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PIBRAC

PIEZO BRAKE ACTUATOR

SPECIFIC TARGETED RESEARCH PROJECT

AERONAUTIC

FINAL ACTIVITY REPORT

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1 PUBLISHABLE EXECUTIVE SUMMARY

1.1 PROJECT OBJECTIVES

The today need for more electric aircraft leads to the development of electromechanical actuators (EMA) with the ultimate objective to eliminate all hydraulic components. Current aircraft brakes are equipped with hydraulic actuators exhibiting specific safety risks and high maintenance costs. For several years, electromechanical brake actuators have been considered. However these EMA actuators, fitted with conventional electromagnetic motors and reduction gears, bring a weight increase and a very high electric peak power consumption. This energy is mainly wasted in the kinetic energy of high inertia motors rotors and reduction gears due to the high frequency of the actuator's command during the anti-skid operation. EMAs with electromagnetic motors will therefore be only a first step and a really new type of actuator is needed.

The PIBRAC objective is to study, to design and to test an innovative type of piezoelectric brake actuator and its control electronics. Emerging high power piezoelectric vibration motor technology, thanks to their high torque/force – low speed characteristic and very low inertia, could allow overcoming the drawbacks (peak power demand, mass) of EMA fitted with electromagnetic motors. SAGEM and its partners have demonstrated in an EUREKA technology project, PAMELA, that high power is achievable with a piezoelectric rotational motor. This technology is based on the conversion of the mechanical vibration (created from an electric current by the inverse Piezoelectric effect) of a stator into rotational movement of a rotor.

Therefore, the specific objective is to have, when compared to an electromechanical EMA, a weight, including the power electronics, reduced by a factor of 2 and a peak energy power demand divided by at least 3 and hopefully 5.

Two configurations (rotational & linear) of piezoelectric motor structures will be studied. The rotational configuration is intended for the medium term; it will be modelled and tested. The linear configuration that is still more innovative is intended for longer term will be only worked on paper to highlight the critical issues that will have to be studied in the future.

PIBRAC is a 3 years project divided in 5 work-packages that include specifications and assessment criteria, research on different functions related to piezoelectric components and their characteristics, technology integration, technology evaluation, and results dissemination.

1.2 PIBRAC CONSORTIUM AND CONTACT

The PIBRAC consortium gathers all skills needed from research to components manufacturers and aircraft manufacturer. The Consortium led by SAGEM Défense Sécurité consists of 11 partners:

4 large industrial companies:

SAGEM DS (Paris, France)

AIRBUS (Bristol, England)

MESSIER-BUGATTI (Vélizy, France)

SKODA (Plzen, Czech Republic)

2 research centres:

Federal Institute for Material Research and Testing (Berlin, Germany)

INEGI (Leça do Balio, Portugal),

4 small & medium size companies:

ABRITO (Porto, Portugal),

Institute of Mechanics of Materials and Geostuctures S.A (Penteli, Greece),

NOLIAC (Kvistgaard, Denmark),

SAMTECH (Angleur, Belgium),

and 1 university (Paderborn, Germany).

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The communication toward General Public is supported by a web site which was released on 1st April 2005:

www.pibrac.org.

1.3 ACHIEVEMENTS OVER PROJECT DURATION

The first and second periods of the project have been devoted to define how high power piezoelectric motors technology could fit in a brake actuator, considering aircraft environmental and system constraint (WP200) and to study and develop building blocks of the new PIBRAC actuator. Its characteristics had to be proved, through modelling, better than those of an EMA and particularly in terms of weight and power consumption.

The last period has been devoted to manufacture a piezoelectric motor and some mechanical functions to form an actuator. Then, this actuator had to be tested in order to assess PIBRAC technology compared to EMA.

PIBRAC performances have been demonstrated better than those of EMA with a specific piezoelectric motor design supplied with an $f+2f$ normal mode electric excitation. Considering the amount of work to demonstrate the feasibility of the $2f$ mode implementation and the limited project budget, it has been decided to design and manufacture a simpler actuator equipped with a $1f$ design motor. Nevertheless, the performances achieved by the $f+2f$ motor structure have to be proved through modelling in WP520. Likewise, performances in temperature range depending of the use of a roller-screw with solid lubricant, feasibility of this component must be proved in WP440.

1.3.1 Achievements

At project start, activities were mainly focused on the definition of the actuator from a system point of view and from the components point of view. The deliverable “Recommended Architectures” was released, as reference document. It compares 3 braking architectures based on 1-hydraulic, 2-EMA and 3-PIBRAC technologies for an A320 aircraft. The comparison was made on weight, power consumption and reliability. Safety requirements were also considered as constraints of the same level as for hydraulic or EMA systems.

Based on this high level specification, design tasks led to a first PIBRAC actuator description in documents “Preliminary functional requirements document” and “Technical specifications document”. One of main outputs was that one brake requires 6 actuators per wheel instead of 4 for an EMA system. The study showed also that the power controller devices and the cables were the main contributors for total system weight. The goal to reduce the weight by a factor 2 compared to an EMA braking system was no longer attainable at this project stage. Preliminary actuator design also points out the need of a new component. When powered-off, the piezoelectric motor is locked, contrary to a brushless motor. In order to meet the reversibility requirement, a clutch shall be included in the mechanical part. This device turned out to be the most critical part of the actuator mechanical functions.

Over first period, several outputs were produced. On the component/material side dedicated testing devices were developed and tests started. First results on fatigue testing of piezoelectric element demonstrated the dependence of piezoelectric material aging with electric field strength. At 0,36kV/mm and after 14 billion cycles PZT stacks did not exhibit any detectable damage. First high frequency tribometer operations at 2kHz and 40kHz allowed wear operation on different selected materials.

Design tasks started by defining a first analytical model of the motor including design improvements compared to the former PAMELA motor, introduction the “Coupling Mass” and the use of lower electric field strength for PZT stack. After evaluation of the state-of-the-art of appropriate converters, control schemes and implementation methods, an analysis of the best solution, for the power converter, were carried out. This analysis was supported by modelling, taking in account 3 models of power converters (resonant converters, two-level and three-level PWM converters) and filters and the motor control strategy. Mechanical functions and a state of the art on technologies used in brake actuators were identified and analysed. Then estimation of the performances of the brake (motor with its roller screw) depending on different geometry configurations and different roller screws led to the need of a clutch device and first definition of the roller/ball screw.

Aside theoretical studies, experimental technology evaluation started with the adaptation of PAMELA bread-board for component testing. New elastic layers coated with materials selected for PIBRAC were manufactured. Piezoelectric material selected for PIBRAC was also adapted to PAMELA size for testing purpose.

Anticipation of PIBRAC performances had shown that one of the specific objectives was not achievable. System weight was demonstrated higher than for EMA. This result was based on conservative and not validated hypothesis. To refine it and, at the same time, establish the situation about the second specific objective (reduced peak power consumption compared to EMA), it was decided, in the second period, to carry on studies on system design.

On the weight side, the main problem being the number of actuators per wheel, it was proposed to use roller screws with solid lubricant characterized by a constant viscous coefficient with temperature. This solution makes a system with 4 actuators per wheel compliant with the brake specification and PIBRAC system weight, at least, equivalent to the one of an EMA.

Going further in system definition (cable and power controller design), the weight was reduced to be lower than for EMA of about 12%.

Intensive modelling was also carried out to compare PIBRAC and EMA systems on power consumption. 4 scenarios which reflect actuator specifications were used as a comparison basis at aircraft level. It results that a 6 actuators per wheel PIBRAC system has power consumption higher than observed on an EMA system. Considering the use of a roller screw with solid lubricant which allows 4 actuators per wheel, led to a similar power consumption level as EMA systems. Although, the motor efficiency PIBRAC was already increased by a factor of two compared to the state-of-the-art of piezoelectric motor, further reduction in power consumption at system level requires an even better motor efficiency.

This improvement could be obtained using a new excitation scheme. A second harmonic with specific properties is added to the fundamental normal mode excitation. The implementation of this solution has been evaluated. Modelling showed that, with few modifications of the motor structure, the 2f mode is active and effectively improves efficiency to higher than 50% (Conversion from mechanical vibration to rotational movement). Consequently, PIBRAC braking system power consumption is then lower than the one of an EMA braking system of some kW. However, implementation of this new feature requires additional studies to analyse and find solutions to raise some risks.

Aside 2f design optimisation has been the 1f design improvement. The motor structure modification led to an increase of efficiency from 35% to 43%, close to figure obtained with the f+2f excitation scheme. Consequently and considering the amount of work to demonstrate the feasibility of 2f mode implementation and the limited remaining budget it has been decided to design and manufacture an actuator equipped with a 1f design motor.

PZT SCMA fatigue testing, which was extended to the end of project, provided a complete characterisation of components tested up to 2×10^{10} cycles. It appears that hard grade PZT characteristics suffer from some degradations while keeping their integrity.

The tribometer was operational at ambient humidity and temperature. A set of material was tested and some of them appear to be good candidate for PIBRAC. The material selection continued in the next period with the new functionality added to the tribometer for temperature and humidity control.

The design and manufacturing tasks just started at the end of second period. Some motor parts like elastic layer were designed and their manufacturability analysed. The assembly of power supply prototype was in progress and components for the control sub-system were under evaluation. The mechanical parts constituting the actuator except the motor were selected and described.

Experimentations on PAMELA motor brought a lot of knowledge for the motor design and manufacturing. They allowed also checking some results of modelling and in particular the resonance mode characteristics. However, due to PAMELA damage, it was not possible to test materials in real motor condition.

Last period was focused on using modelling results to design and manufacture actuator with its controller.

A piezoelectric motor was designed, using modelling results provided by SAGEM and SAMTECH. In parallel, SAGEM defined, with NOLIAC, procurement specifications of tangential and normal piezoelectric ceramics stacks (SCMA). These non standard components induced some problems as they were not fully compliant with their specifications.

A specific stator assembly tool was realised and constantly improved. Several attempts were necessary to establish a correct assembly procedure. Despite dimensional defects, resonance mode measured with a 3D vibrometer or electrical means appeared to be compliant with FEM model. Just two days before the contract end, the motor was finally assembled and connected to its power supply. However, it did not run as it turned out that the stacking of dimensional defects of the motor parts lead to a large dispersion of the preload applied on each column. Consequently, they required each a specific voltage higher than the one provided by the power supply developed by UPB.

A mechatronic model of the complete actuator, based on coupling of Matlab and FEM models, was developed by SAMTECH. Validation of the coupling principle was demonstrated by running a SAMCEF simulation in which a Matlab model (provided by SAGEM) of the motor is connected to some finite elements. Only few basic braking control strategies have been tested as it has not been possible to operate the motor and get its real characteristics to tune the models.

Motor power supply was based on the agreed modelling and converter topology studied during research phase. A first two phase three-level inverter with LLCC filter was designed and implemented. An experimental prototype of 1.5kW was built to verify the operation principle. The results of the experiments validate the theoretical investigations. A second prototype was realised with some improvements based on the commissioning results of the first prototype.

The power supply control loop serves as inner control loop of the whole piezoelectric brake actuator control system. It controls the voltage amplitude and operating frequency of the tangential and normal modes of the motor. A cascaded voltage and current control scheme based on PWM principle was designed to satisfy the brake system requirements and provide the flexibility for commissioning. In order to limit THD (Transient High Dynamic), four different modulation schemes were investigated.

Outer control loops are provided by a digital signal processing board (DSP). DSP performance was tested using real FFT algorithms. Furthermore, several routines for online identification of state values of the system have been written and tested. Braking control loops (position, speed and force) have been designed and simulated. Although motor does not yet run, preliminary experiments have been done using passive load.

Prototype mechanical integration consisted in assembling the motor with 3 main mechanical functions to realise a brake actuator: a Roller-screw, a Clutch and a Position sensor. The design of the clutch has been the major effort of this task. A design integrating an electromagnet was proposed. However, electromagnet manufacturers showed that the electromagnet technology was irrelevant, because of the (force, stroke) requirement in very constraining dimensions. Clutch design in a deadlock, no parts of this function, as well as the others, were manufactured.

Fatigue testing of hard piezoelectric ceramic stacks continued and reached the required 10^{11} cycles. It confirmed the observation of second period. The characteristics of the examined components changed slightly but the degradation should not impair motor performances.

Final tribology activity was devoted to test and improvement of the high frequency tribometer and evaluation of friction and wear of candidate materials. After several improvements following experimentations, two Ultra-High Frequency Tribometers were made available for material testing under temperature and humidity defined conditions. Different promising materials retained for PIBRAC were tested up to 10^{11} cycles. Experimentations aimed at selecting best material in terms of wear rate K_v and coefficient of friction. At project end, two materials were selected.

Technology evaluation and final assessment were largely reduced as the piezoelectric motor did not run and mechanical functions were not manufactured at contract end. However many intermediate results can be highlighted. PIBRAC project has led to design a new high power piezoelectric motor. Different challenges have been tackled like motor miniaturisation and selection of materials which last whole actuator life time and risks have been raised for most. A prototype motor has been assembled and partially tested. Even it has not still rotated, its feasibility is confirmed.