Design of lightweight, temperature stable and highly dynamic amplified piezoelectric actuators

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1.1 Abstract:

For demanding applications such as in the field of aerospace, the applicability of piezoelectric actuators is limited by the large mass and inefficiency implied by the required amplification mechanism. In the example of active rotor control, although the benefits (reduction of the vibration levels by up to 80%) are well recognised, up to now no application has reached commercial success. In the UK Technology Strategy Board (TSB) funded REACT project, Noliac A/S and Anglo-Italian helicopter company AgustaWestland, part of the Finmeccanica Group, team-up to provide a more effective solution. This work resulted in the development of a new actuator design, providing improved performance for a minimum mass. Two generations of prototypes have been manufactured and tested. The actuators demonstrate a high ratio of available mechanical energy to mass, are compact, stable in temperature and provide a high resonance frequency, making them ideal for demanding applications where mass, dimensions and dynamics are critical.

Keywords: Piezoelectric, mechanical amplification, high energy, temperature stability, optimised mass

1.1.1.1 Introduction

The field of active control of helicopter rotor blade has raised a consequent interest in the last 20 years. The research effort has been supported by several national and international programs both in the USA and in Europe.
The reason for this interest is the expected benefits of this technology. With an expected 80% vibration reduction and a 10dB noise reduction [6], this technology will give rotorcrafts a tremendous advantage both in civil and military applications. In addition, active control is also expected to improve rotor aerodynamics, therefore enlarging the flight envelope and reducing power consumption.
Because of the high operating frequency, smart materials such as piezoelectric actuators are well adapted for this task. The relatively large displacements (in the sub-millimetre to millimetre range) require some sort of mechanical amplification of the movement.
Moreover, the field of aerospace implies specific and very demanding requirements. In particular, a special attention is given to the mass of the equipment. In addition, the wide temperature range, large accelerations and high vibration levels are demanding requirements that need to be taken into account for the design of an active device. The design has to fulfil all the requirements while optimising the mass. To illustrate that, the various actuators in this paper are compared according to their energy density, i.e. the ratio between available mechanical energy and mass of the device.
The issue of the temperature range has rarely been addressed in publications. It is however a concern, since differential thermal expansion between the piezoelectric ceramic, the metallic components of the amplifying system and the composite material of the rotor blade will inevitably cause an apparent and unwanted movement of the actuator.

1.1.1.2 State of the art

A number of publications can be found on the topic of active rotor control.
Some reviews [1, 2, 3] list a number of concepts. Some of them (blade twist, active blade tip) are not relevant for this search. Rotor blade flap technologies are analysed specifically and several concepts can be listed:

- Bender concept, from 1989 (Boeing CH-47D)
- “V” stacks (magnetostrictive) 1993 [4]
- Bender and tapered bender from 1994 (MIT)
- Extension-torsion mechanism 1995
- Hydraulic amplification 1995
- X-Frame, from 1997 (Boeing CH-47D) [5]
- L-L amplification concept (double lever amplification), from 1999 [7]

- Double X-frame concept, from 2000 [6]
- Amplified stack 1998 (EADS) [2, 10]

In addition, different electromagnetic actuation systems are described. They won't be addressed in this paper.
When data has been published, the different concepts can be compared according to the energy density criterion defined above. Table 1 gives the collected data and the data is plotted on Figure 5.

Developer	Product	Energy (N.mm)	Energy density (N.mm/g)	Ref.
CEDRAT	APA 1000L	46,6	0,25	[9]
CEDRAT	APA 1000XL	97,8	0,16	[9]
DSM	FPA 1450C	54,4	0,25	[8]
DSM	FPA 2000E (Ti)	36,3	0,21	[8]
MIT	X-frame	41,0	0,34	[5]
MIT	Double X-Frame	129,3	0,13	[6]
EADS	RACT actuator	175,0	0,39	[2, 10]
SatCon	V stacks MS	236,3	0,08	[4]

Table 1: Energy density comparison

Energy (W) is calculated at the most advantageous operating point, i.e. half the free displacement (d_F) and half the blocking force (F_b), assuming linear stiffness. In other terms:

$$W = \frac{1}{8} \cdot d_F \cdot F_b \qquad (1)$$

It can be seen that all the points are below 0,4 N.mm/g. Furthermore, energy density tends to decrease for high energy levels.
In addition, it should be noted that a vast majority of the designs is not temperature stable. Only the RACT system is made stable to some extent by having two actuators in opposition.

1.1.1.3 New design

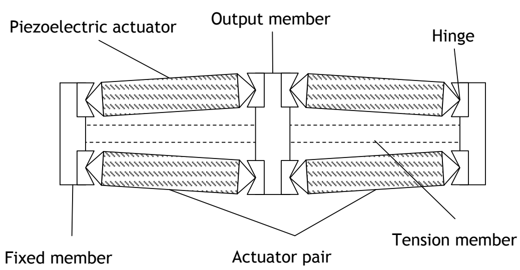

Fig. 1: "Diamond frame" principle

A new design was developed to address the limitations in terms of energy density and temperature stability.
It is based on four piezoelectric stacks, connected in pairs. Each stack is hinged at its ends and maintained in place with a small angle. The arrangement is shown on Figure 1.
The whole assembly is preloaded through the use of a tension member maintaining the fixed members in place. This ensures that the piezoelectric stacks operate in optimal conditions.
The actuator is operated as follows. When the applied voltage is increased on one pair of stacks, it is decreased on the other pair. This contributes to a movement of the output member in one direction. It should be noted that in the

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case of a free displacement, the tension in the piezoelectric stacks as well as in the tension members (therefore the preload) remains almost constant.
Upon temperature change, differential thermal expansion between the ceramic and the other materials in the assembly will lead to a change in force repartition. This will result in a change in the internal preload. However unlike most of the existing schemes presented above, this will not result in a movement of the output member.
Thanks to the compact design and the large proportion of active material, this design was expected to provide high performance levels as well as high energy density.

1.1.1.4 First prototype

A first prototype was designed to assess the performance of this layout. The design is based on custom-designed piezoelectric actuators manufactured by Noliac. The mechanical parts were manufactured such that they would allow some flexibility for the assembly and testing. The mobility of the stacks is ensured by rolling contacts.

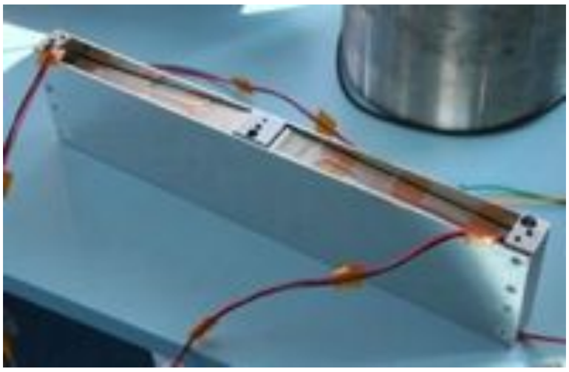

Fig. 2: First "Diamond frame" prototype

The characteristics of the piezoelectric stacks are given in Table 2.
In order to evaluate the performance of the actuator, a test was performed using a materials testing machine (INSTRON 6025 with external displacement sensor). The stiffness of the actuator was measured at middle position and in the extreme positions. Figure 3 gives the results of the test for middle position and fully extended.

Property	Unit	Value
Material	-	NCE51
Cross-section	mm x mm	24,6 x 24,6
Total height	mm	163,5
Operating field	kV/mm	0 to +3,0
Free displacement	µm	245
Blocking force	N	25400

Table 2: Piezoelectric stacks properties

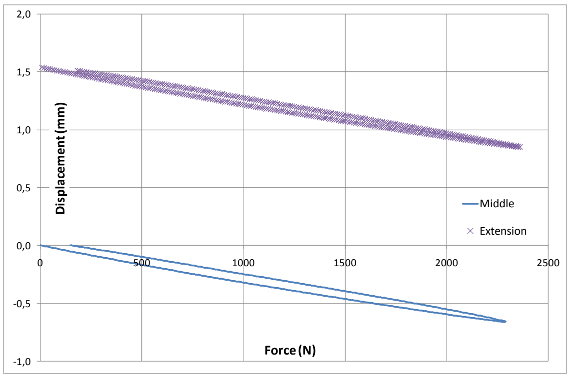

Fig. 3: First "Diamond frame" prototype force-displacement diagram

It should be noted that on this graph the free displacement is over evaluated because of the contribution of the creep effect over the duration of the experiment (several minutes). The actual free displacement given below was measured in quasi-dynamic mode (0,1Hz) to reduce this effect.
As it can be seen, stiffness is very consistent (<5% difference between middle and extreme positions).
From these measurements and additional performance measurements in Noliac, the performance of the amplified actuator can be expressed in Table 3. Blocking force is estimated by multiplying the measured large signal stiffness with the measured free displacement.

Property	Unit	Value
Free displacement	µm	±1370
Blocking force	N	±4460
Mass	g	5800

Table 3 Amplified actuator properties

This represents an energy density of 0,53 N.mm/g.

1.1.1.5 Second prototype

Based on the success of the first prototype, a second generation of actuators was designed, aiming at lower energy levels while maintaining the high energy density.
The design is a down-scaling of the first prototype, with less flexibility and components adapted to the aerospace application.

Fig. 4: Second generation "Diamond frame" without attachments

The construction uses lightweight materials such as titanium alloy and carbon fibre reinforced polymer (CFRP). Interface with the blade structure and with the active element is realised by additional attachment parts. The properties of the piezoelectric stacks are summarised in Table 4.

Property	Unit	Value
Material	-	NCE51F
Cross-section	mm x mm	12,2 x 13,7
Total height	mm	120
Operating field	kV/mm	0 to +3,0
Free displacement	µm	190
Blocking force	N	7020

Table 4: Piezoelectric stacks properties

Performance was measured similarly to the first prototype. Although the specific force and displacement values cannot be disclosed, the actuator provided a maximum energy of 461,6 N.mm. With a mass of 832 g (without attachment parts), this represents an energy density of 0,55 N.mm/g.
Despite the use of lightweight materials, the energy density of the second prototype is not significantly higher than the first demonstrator. This can be explained by three effects. First, the smaller piezoelectric stacks have a slightly lower proportion of active volume. Furthermore, accessories (wires…) cannot be scaled down and account for a

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larger proportion of the total mass. Finally, the second generation prototypes include additional features (feedback system, end-stops) that penalise energy density.
A number of these second generation prototypes were manufactured and tested. They were run in burn-in for 10^7 cycles, full amplitude, without problem.

1.1.1.6 Comparison with the state of the art

The performance of the two "Diamond frame" Piezoelectric Actuators (DPA) can be compared to the state of the art on a graph showing the energy density versus the total available energy (Figure 5).

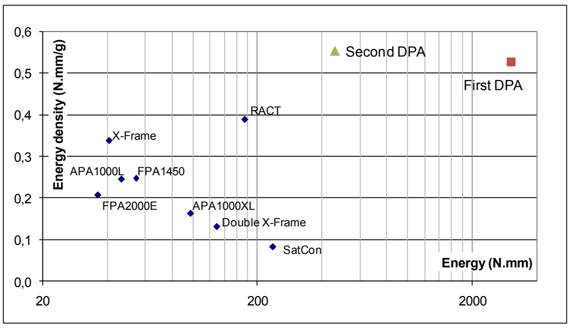

Fig. 5: Energy density comparison

It is obvious from this graph that both "Diamond frame" prototypes generate higher energy levels than previously published literature. It is also clear that they demonstrate a significant improvement in terms of energy density (respectively +35 and +42%).

1.1.1.7 Future work

In the next steps of the project, Noliac will continue the characterisation of the "Diamond frame" actuator prototypes. Tests will focus on dynamic performance and reliability.
It is also a crucial point to develop the active rotor control application and make sure that the performance of the actuator is adapted to the requirements. Other aspects of the application include mechanical interface and validation of the performance of the drivers.
In addition, Noliac will adapt the design to other applications and demonstrate the benefits on a range of products.

1.1.1.8 Conclusions

Although the field of active rotor control has been widely covered in the literature, no application has reached commercial success. The main reasons are the mass penalty implied by the actuators and the issue of temperature stability.
In the UK Technology Strategy Board (TSB) funded REACT project, Noliac and Anglo-Italian helicopter company AgustaWestland, part of the Finmeccanica Group, team-up to provide a more effective solution. This research has led to the design of a new type of amplified actuator called "Diamond frame" Piezoelectric Actuator (DPA).
Two generations of prototypes have been manufactured and tested. They demonstrate a 35 to 42% increase in energy density compared to the literature. In other words the actuator would be capable of the same performance for 70 to 74% of the mass of the best existing solution. It is thought that this figure can be further improved through further refinement of the design.

1.1.1.9 References

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