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Potentialities for aeronautics of the development of an active core PZT fibre.

Opportunités pour l'aéronautique du développement d'une fibre PZT active à coeur métallique.

par

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Résumé traduit :
Dans un avenir plus ou moins proche l'aéronautique pourrait plus largement faire appel à des structures adaptatives déformables et légères qui devraient avantageusement remplacer les solutions classiques d'actionnement nécessaire pour la manoeuvrabilité des avions. Cette technologie de rupture peut être facilement évaluée initialement et sans risque sur les drones. Les actionneurs laminaires existants utilisant des fibres monolithiques et souvent collés en surface des structures sont de petite taille, utilisent des tensions de commande élevées et sont donc assez fragiles. L'idée de base est de produire à faible coût une fibre basse tension suffisamment longue et assez robuste qui puisse être facilement manipulée pour d'une part produire des actionneurs fiables et qui puisse être d'autre part à l'avenir intimement mélangée avec des fibres passives par des moyens classiques de production textile en vue de réaliser avec une meilleure efficacité la déformation de surfaces de grande taille. Des capteurs robustes et des dispositifs de récupération d'énergie peuvent également être imaginés. Pour réussir un tel défi ambitieux qui a motivé la présente recherche de développement de fibres piézoélectriques à cœur métallique (FPCM) et la modélisation numérique de leur comportement, deux processus ont été étudiés. Pour chacun d'entre eux quelques obstacles doivent encore être surmontés.

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POTENTIALITIES FOR AERONAUTICS OF THE DEVELOPMENT OF AN ACTIVE METAL CORE PZT FIBRE

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Abstract:
In a more less near future, aeronautics could largely use light morphing structures which can advantageously replace the classical heavy actuation able to improve aircraft agility. This breaking technology can be easily initially evaluated without risk on drones. Existing laminar actuators using monolithic fibres and often bonded on surfaces, are small, use high driving voltages and are therefore rather brittle. The basic idea is to produce at low cost a sufficiently long, low voltage and robust enough fiber which can be easily handled to already produce actuator and which can be also in the future intimately mixed with passive fibres by conventional textile production means in order to realize with a better efficiency the deformation of larger surfaces. Robust sensors and energy harvesting devices can be also imagined. To succeed in such an ambitious challenge which has motivated the present research of development of Metal Core Piezoelectric Fibres (MCPF) and their numerical behaviour modelling, two processes have been investigated. For each a few obstacles have yet to be overcome.

Introduction

The desire to fly like birds, overcoming obstacles with grace and ease, subject which has always aroused admiration and curiosity, dates back to antiquity. At the beginning of the twentieth century the first aircraft concepts which tried to imitate birds used light and flexible flapping wings. Progress in propulsion and the abundance of cheap energy encouraged then the birth of aircraft with stiffer and heavier structures. The emergence of composite materials in the 70's with the economy related to the energy crisis and progress made in aerodynamics controls has led to a return to lighter and more flexible structures. The dream of having a progressive wing adapting in real time conditions to multiple variable use (gliding flight, rapid dive on a prey...) or reporting weaknesses and thereby exploit the possibilities of the aircraft in the near future could be realized through the development of active materials and adaptive structures. So an active camber of the wing with wingtip permeability varying with flight conditions may allow expect a reduction in drag with a deletion of slats and flaps, (figure 1). Active torsion of a helicopter blade is approached as a means to push the limits of dropping out, reduce vibration and noise pollution of aerodynamic origin, particularly intense in the descent phase.

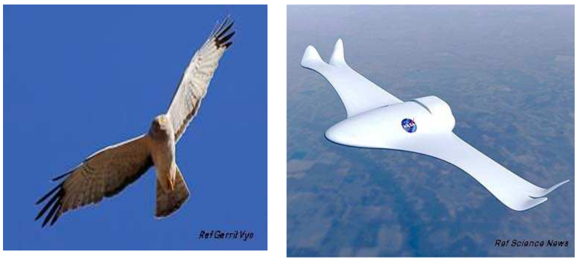

Figure 1: *bird and aircraft wingtip morphing.*

In this domain, activity on smart materials at the centre of Lille of ONERA concerns applications of Shape Memory Alloys and piezoelectric actuators. Among these latter, APA® from Cedrat Technologies, by their mode of action at 90°, was well perceived to be applied to the flap motion of active blades of helicopters. The use of carbon composite shell allows obtaining a noticeable energy density gap, and makes them now more competitive, [1].

At another scale closer to that of the fibres of the composites, piezoelectric fibres and ribbons are promising in respect of their capacity characteristics and maximum strain energy density. They also have the added benefits of conformability, the controllability of the anisotropy.

Existing AFC and MFC laminar actuators are however small and supplied by high driving voltages are rather brittle and don't have the ability to safely cover large areas use, (figure 2). They are more often bonded on surfaces and the efficiency of the force transfer is lower because they are not intimately interwoven with passive surrounding fibres.

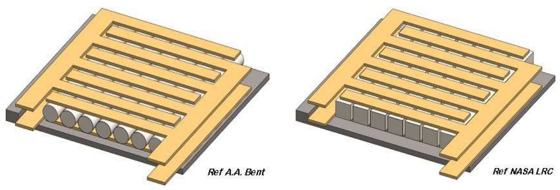

Figure 2: *AFC and MFC laminar actuators.*

Short PZT hollow fibres exist but they are very brittle and not adapted to a continuous production process of long fibres.

The idea of developing a low voltage Metal Core Piezoelectric Fibre (MCPF) was motivated to try to overcome these deficiencies. The fact that this fibre is likely more robust, continuous and sufficiently long should also allows it to be worked with conventional textile processes. Moreover the fact that the metal core can serve as an internal electrode may allow

integrating directly these fibres in conductive matrices (CFRP or GFRP).
The aspect ratio of a MCPF fibre is defined by:

$$\alpha = t / r_0 = 1 / (1 + r_c/t)$$

First analytical calculations have been made with a mono dimensional model.
The capacity of deformation is reduced by metal core presence and all the more so that the stiffness is high. Curves exhibit various optimum aspect ratios depending on the core elastic modulus (figure 3). Potential candidates for the core are listed in table 1.

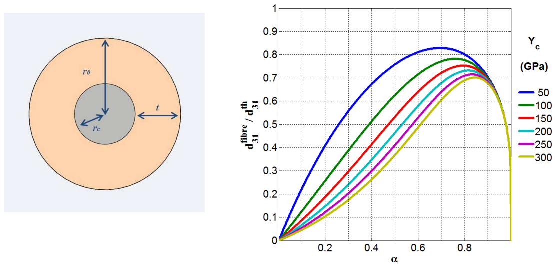

Figure 3: d_{31} versus α and core elastic modulus Y_c.

The optimal aspect ratio ranges from 0.70 and 0.85 procuring a d_{31} from 0.82 to 0.70 of bulk ceramic.
However, the analytical model does not take into account the transverse effect of the Poisson coefficient.

Materials density	Pt 21.50	Inconel 600 8.42	$Ni_{80}Cr_{20}$ 8.4	Ag 10.50	Au 19.30	Ni 8.90	Cu 8.92	Ti 4.5
E (GPa)	170	157	180	104	171	177	138	108
T_f (°C)	1772	1370	1400	962	1064	1453	1084	1660
T_{max} (°C)	1600	1200	1150-1250	900	950	1200	750	880
α (10^{-6} K^{-1})	9	12.4	12-17	19.1	14.1	13.3	17.0	8.9
λ (W.m-1.K^{-1})	71.6	14.8	13.4	429	318	90.7	401	21.9
ρ (µΩ.cm)	10.6	103	10.8	1.63	2.20	6.9	1.69	54
Oxydation	---	++	+++	-	+	+	+++	++
Cost (€/m) – wire ∅50µm	230	2.5	3.5	11	245	15.3	1	26.4

Table 1: *Properties of potential metals and alloys for the metal core.*

Piezoelectric material

A soft PZT powder was used as starting material. It can be fully densified at 1200° C for six hours in air atmosphere.
The different phases of the work concerned the synthesis of powder (composition, grinding, calcination) to have a good densification and get optimum properties compared to bulk ceramics, the selection of the core material, the fibre forming and the sintering technique in order to produce a cheap fibre.

Manufacture techniques

Four processes have envisaged: the hydrothermal synthesis, the deposit by electrophoresis, the co-extrusion, and the dip-coating. Hydrothermal synthesis and electrophoresis appear to not be suitable to produce long fibres with high ceramics thickness. So only co-extrusion and dip-coating have been investigated.
Co-extrusion involves extruding the wire and simultaneously paste temporarily plastic containing ceramic particles. Ceramic paste is a Thermoplastic mixture of solvents, organic agents (binders, plasticizers ...) and PZT ceramic particles. The medium may be aqueous or non aqueous.
The co-extrusion technique should allow have a perfectly centred wire and a homogeneous deposition**.** The adjustment parameters (temperature, pressure, extrusion speed...), the wire tension and the load rate of PZT powder should be properly selected**.** A copper wire of diameter 150 µm was chosen for these preliminary tests, figure 4. It seems however that the method does not allow obtaining fibres with an outside diameter less than 200µm because extrusion pressures become too great [3].

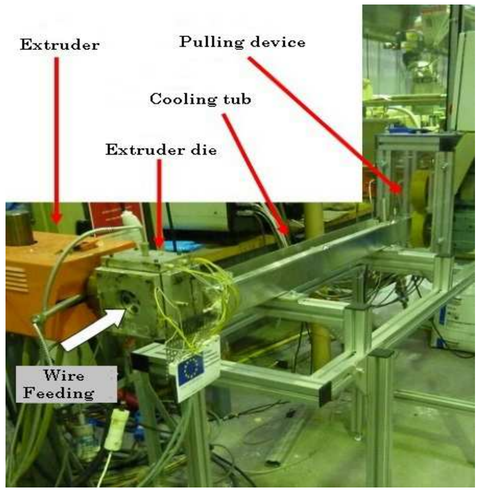

Figure 4: *co extrusion device.*

Dip-coating has been largely used in this research. It consists in plunging the material, here the wire, in a bath and in removing it at a constant speed for depositing a film thereon (figure 5). The deposited thickness depends primarily on the speed of withdrawal and of the rheological properties of the bath (which depends on the composition and on the temperature) but also the dimensions of the substrate and its surface finish. The withdrawal speed was limited to 1.4 mm/s.
Dip-coating test have been done on a platinum wires of diameters 0.4 and 1 mm. With the slurry composition used, dip coating allows to deposit layers of about 15 microns. A multiple dipping process has been used to obtain higher ceramic thickness compatible with actuation mode.
Intermediary thermal treatments are done between each ceramics deposit to insure a good microstructure homogeneity inside the thickness. Various coated alloys core have been also experimented but because of the high sintering temperature presented some diffusion problems occur.

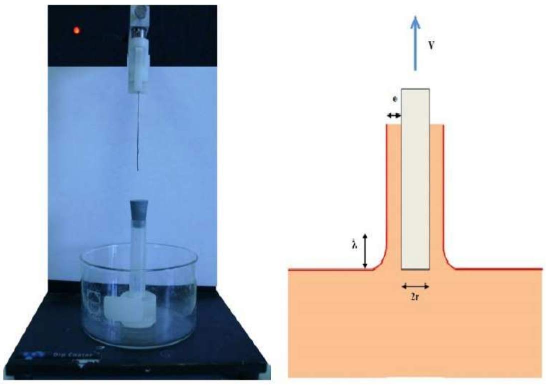

Figure 5 : Principle of dip-coating.

Main tests have been done with 3 to 5 layers, corresponding respectively to 0.38 and 0.6 for the aspect ratios.

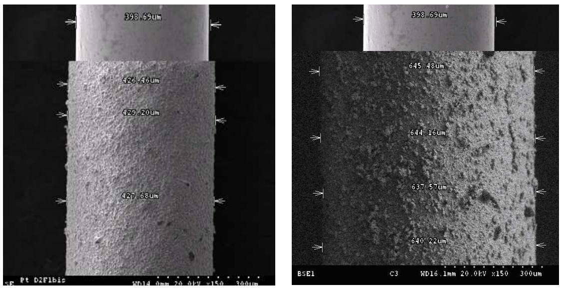

Figure 6: Pt core coated with 1 and 5 PZT layers.

Sintering operation

The technique should allow densification of the ceramic without damaging the metal core.

The standard sintering operation consists in a heating at 1200°C during 6 hours in an industrial air oven. A work atmosphere with an oxygen partial pressure is however preferable

Some tests have been done by classical laser sintering but the result was inconclusive because of the too high power of the available laser. Flash Spark Plasma Sintering (SPS) has not been tested but seems difficult to implement on a so small cylindrical shape with such a dual PZT/metal core combination.

Microwave sintering has been tested at the University of Caen. First results are encouraging. The advantages are a lower heating with few mechanical stresses and a very short sintering duration. Twenty minutes at 950°C seem to be a feasible goal, which is very promising to choose a core material less onerous than platinum, to reduce the manufacturing duration online, and therefore the global cost of the fibre.

Adjuvants such a mixture of Cu_2O and PbO have been added to reduce the sintering temperature to 900-950°C instead of 1200°C allowing the use of other pure metals, refractory alloys or metals and alloys coated with gold or silver without risk of oxidation and also reduce the sintering duration. However the use of a glass phase will necessary lead to a reduction in piezoelectric property of the metal core fibre.

Analytical and F.E modellings

Simultaneously analytical and F.E modellings of the MCPF, of actuator with several fibres embedded in a resin or in a reinforced carbon composite have been performed to compare and consolidate the experimental results.

More accurate and detailed calculations are done with ATILA F.E Code and the GiD pre-post processor. The mesh of the MCPF fibre is built in cylindrical coordinates with 6 to 15 nodes triangular volume elements. To reduce the number of nodes, linear interpolation functions have been used. Patran MSC Software has been also used to define more precisely the fibre mesh and properly the good connectivity with the other middles.

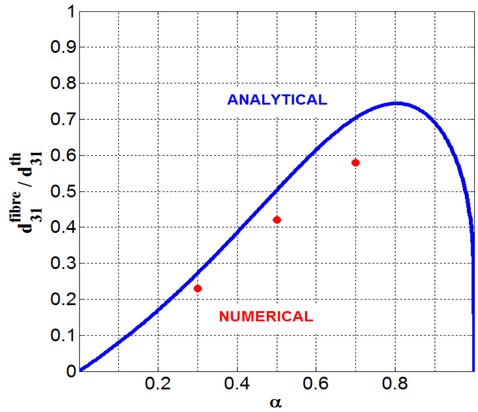

Figure 7: *Comparison of analytical and numerical modelling for single fibre.*

The finite element calculation performed to model the behaviour of the fibre and determine the longitudinal strain has shown that the analytical model, which neglects any transverse effect, overestimates by almost 15% deformation (figure 7). Considering fibre 250 microns with a platinum core and an aspect ratio of 0.7 the free deformation is about 160 µdef and clamping force is about 0.60 N. The integration of these fibres in structures (with high volume fractions (60% of active fibres) reduces the maximum strain: about 5% for a flexible epoxy structure and about 55% for structure CFRP UD, (figure 8).

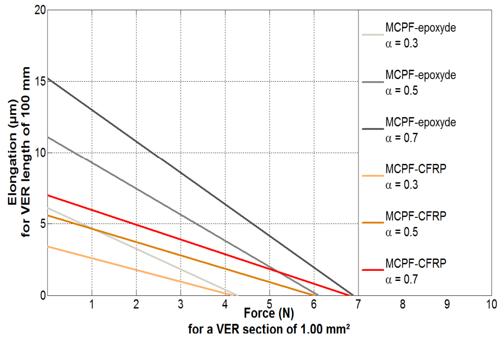

Figure 8: *Elongation versus force for various aspect ratio and soft and rigid matrices*

Some simulations using these fibres were made:
- Bending strains obtained by integrating these fibres on the surface of a structure. The deflection obtained depends on the thickness and stiffness of the structure;
- Complex deformation profiles obtained by activating each independently fibres in a network;
- The monitoring of the voltage across the fibres to imagine sensor applications detecting structural faults. Although the principle could be point out, the sensitivity to the size and the fault distance yet to be assessed.

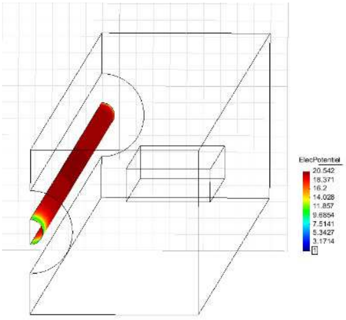

Figure 9: *Operation in sensor mode.*

The use of samples with higher aspect ratios and therefore more sensitive will eventually allow better correlate the modelling results with the experimental results of the tests made.

Electromechanical tests

Vibration tests have been done to verify the good running of fibres as actuator and sensor. For an aspect ratio of 0.4, an effective piezoelectric coefficient d_{31} of -16 pm/V has been measured.
Other tests realized on tensile micro machines at the USTL of Lille and at the Ecole Nationale Supérieure des Mines de Douai (ENSMD) has given -21 pm/V, (figure 10). The objective of these tests where the fibre is pulled and more linear is also to determine the blocking force and the free stroke of the fibre.

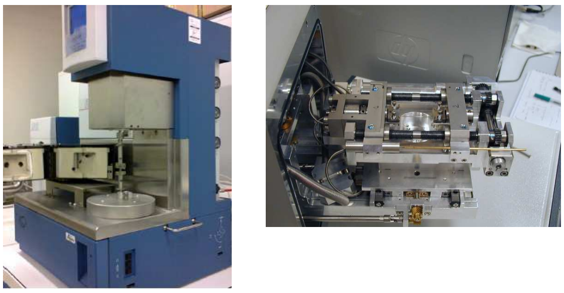

Figure 10: *Tests on micro tensile machines.*

Numerous tests on a great number of perfectly linear samples and for various and higher aspect ratios have to be done to assert these results.

Applications

Various uses and products are perceived for this fibre: confection of low voltage unidirectional patches, woven, knitted fabrics, smart furs and robotized fibre placement.

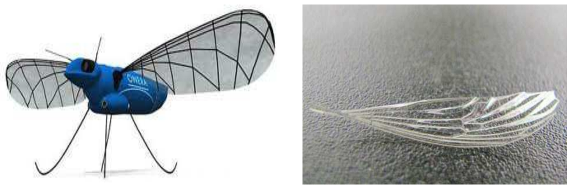

Figure 11: *ONERA microdrone Remanta and wing prototype obtained by stereo photolithography*

ONERA Remanta project is inspired by insect bio mechanism which is to recreate the vibration deformation of the thorax of the dragonfly, inducing the wings flapping, (figure 11). This technique allows insects flap their wings at very high frequency using a minimum of energy. At present time, the torsion of the passive wing is a flapping result. It can be imagined that bundles of fibres may replace the carbon ribs as the veins of a leaf and electrically powered by selective electrodes contributes to the deformation of the light and flexible wing to reach the 3D wished shape.
Active concepts can also be evaluated safely on fixed wing UAVs.

Conclusions and further investigations

Multi dip-coating is a good technique for the elaboration MCPF fibre. Investigation has still to be made to replace onerous platinum by another metal.
The goal of realizing thinner fibres is not yet reached and the dip-coating technique needs to be adapted. An investigation on another process such Viscous Plastic Process (VPP), has also to be examined.
Electromechanical tests will be made on a greater number of samples and better quality to develop suitable characterization techniques to measure effective properties of such fibres.

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