30W - mainly capacitive) and the intrinsic loss of the switching stages. This stage is oversized to take into account the possibility to drive 4 SA75D channels.
Regarding the capacitive behavior of the actuators and to achieve high efficiency levels, a H-bridge topology is proposed for the DC-AC converter to ensure better energy transfer [3]. The output signals are filtered via an inductor to be suitable for the piezoelectric operations modes.

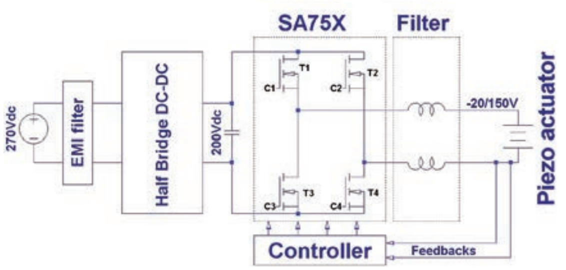

Fig. 4: *Synoptic of aeronautic driving circuit for piezoelectric actuators.*

The switching frequency is fixed at 100 kHz to minimize the output signal noises (THD) with dead times closed to 100ns. The two converters (DC-DC and DC-AC) were synchronized to operate at the same switching frequency to avoid problems related to delay times. Using feedback from the piezoelectric sensors side and conditioner signals; a controller board has been designed to monitor the output voltage, current, and actuator positions. Current limitation technique is also developed to avoid harmful peak current passing through the actuator.

Simulation results

The coupled system (SA75D-filter-actuator model) is simulated with different piezo-capacitance values in open and closed loop and with input inhibition frequency up to 1 kHz. As mentioned in figure 5, Proportional and Integral voltage controls associated to a current loop gain (Ki) are used for control in closed loop operation mode. The first loop is standard but due to the type of load, the stability of the closed loop is not easily reachable (low damping ratio of the LC filter). To improve the damping and as the load is purely capacitive, an additional current control was added to reduce the electrical resonance of the filter.
A specific work on the dead times is done to improve the THD in open loop of the DC-AC converter. Even if the converter is in feedback with the voltage and current sensors; the control loop requires a low THD in open loop to be compatible with a linear control of the output voltage.

Tab. 1: *Simulation parameters*

Input Voltage	200Vdc
Output voltage	-20/150Vac
Switching frequency	100kHz
Dead time	100ns-140ns
Filter inductor	90uH adapted to the load
Voltage gain (Kv)	20V/V
Controller parameters	
Tp	1
Ti	100 000
Current loop Gain(Ki)	0.3

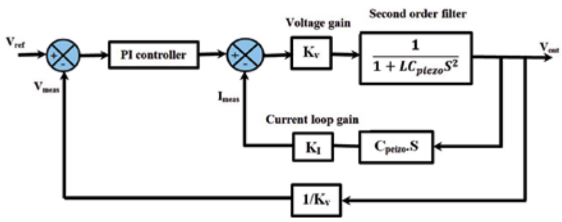

Fig. 5: *Voltage control scheme*

Figure 6 shows the output voltage, current and bridge voltage for sinus order (500Hz).

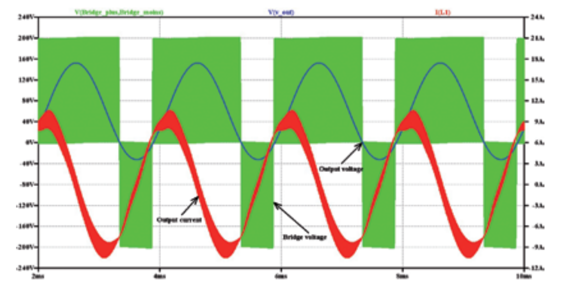

Fig. 6: *SA75D output signals (500Hz); Iout (R), Vout (B), Bridge voltage (G).*

As aeronautic application demand light components, efforts were done to reduce the surface of the switching functions. Specific switching components are selected to suppress the standard parallel recovery diodes and the additional serial schottky diodes validating a surface saving of 8 power components.

Experimental results

The final architecture of the SA75x series consist of a design of 3 Daughter Boards (DB); one with 5A output current (SA75A), one with 10A output current, and one with 20A output current (SA75D). To facilitate the packaging and integration, the mother board (MB) is designed to support a daughter board (DB), output filter, and all required controller connectors. The output signals of SA75D are verified with different loads (30uF, 60uF…) and under frequency up to 1 kHz.

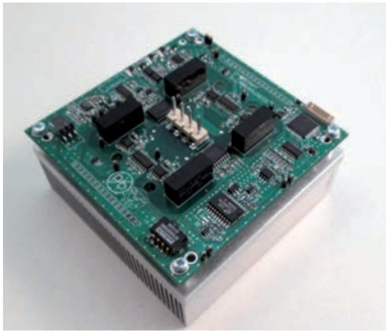

Fig. 7: *SA75D Daughter Board.*

Figure 8 shows output signals of the amplifier at 1 kHz (20A.max) in an open loop system. It was observed that the SA75D is able to handle an output power up to 1.5KVA under 1kHz with acceptable signal noise.

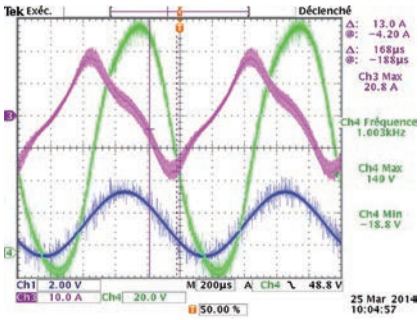

Fig. 8: *SA75D output signals (1 kHz); order (Ch1), Iout (Ch3), Vout (Ch4).*

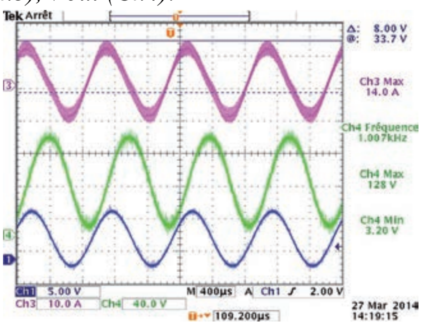

Fig. 9: *Closed loop response for sinus order (1 kHz); [Ch1]: order, [Ch2]:Vout; [Ch4]: Iout.*

This performance is important in aeronautical applications and allows reducing the actual heat sink (0.08°C/W) to improve the power/mass ratio. The performance of SA75D in closed loop operation mode is tested with both sinus and rectangular order (Fig. 9). The output filter is fixed to 90uH.

The voltage and current measurement coefficients as the controller parameters are adjusted to ameliorate system response.

Test result shows that the system can maintain stabile in closed loop with higher frequency (up 1 kHz for sinus order) with an acceptable response time.

Conclusion

The study has shown that the lifetime of the composite piezo-actuators can compete with regular piezo-actuators. In addition, it was found that the mechanical bandwidth of the actuator can be doubled in certain conditions. This means that the actuators with composite shells have not only a lower mass, but also they have a higher performance than regular piezo-actuators. The thermal tests showed that the piezoelectric actuator with composite shell can meet the requirements of the aviation industry. An integrated ECS displacement sensor allows high accuracy positioning. With the new high power switching amplifier the composite actuators can be used in closed loop control systems. When driven with a switching power amplifier (SA75x), the efficiency of the actuation chain is very high (>80%). In addition, the system is more compact and light, thus it can be more easily integrated for embedded applications. The high current generated by the amplifier can be used to drive the actuator in high dynamic conditions. The SA75D can be also be used to drive many actuators just with one amplifier. The proposed chain for aeronautic application can be easily modified to fulfill an industrial environment.

Acknowledgement

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