NEW ACTUATORS FOR AIRCRAFT AND SPACE APPLICATIONS

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Abstract
Novel actuation systems are driver of product innovation in aerospace industry. In aircraft industry EHA technology has been recently introduced illustrating the stream of innovation directed on improving performance, reliability as well as economy. On the far side there is the radical concept of a morphing wing which offers optimizing the aerodynamics of an aircraft considerably by shape control. Rotor Active Control utilizing piezo actuation has been proofed to be very successful for vibration and noise reduction in helicopter flight test inspiring confidence in smart structure technology.
In Space, new technologies meet both extreme and various requirements. This is especially true for actuators noting that some heavy trends (more active optics, complex instruments, robotic missions, micro-satellites) demand small & smart actuators. So new actuators such as magnetic actuators, Shape Memory Alloys, Electro Active Polymers and even more piezoelectric actuators have been selected for a growing number of space missions for these last years. The goal of the presentation is to enlighten new actuator developments driven by Space and Aircraft needs.

Keywords: actuation, smart materials, piezoelectric, space qualification, aerostructures, morphing structures

Introduction

As in any industry technology is the key to maintain market leadership. Drivers of technological innovations are to reduce costs for manufacturing and operation, and to increase product performance. In aerospace business safety is a major concern and there is high pressure to increase reliability, to reduce weight and downtime. Obviously, the common technology stream provides high-performing electronics at small size allowing optimized packaging. Advanced signal processing allows realizing complex, reliable and distributed embedded computing capabilities. Electrical energy allows in a very elegant manner to distribute power to consumers. It is a corollary to close the electrical loop of power and data by deploying electrical actuators to achieve fully integrated active mechanical systems. The all electric aircraft may represent a next milestone in the technology roadmap after "Fly By Wire" [1, 2, 3], the current flight control system technology for large transport category airplanes.

From these principles two main options for product development can be deduced: (I) replacing hitherto used non-electrical actuators, and (II) introducing novel active mechanical systems.

Electro hydrostatic actuator technology (EHA) is a candidate of the first category. An EHA system represents an electrical subsystem providing locally hydraulic actuation capability. EHA allowed the more electric design of the A380 aircraft [4].

A technology on the far side is the concept of smart aerostructures. This concept includes shape changing (morphing) structures as well as direct aerodynamic control. It has been an active area of research for nearly two decades.

In Space, the need for smart & miniature actuation functions is increasing because of several trends. More and more complex instruments are implemented in satellites or robotic missions and needs 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 met. In this context, space is actively looking at all the new smart & miniature actuation technologies [23,24].
In this paper, the research in the field of actuators for Aerospace will be reviewed. Among these, the piezoelectric actuators from Cedrat Technologies are presented. They have been initially developed and qualified to meet space requirements. This leads to successful developments, which are also presented.

1 General Research Directions

Today, it is clear that actuators are the technical bottleneck and represent keys for realizing ambitious technological visions. Successful realisation requires actuators which excel in:

- functional and structural integration

- actuation authority (power and work capability)
- safety and reliability
- small envelope and lightweight

Today's research efforts are focussed on two major areas. First, electromotor based concepts are pushed ahead improving weight data and reliability while in contrast to most other fields of application motor efficiency is not so much an issue (figure 1). The added value comes in terms of performance, maintenance cost and safety.

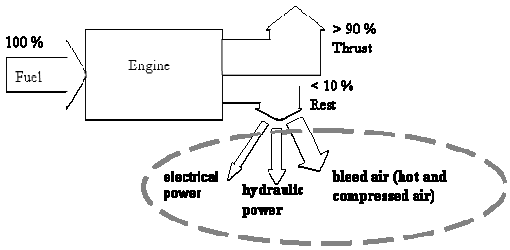

Figure 1: Typical values of energy flow for a commercial transport aircraft.

The second area comprises active materials which allow radical innovation of actuation technology such as Piezoceramics, SMA, EAP.

2 Electro-Mechanical Actuation (EMA)

Drive systems based on electric motors represent a base technology in many industries. A variety of motor types and a whole set of drive train related technologies such as gears (linear and rotary), sensors, electronics and control algorithms are readily available from industries like automotive or automation.
In recent years significant effort was spent to transfer and adapt these technologies to aerospace applications addressing the aforementioned challenges - especially realizing a lightweight design (figure 2) while complying with safety and reliability requirements and relevant regulations [8].
Examples are:

- Dispatch of transport aircraft shall still be possible after any single electrical failure necessitating system topologies providing a certain level of redundancy [5], [6], [7].
- Single failures in actuation systems – be it mechanical, electrical or control – must not have catastrophic consequences for the aircraft necessitating for example jam-free drive trains for control surface actuators and improved diagnosability to prevent dormant faillures.

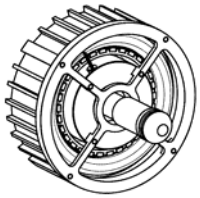

Figure 2: Weight optimized design of a torque motor for an aerodynamic control surface actuator. EADS Prototype.

Some other aerospace specific challenges are:

- wide temperature ranges (typically -74 to +110°C survival temperature for control surface actuation) for control surface actuators (figure 3)
- CTE mismatches due to extensive use of light-weight materials and high-performance permanent functional materials (e.g. permanent magnets)
- Suitable anti-corrosion coatings and adhesive materials
- water-proof encapsulation or other strategies to address water ingestion and icing

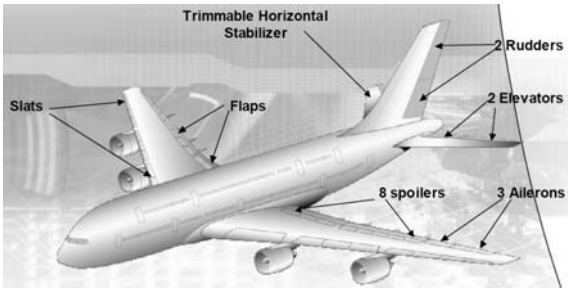

Figure 3: Aerodynamic control surfaces of commercial transport aircraft.

In line with these topics are several international research programs co-funded by the EU framework programmes to strengthen the European research area: POA, MOET, ALCAS, and NACRE.

3 Active Rotor Control for Helicopter

Active helicopter rotor control has the following technical objectives:

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

3.1 Servo Flap Control

One approach for highly dynamic blade control with little control power can be realized by using servo-flaps installed in the outer part of the rotor blades [9]. A solution for this purpose is the piezo actuation system that has been developed by EADS Corporate Research Centre in recent years [10]. This technology has been proofed to be successful in an ongoing test flight campaign since September 2005.

3.2 Active Trailing Edge

An alternative approach to the servo flap is the active trailing edge concept. It is based on the "smart aero-structures" paradigm, i.e. structurally integrated smart material actuation [11].

A smart tab is attached to the trailing edge of the airfoil or an active trailing edge is integrated into the airfoil. It is realized by a multi-morph bender including piezoelectric ceramics and glass fibre reinforced plastics, see Figure 4.

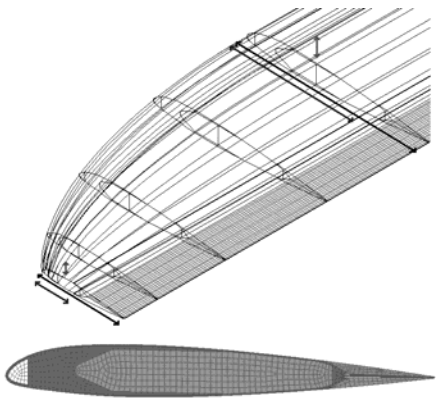

Figure 4: Active trailing edge for helicopter rotor blade. EASD Design.

It is current opinion that integration of distributed smart material actuators into the base structure is highly desirable. However, designing the active structure for both active deformation and load carrying capabilities simultaneously is most challenging. In the case of adaptive helicopter rotor blades, performance requirements result from the aerodynamic effectiveness of active blade deformations like twist or camber variations. On the other hand, the corresponding aerodynamic loads act on the active structure, counteract the active deformation and reduce aerodynamic effectiveness. For optimization detailed aero-servo-elastic investigations are necessary, see [11, 12] for some recent aero-servo-elastic studies of adaptive airfoils or helicopter rotors in transonic flow.

4 Active Flow Control

Applications of active flow control in aerospace include:

- Drag reduction by influencing laminar-turbulent transition
- Separation control for high angle of attack

Saric et al. [13] discuss remaining challenges concerning laminar flow control while Greenblatt et al. [14] give an overview concerning control of flow separation by periodic excitation.

4.1 Surface-bound effectors

Actuators for surface-bound active flow control are completely different from actuators for classical control surface actuation like for example ailerons.

Breuer et al. [15] have been among the pioneers of this field. Example devices are vortex generators, zero mass flux jet actuators and smart mesoflaps [16, 17, 18]. Due to the special requirements of flow control Microfabricated Electro-Mechanical Systems (MEMS) have been investigated as a new class of actuator technologies [19]. Recent research in active laminar control of boundary layers has been conducted by [20]. Typical characteristic frequencies of structures within the flow which have to be stimulated by the actuator are one to some kHz. Again piezoelectric actuation principle appears most suited.

Surface bound actuators for boundary layer interaction are a further step towards systems integration. The experience of structural integration obtained from the smooth trailing edge smart tab can be directly applied. Flat piezo sheets are mounted in a subsurface manner which protects the smart material from environmental influences and greatly reduced actuator thickness dimensions. In contrast to a cavity actuator with a piezoelectrically actuated membrane [21], here the flexible substrate is an integral part of the aerodynamic surface itself. The surface is maintained flush and thus no unwanted disturbances are introduced into the flow. Nevertheless this type of actuator is believed to introduce momentum into the boundary layer flow [22].

The technology currently allows active patches of about 5-30 mm in-plane dimension with a very high bandwidth e.g. for transition control. The integration into typically curved airfoil structures can also be accomplished, see Figure 5.

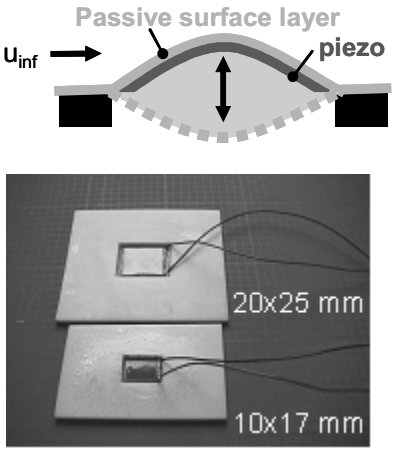

Figure 5: Subsurface Piezo-Actuator principle and specimen back-side view

Due to the relatively small size of one active device, for real aircraft application a large number of devices is foreseen. The effort for power supply and control / monitoring system architecture has to be considered, e.g. by limiting the application of such small devices to determined areas on the wing where the effect is locally beneficially applied.

5 Space Requirements & Actuators

In space vehicles, onboard place and available electric power is very limited. Thus there is often less than 100W in total for all the instruments in a micro satellite. So generally, allocated electric power per actuator is typically between 0.1 to 10 Watt. Because of the high cost of embedded mass, space actuators needs also to offer high output energy to mass ratio. Sspace environmental conditions add other constrains. 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, which has to be analysed with the associated moving masses, to get the external forces. Another difficulty is the vacuum conditions, which can induce difficulties for getting the heating out off the actuator or for out gassing near optics. In some cases, the thermal range is very large because of the change of exposure to the sunlight. It can be typically –150°C to 150°C, but it can be even warmer in case of Mercury or Venus missions, or much colder in deep space missions. The capability to withstand radiation may also be a serious difficulty for some technologies. For all these reasons, space missions are looking for smart actuator solutions.

At the opposite of aircraft, hydraulic and pneumatic actuators are so commonly found in space. One reason is the gas/fluid leakage. Another is the thermal dependency. An example of mechanism showing such constrains is given by [25].

A rather well established family of solutions is formed by space qualified rotary Electro Magnetic (EM) motors [26,27,28] benefiting of a trend to miniaturisation of harmonic drives [23] to get small high precision rotary actuators [30]. For ex, a Micro Harmonic Drive [31] offers small size, low weight (<6gr) and high repeatability (10 arc sec). A recent application of geared EM motors is given in [32]. Another is an antenna Pointing mechanism for mercury mission, based on a stepper motor designed for working up to 295°C [33].

When linear direct drive is needed, a possible way consists of electromagnetic actuators. Among these, moving coil actuators, also called voice coils or Lorentz actuators offer the advantage of medium strokes (1-10mm) associated to a high resolution (in the nm range). Cedrat has presented such a space compliant voice coil [34]. Recent applications in space are 2 d.o.f. tilt mechanisms for satellites laser communication [35,36]. One difficulty is the absence of stiffness and holding force at rest, which may impose to use a locking for launching.

Bistable magnetic actuators are used in space for locking and valves [37]. The miniaturisation by Cedrat of such type of actuator (<1gr) is discussed in the conference [38]. Bistables offer larger force to mass ratio than voice coils (typically 10 times more) but they cannot be used for positioning.

Because of the limitations of the previous linear actuators, new smart actuators are emerging [39]. They include piezoelectric actuators & motors, magnetostrictive actuators, Shape Memory Alloy (SMA), Paraffin actuators, Electro/magneto Rheologic (ERF/MRF) devices and Electro Active Polymers (EAP).

Piezoelectric actuators [40] are expending in space applications because it offers direct drive linear motion with a high positioning resolution, a high stiffness and a low power consumption. It offers a wide variety of solutions [41].

Typical applications of piezo actuators in space are telescopes, optics and fine instruments positioning. In the telescope of CNES (French Space Agency) satellite [42] the Cedrat piezo actuators (fig 4) are in a stable thermal area (20+/-5°). They have passed the vibration tests thanks to some frequency notching and some specific design increasing their prestress. The James web telescope would need 4000 actuators [43]. In this case, because of cold temperatures, piezo ceramics operating in cryogenic temperatures are envisaged [44]. In the Rosetta mission of ESA (European Space Agency), the Midas Atomic Force Microscope is motorised by a XYZ piezoelectric scanning stage (Fig 6) from Cedrat [45]. Another type of growing application is the active control of

vibrations, which can be done using piezo actuated Stewart platforms [46,47,48]. Other applications of piezos are discussed in the next chapter.

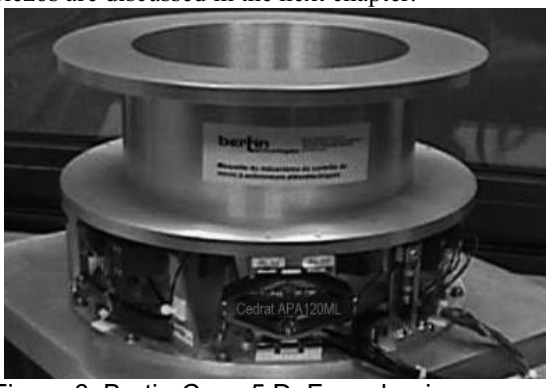

Figure 6: Bertin-Cnes 5 DoF mechanism

Figure 7: ESA Rosetta Midas 3 DoF scanning stage

Magnetostrictive actuators are not often considered in space applications. They compete with piezo offering higher displacement per volt but lower output energy per watt [49].
Space qualified SMA actuators [50] are available and used for making locking actuators for passing launching vibrations. A first European application is given on the Cedrat Rosetta/Midas stage, which includes 2 SMA actuators from TINI (Fig. 7).
Paraffin actuators are also space qualified for locking [51] competing with previous SMA.
ERF and MRF devices are not today used in space but are considered by JPL for haptic applications for astronauts [52].
EAP actuators, also called artificial muscles, are new actuators supported by NASA [53]. Dielectric types present very large strains (>50%), but the very large required E-field is today a strong practical limitation. Low voltage ionic types offer less strain (1-10%) and could be used for space inflatable structures [54].

6 Cedrat Piezo Actuators in Space

Cedrat actuators have been initially developed to meet space requirements. The Amplified Piezo-electric Actuator (APAs) invented in 1995 [55] was designed with 3 main objectives: To offer larger deformations than piezo stacks (typically 0.5 to 4% according to the amplification ratio), at medium voltages (<200V). To offer large output energy density compared to other piezo [56]. To support vibrations and shock even when mass loaded. An elliptic shell offering amplification and prestress of the piezo ceramics fill these objectives. So APAs have been space qualified with CNES support [57].
A first application realised with ESA is the Rosetta Midas piezo stage (Fig. 7), which uses 8 APA50Ss and 1 Parallel Prestress Actuator PPA10M [58]. It has successfully passed the launching on Ariane 5 in March 2004 and is now flying. Using this space heritage, several applications are in progress [59]. For ISS/ACES/Pharao, Cedrat has delivered to EADS the flight models of piezo tilts based on APA XS for the laser Flux Equilibrium Mechanism and PPA10Ms for the Extended Cavity Laser Mechanism [60]. For the first European LIDAR ALADIN on board on AEOLUS spacecraft, Cedrat has delivered to GALILEO the refocusing mechanism of the laser source [61]. For Mars MSL, Cedrat has delivered to NASA JPL several 10th of APAs [62]. At the R&D stage, other applications of Cedrat technologies are also in progress with ESA such as Piezo valves [63] and Ultrasonic or Stepping Piezo Motors [64,65].
The properties of these piezo actuators (ie large energy density, robustness to vibrations…) are also beneficial to many applications outside space. This is checked for example in the field aircraft, military or embedded optics [66,67,68,69,70,71].

Conclusion

Active mechanical structures represent some of the most ambitious visions in aerospace. Their realization demands for radical actuation solutions. This puts a strong impetus for research in the field actuation and motivates especially the emergence of various smart actuators. Among these, the applications of piezo actuators are fast growing noting recent space achievements and space qualified products. The short review this paper provides reveals some first success stories.

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