New Actuators for Aircraft and Space Applications

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Abstract

Actuators are key elements of air- and spacecrafts. In the recent years the concept of the more-electric aircraft pushed the development of electrical actuation systems to substitute hitherto used hydraulic actuators in a broad range of applications such as flight control, landing gear and brake actuation. On top of that the superior dynamics of electrical actuators, especially when utilizing the piezoelectric principle, open new fields of application in noise and vibration control. Novel electrical actuation technologies have to comply with demanding requirements concerning life, reliability, weight, environmental conditions and installation space. The main principles pushed forward in the recent years are electromechanical actuators (EMA) and piezoelectric actuators. These new actuators put strong requirements on electronics systems design and power amplifier stages. It requires highly efficient and reliable electronics to achieve flight worthy products.

In Space & Military fields, there is a trend for miniaturisation meet in active optics, fine instruments, robotic missions, micro-satellites, UAVs, MAVs, which directly impact on the actuators. A new generation of small and smart actuators such as piezoelectric actuators and magnetic actuators, are responding to this trend, thanks to their capacity to offer high energy density and to support both extreme and various requirements.
The paper presents typical applications to discuss the state-of-the-art performance and deduce further needs.

Keywords: actuation, smart materials, piezoelectric, noise & vibration reduction, space qualification, aerostructures, UAV, MAV

Introduction

In the last years the “mechatronics” gained impetus in aerospace. Industry and academia intensified research effort on electric powered actuation systems to contribute to the realization of all-electric-aircraft. Large projects such as MOET [1] were launched to establish a new standard of electrical system design of commercial aircraft. For any fixed wing aircraft actuators are needed to command the aerodynamic control surfaces such as rudders, ailerons, horizontal stabilizer or flaps. For helicopters swash plate systems are used to command the vehicles flight path. To achieve electrically powered control systems research is focussed on replacing hitherto used hydraulics by electrical drives to actuate the swash-plate, or using electric drives to directly control the individual blade pitch angle [2]. Beyond these concepts development activities are directed on active control of the rotor aerodynamics by using piezo actuators either for flap devices [25,5] or morphing blades [16].

Beside the field of flight control there are exciting opportunities to apply unconventional actuators specifically piezo actuators in aerospace. Piezo meet perfectly the requirements of anti- noise and vibration systems as they provide high structural forces and high dynamics [2]. A variety of system solutions have been developed and tested at EADS during the last decade to manage different noise phenomena: strong structural vibrations in launchers e.g. Ariane V [6, 12], structure born noise caused by gear meshing [7], buzz saw noise tones generated by jet engines which occurs in aero engines at take-off conditions due to a shock wave system produced at the fan tip at supersonic fan tip speeds [8], reducing vibrations in helicopter fuselage by applying piezoelectric tuneable vibration absorber technology [9]. To improve the noise comfort in commercial aircraft active noise control and/or structural control concepts appear quite attractive and have been investigated intensively. A new concept based on a trim-panel suspension with active attachment elements using piezoelectric actuators has been developed by EADS [13].

In Space, the need for smart & miniature actuation functions is increasing because of several trends. Even more complex instruments are implemented in satellites or robotic missions and need actuation functions. Space vehicles, such as robots micro-satellites are smaller and smaller for launching cost reasons. This induces requests for smaller actuation functions not only on the payload but also on the platform, such as in the thrusters. In addition, severe and various environments are meet. In this context, space is actively looking at all the new smart & miniature actuation technologies [35, 36].

This trend for small & smart actuators is found also in military applications. For example, in 1996

DARPA initiated the Micro Air Vehicle (MAV) Program initiative, seeking to develop emerging technologies for military surveillance and reconnaissance applications [37]. MAVs are micro or nano Unmanned Aerial Vehicles (UAVs) requiring tiny actuators & motors. Another type of example is given by the complex optic instruments, such as Infra Red (IR) cameras, embedded on military vehicles or aircrafts. Such cameras also request small & smart actuators working in severe environment.

In this paper, the research in the field of smart & small actuators for Space & Military fields will be reviewed, updating [38] with a complementary approach: To illustrate the trend, the actuators and mechanisms from Cedrat are presented. They have been initially developed and qualified to meet space requirements but logically found also applications in military and micro aerial vehicles fields, for various micro-mechatronic functions. For all these reasons, the growing demand for smart actuators in space and military fields presents several similarities, which is benefited for Cedrat business development.

1 Novel Actuators for Flight Control Systems

The All-Electric Aircraft concept has been established for many years describing an a/c with all systems fully electrically powered and no hydrostatic or pneumatic systems remaining. The envisioned benefits are:

- increased safety due to elimination of poisonous and flammable hydraulic fluids
- easier and reduced maintenance due to elimination of hydraulic leaks and better diagnosability
- reduced weight and complexity of power transmission paths
- better energy efficiency of electrically powered systems
- weight benefit on a/c level [26]
- better actuator dynamics (esp. flow control or helicopter applications)

Realizing this vision has proven very challenging – especially in the area of flight control actuation where the trend towards the all-electric aircraft causes a strong need for novel optimized electrical actuators. Although for many years there has been substantial research effort in the area there still is no large commercial aircraft on the market or even in development that fully implements the concept. However first steps ahead have been taken by the A380 (stand by electro-hydrostatic flight control actuation system, 2 instead of 3 hydraulic systems [10, 11, 26]) and the B787 with electromechanically actuated airbrakes [27, 28].

Main challenges in developing solutions for electromechanical flight control actuation are

- weight optimized design of power electronics and the electromechanical drive train to be competitive with hitherto used and mature hydraulic actuation technology
- electromechanical/piezoelectric actuator and electronics designs offering low failure rates under prevailing adverse environmental conditions (temperature, pressure variations, humidity, contamination, radiation, vibration…)
- Redundant system topologies to achieve a very high safety and availability level

As there is little experience with the relevant failure mechanisms and failure probabilities of EMAs for failure modes such as actuator jamming, the first generation of electrically powered flight control actuators introduced on the A380 transport aircraft recently [10, 11] uses EHA (electro hydrostatic actuator) technology. The EHA concept comprises an electric motor and a pump acting as a local source of hydraulic power and a conventional hydraulic cylinder for linear actuation. Similar challenges exist for piezoelectric actuators for flight control applications like e.g. dielectric breakdown of the actuators in humid environment.

To get to all electric solutions the above mentioned challenges have to be addressed e.g. by novel gear technologies to exclude jamming and/or free wheeling of linear drives, encapsulation technologies to protect piezoelectric actuators from moisture or by system topologies sufficiently tolerant against the occurrence of these failure modes in individual actuators.

EADS and its business units Airbus and Eurocopter have a long history of cooperation to push ahead the EMA as well as piezoelectric actuator concepts for secondary flight control applications [16, 18, 19, 23, 24, 29, 30]. Future research work will also address EMA primary flight control applications.

In the following chapters some developments and ongoing projects shall be briefly described.

1.1 Electro-Mechanical Actuation (EMA) for primary flight control

An important objective within this technology stream is to develop electrical actuators based on permanent magnet synchronous motors (PMSM) and the associated inverter and control electronics. The motors are combined with a jack screw mechanism either on basis of a roller screw or ball screw principle to transform rotary into linear motion.

Alternatively high gear ratio planetary gear boxes with a rotating output lever providing quasi linear output are applied.

These topics are addressed by several large scale research projects that are expected to forward important pieces of technology to a flight demonstration level during the next 5-10 years.

A prominent examples is MOET (More Open Electrical Technologies, 2006-2009, [1]), an EU 6th Framework Program Integrated Project with one large work package solely dedicated to Electromechanical Actuation. Its target is to show the feasibility of an EMA with a sufficiently low jamming failure rate for fixed wing aircraft primary flight control actuation and demonstration of its competitiveness in terms of several evaluation criteria. Among the topics addressed is the development of an EMA fault anticipation system.

Within the EU 7th Framework Program the “CleanSky” JTI (Joint Technology Initiative) [31] covering the period 2008-2015 includes substantial research and demonstration activities on “Systems for Green Operations” including EMAs for flight control actuation. Its target is to deliver full scale demonstration hardware, validate it in aircraft relevant environment and thus shorten significantly the time to market of the solutions developed.

As part of the British DTI sponsored “More-Electric Aircraft Challenge” the “Helicopter Electro-Mechanical Actuation Technology” (HEAT) program was started in 2001. Main members of the HEAT consortium were Agusta Westland, BAE Systems, and Claverham Ltd. Within the program an electromechanical actuation system for helicopter flight control, i.e. electromechanical actuators and the associated control and power electronics for swash plate and tail rotor pitch actuation have been developed [32, 33]. In 2006/2007 flight tests have been performed. Rotorcraft specific issues addressed in the program are the mitigation of jam of mechanical transmission elements and the operation in a continuous vibration environment.

1.2 Distributed EMAs for secondary flight control

In the framework or the EU funded AWIATOR project (Aircraft Wing with Advanced Technology Operation, 2002-2006) distributed electromechanical actuators and electrical power & information networks have been developed for a novel flight control element [23, 24] influencing lift and span wise lift distribution of the aircraft wing.

The system is composed of 6 thin control surfaces called "Mini Trailing Edge Device" (Mini-TED) integrated in the flaps and comprising a total of 20 Electro-Mechanical Actuators (EMA). Due to the low torsional stiffness of the control surfaces multiple actuators and load introduction points have to be implemented on one surface. This poses special challenges for the control concept (Fig. 1): when active, all actuators have to operate synchronously but after a power supply or actuator failure the affected actuator(s) have to be transferred into a passive damping mode. A further technological challenge was the very tight space envelope for the actuators which required high power densities of electric motor, drive train and power electronics.

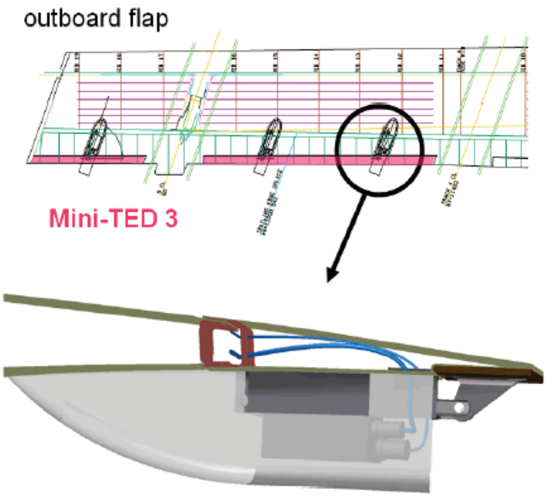

Fig. 1: Decentralised actuation concept

Extensive ground and flight tests in 2006 provided numerous experiences in operating electro-mechanical actuators in an aircraft relevant environment.

Another possible application of distributed EMAs in fixed wing aircraft are slat or flap actuation systems. In this case the distributed EMA system substitutes conventional slat/flap actuation systems (Figure 2) and can provide additional functionalities.

State of the art actuation systems consist of a central motor located inside the fuselage which drives the individual slat/flap drive stations via a rotating torque shaft system. Both electrically and/or hydraulically powered central motors are used. While conventional drive systems only allow for synchronous operation of the flaps, distributed EMA systems enable different settings for each flap/slat panel which can be beneficially exploited on a/c level e.g. for wake vortex attenuation or wing load alleviation by modulation of the span wise lift distribution. Figure 3 shows a functional demonstrator for a track integrated flap actuator developed by EADS and Airbus [29, 30].

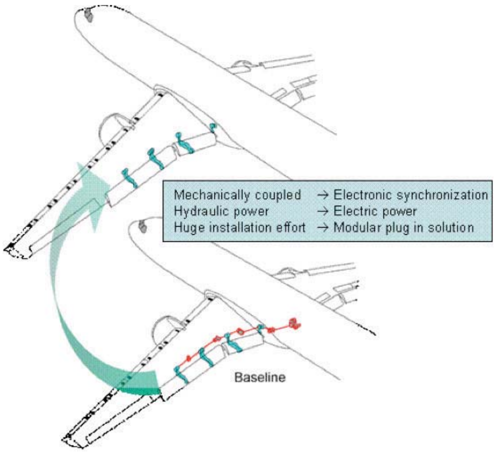

Fig. 2: *Distributed flap drive system vs. conventional system*

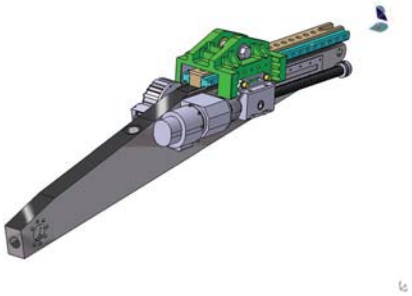

Fig.3: *Track beam integrated electrical flap actuation system.*

In the EU funded 6th Framework Program NEFS project ("New Track Integrated Electrical Distributed Flap Drive System", 2007-2010, [34]) EADS, Airbus and important players of the supplier industry have partnered to forward this technology. Some specific challenges addressed are tight envelope constraints, high power density, weight optimized but still robust design, high safety requirements to avoid excessive asymmetry in flap deflections on both wings, capability of the system to react aerodynamic flap loads even after any electrical or mechanical failure and thermal management of actuator and electronics in a thermally vulnerable CFRP environment.

1.3 Piezo Actuators for Active Rotor Control

Active helicopter rotor control has the following technical objectives:

- Reduction of rotor noise and cabin vibrations
- Improvement of rotor aerodynamics
- Reduction of rotor power consumption

Eurocopter and EADS pushes the concept of highly dynamic blade control by applying servo-flaps installed in the outer part of the rotor blades [5]. The solution of piezo actuation system developed by EADS Innovation Works in recent years [18,19] has been proofed to be successful in ongoing flight tests since September 2005.

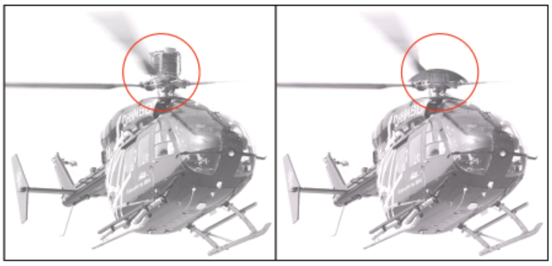

Fig. 4: *left - Status and right- target layout*

The piezo actuators developed by EADS (fig. 5) fully meet with the requirements: the very compact actuators delivers 1000 N force, 1.4 mm stroke at a weight of 450 grams and has a mechanical efficiency of 83%. But, the electronics system is by far too bulky and power consuming. So, the current development activities are focused to minimize size, mass, and complexity of the electronic system (see fig. 4).

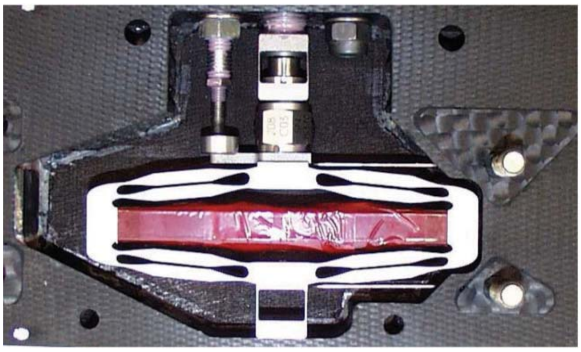

Fig. 5: *Amplified piezo stack actuator*

An alternative approach beyond the concept of servo flap is the active trailing edge. It is based on structurally integrated smart material actuation [11]. A "smart" tab is attached to the trailing edge of the airfoil. It is realized by a multi-morph bender including piezoelectric ceramics and glass fibre reinforced plastics.

The integration of piezo actuators into the base structure is highly desirable for many reasons. However, designing the active structure for both active deformation and load carrying capabilities simultaneously is most challenging. For optimization detailed aero-servo-elastic investigations are necessary, see [11, 12].

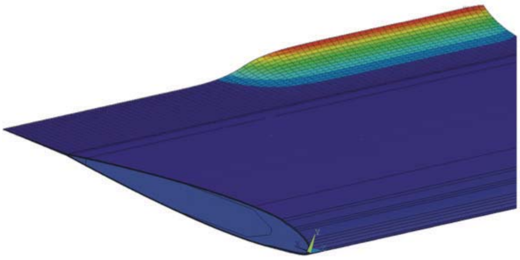

Fig. 6: Smart trailing edge concept using piezo

2 Vibration and Noise Control Actuators

In this chapter some selected applications are presented in which piezoelectric actuation were applied to master vibration and noise levels of air vehicles.

2.1 Interior Noise Reduction by using Active Gearbox Struts in Helicopters

Active noise and vibration control systems using piezo actuation have been a topic of intensive research of the last decade. These systems use the phenomena of destructive interference between the primary disturbance and the inverse secondary signal produced by a control unit. A topical schematic block diagram is shown in figure 7 for helicopter interior noise reduction. An active noise vibration control system developed by EADS and Eurocopter was integrated on a test helicopter. All seven struts connecting engine/gearbox unit with the fuselage of the test helicopter have been replaced by active struts as shown in figure 8. By using three piezoelectric actuators, it is possible to excite longitudinal as well as bending vibrations in any direction. For optimal actuator authority the actuator design utilizes highly efficient d33-multilayer stacks.) See figure 8 and [21, 22]. It could be shown that the actuator authority is sufficient to reduce the 1st gear-meshing frequency independent from the actual flight condition up to 19.5dB.

2.2 Active Isolation of Vibration Loads for Ariane V launcher

Launcher payloads as well as the launcher itself are underlying during ascent severe dynamic excitations. The principle of active isolation by using a multitude of actuators and control system was applied to the case of ARIANE V launcher vehicle. A study performed within the frame of the ESA GSP program proved that the approach can reduce the vibration below 100Hz by more than a factor 4. The active payload adaptor is thought to replace the conventional passive payload adaptors, which are for instance conical CFRP shell structures with a truss structure comprising 24 active struts in the load path. The actuators used are large piezo-actuators dimensioned according to Ariane5 loads and environment. Figure show a demonstrator strut in original size manufactured and assembled for dynamic testing. The strut developed delivers more than +/- 16kN force and +/-0.25 mm stroke.

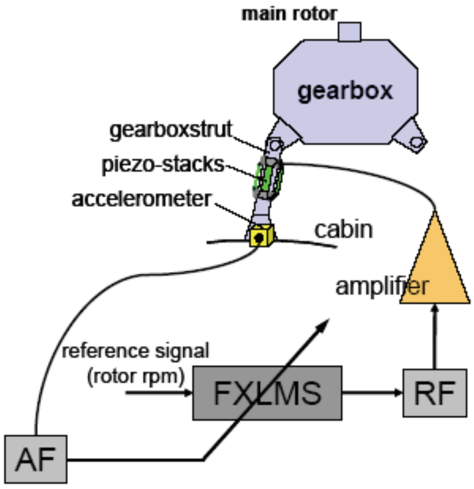

Fig. 7: Schematic Block Diagram of the control loop [20]

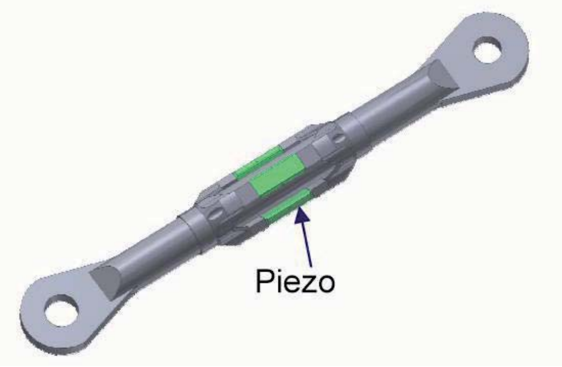

Fig. 8: EADS active gearbox strut using piezo stacks

2.3 Active Anti-Vibration system using Piezo Force Generators

A novel anti-vibration system using inertial forces controlled by piezo actuators was developed and successfully applied to a test helicopter [2, 9]. Piezo stack actuators are attached both sides of a leaf spring to generate structural forces acting on the inertial mass. This design allows to extending the operation frequency of conventional absorbers to a broader band. The patented generator [17] (fig. 10) is built in GFRC technology and is able to generate up to 1000 N absorber force. Flight on EC135 test helicopter [2] using two absorbers resulted in 26 dB reduction of cabin vibration levels at the pilot seats.

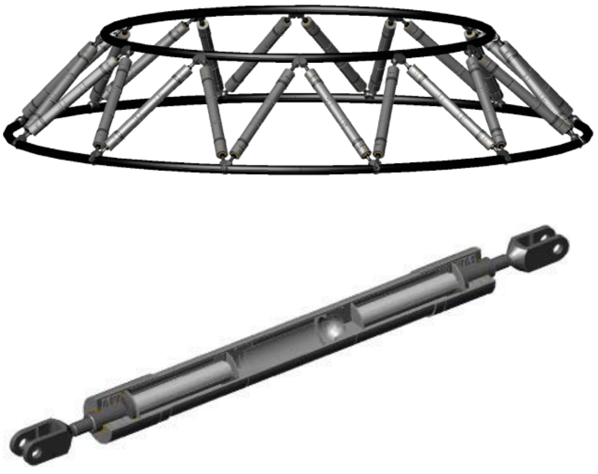

Fig. 9: *Active truss structure and active piezo strut*

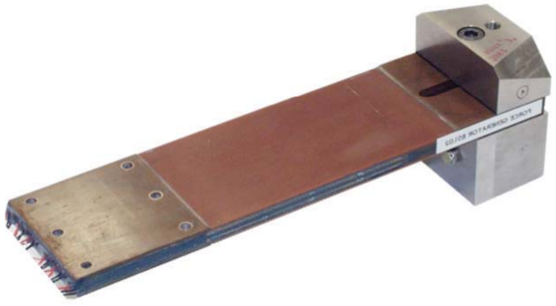

Fig. 10: *Piezo Force Generator F_{max} 1000 N.*

3. Space & Military Actuators

In Space vehicles, UAVs, missiles, military vehicles, etc onboard place and available electric power can be very limited. Thus in a micro satellite there is often less than 100W in total for all the instruments. So generally, allocated electric power per actuator is typically between 0.1 to 10 Watt. This is also the case in small UAVs and in MAVs.

Because of the high cost of embedded mass, space & military actuators need also to offer high output energy to mass ratio. One of the main difficulties is often the ability to withstand launching vibrations and shocks. Typical level of vibration is often larger than 20g rms in space. It can be worst (as in missiles) or easier (military vehicles), but the main difference is that the vibrations are combined with the operations, which is not the case in space as the operation is after the launching. Space environments add other constrains. One difficulty is the vacuum conditions, which can induce difficulties for getting the heating out off the actuator or for out gassing near optics. A large variety of situations is met for the thermal range as well as for radiations. At least but not last resistance to humidity is often an issue, especially for piezo ceramics. Success of application relies not only on design issues but also on material reliability. Specific actions at this level may be undertaken to secure space projects.

A few years ago, a source of multilayer piezo ceramics for actuators (MLA) was space qualified by CNES and Cedrat [39] but the manufacturer leaves the space market. Instead of qualifying a new manufacturer, a recent solution [40] was to establish a Lot Acceptance Test (LAT) plan. Two sources were selected on the basis of the known reliability of their actuator and the available sizes. The LAT plan covers several tests (electric, mechanical, thermal, life time, humidity …) as well as a Destructive Physical Analysis (DPA). A DPA is useful to support failure analysis (for ex sources of electric breakdown). Example below shows porosity which could cause different types of failures.

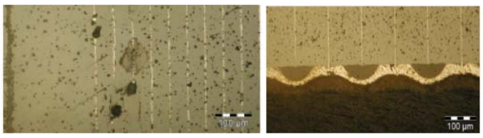

Fig 11: *Examples of DPA for 2 different MLA*

Among all tests, 2000hr humidity tests under DC voltage (150V) reveal the most various situations by monitoring the leakage current. The current starts under 0.1mA for all the piezo of the 2 sources, but after some tens of hours, it increases progressively, but with a wide dispersion. The insulation resistance deterioration is permanent after the test. The on/off cycle is the most critical driving mode regarding to humidity resistance. This sensitivity to humidity is still a limitation, which has to be carefully accounted in the lifetime of the applications. Although performed in a space program, these LATs are of interest for other fields.

The APAs are Amplified Piezoelectric Actuators offering a large deformation and designed for space applications. It benefits of a space qualification [39] and a large space heritage, and may apply LATs for MLAs in space or military projects. APAs are used in several optics instruments for positioning or scanning applications where compactness and reliability to external vibrations are required.

A typical mechanism based APAs is the XY stages. The first APA based XY stages have been developed for the European Space Agency for the ROSETTA MIDAS AFM instrument [41,42]. It uses 8 APAs and 1 Parallel Prestress Actuator PPA. It has successfully passed the launching on Ariane 5 in 2004 and is flying. Using this space heritage, several piezo mechanisms (flight models) have been developed for Eads, Galileo, Nasa, Redshift [43,44, 45,46].

A typical recent application of piezo actuators in space is Optical Path Difference Actuator (OPDA).

Fig. 12: OPDA with its triple prism

Two OPDAs are used in the Laser Modulation Unit (LMU) of the Lisa-Pathfinder interferometer [35, 47]. The optical configuration was designed by Oerlikon Space AG. The optical delay line is based on a triple prism, whose position is actuated by a guided APA-based mechanism, designed and qualified by Cedrat, including a LAT [48]. The OPDA has a stroke of 60 µm and a bandwidth of 10 Hz. Most severe issue during the qualification campaign was to guarantee the metrology of the OPDA: the absolute position of the prism along the motion axis max should change less than 10 µm for its complete life (FM acceptance tests, launching and flight life time).

New stepping piezo actuators based on APAs called SPA, are developed with some CNES support. These non magnetic piezo motors offer a long stroke (>10 mm), a high miniaturisation, a low current need, a nano resolution and space compatibility [49]: They take advantage of Cedrat previous experiences in piezo motors for space environment [50,51,52] to comply with worst requirements and to avoid known difficulties meet with standard piezo motors: Generation of dust [53], loss of forces or torque when in vacuum, needing retrofit [54].

Hydraulic actuators are new challenging alternative in space to piezo motors [55]. This actuator is based on a piezo pump and piezo valves. For some long stroke motion, Shape Memory Alloys are used in [56,58].

To complete the space review, one should mention activities on magnetic actuators. Stepper motors are probably the most popular magnetic actuator. They are used in pointing, focusing or shutter mechanisms to produce either a fine direct rotary motion [57,58], or using a gear (as an Harmonic Drive System) to get a high torque motion [59,60] or a linear motion [61,62]. Direct drive magnetic actuators are developing also: Reluctant actuators are used in [63]. It could be improved by new MICA [64]. Space Voice Coil [65] are developed by Cedrat under ESA GSTP project.

One typically new military application is a XY piezo micro-scanning stage used in THALES Infra Red CATHERINE MP and XP cameras [66]. The micro-scanner includes 4 micro actuators APA25XS acting in a push-pull configuration. APA25XSs are about 6mm in height and 2gr in mass. The central frame which supports the lens can move in X and Y directions with a displacement amplitude of +/– 10 µm, which corresponds to ½ the sensor pixel size.

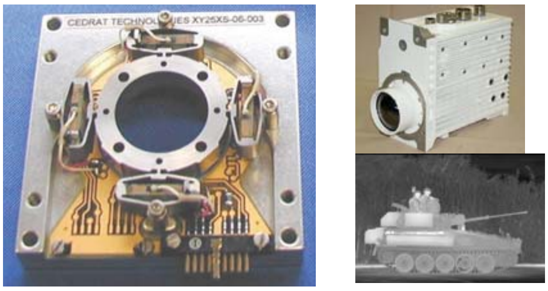

Fig. 13: XY microscanning stage for IR cameras – Thales Catherine XP IR Camera & IR Image

Such microscanner improves by 4 the resolution of the camera sensor by over sampling technique: Shifting the image in XY on the sensor, 4 images are taken and combined. Because of the stiffness of the actuator, the unloaded resonant frequency is 2.2kHz. The frequency loaded with a lens is above 1kHz. As the actuators are pre-stressed, the micro scanning can be performed at high frequency, above 100Hz. The pre-stress also allows the XY stages to pass the qualification vibration tests, as requested in the military environment.

An example of MAV is given by Mufly project lead by ETZH [67,68] which consists in the development of a fully autonomous helicopter comparable in size and weight to a small bird (<30gr). In this MAV, 2 small (5gr) rotary Brushless DC motors (BLDC) are used to drive the rotor are being optimized in term of power to mass ratios [69]. The rotor is tilted by a set of micro Amplified Piezo Actuators APA – MuXS (0.25gr) combined with a lever arm mechanism. The electronic including micro-controllers is less than 1gr. The Mufly carries a camera and shows enough agility to fly in-door (see video [70]).

Other military applications in helicopters, missiles, UAVs, re-entry vehicles testing are listed in [38] or presented in this session.

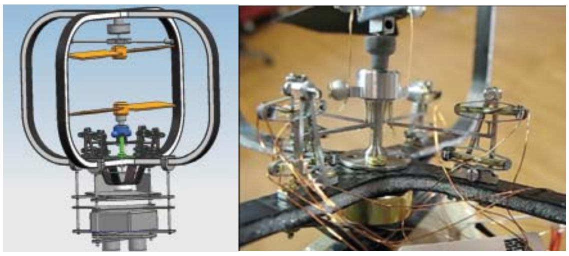

Fig. 14: CAD view of Mufly & zoom on actuators

Conclusion

Actuation technology is one of the critical technologies in aerospace. During the last years the concept of the more electric aircraft was pushed ahead by industry and scientific community. The adaptation of electric drive train technology to meet with the demanding requirement of aerospace is in the focus of the activities. Besides electro motors a broad variety of applications have been developed based on piezo actuation. The paper revealed promising application of piezo actuators especially for reduction of noise and vibrations.

Space field is motivating the emergence of various small & smart actuators. Among these, piezo actuators are expanding in other fields as military benefiting of space heritages and qualifications.
The short review this paper provides reveals some first success stories.

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