Smart Helicopter Blade Using Piezoelectric Actuators for both Cyclic and Collective Pitch Control

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ABSTRACT

The present work focuses on the design, construction and testing of a smart actuating system for the cyclic and collective control of helicopter blades for UAV applications. The actuating mechanism consists of a multilayered actuator made of PZT 5H layers bonded together on an aluminum substrate. The design of the actuator was performed using finite element techniques and introducing coupling mechanics in order to improve the simulation capabilities of the numerical tools. The construction and implementation of the smart actuation system are presented and finally static tests were performed (no blade rotation), mostly for the investigation of the cyclic pitch control. The actuation signal send to the piezoelectric actuator was in the frequency domain of 10-15 Hz, that covers the area of 700-750 rpm which is considered as the operational rotational velocity of the blade. The combination of velocity and radius of the rotor (1 m) impose severe loading to the actuator, however, the intelligent use of piezoelectric materials leads to functional structures that fulfil the design requirements.

1.0 INTRODUCTION

Helicopters constitute one of the aeronautical domains that could benefit a lot from the use of smart materials. Hereby, rotor and blade design can profit most of this technology since the application of smart materials can improve aerodynamic performance as well as reduce noise and vibration. Most of the research done on using piezoelectrics in helicopter blades is focused on the IBC (Independent Blade Control) technique. An example of this work is the one of Butter et al. [1]. In this work the blade tip is equipped with an internal piezoelectric actuator that actuates in twisting mode the blade tip due to the tension torsion coupling of this part of the blade. The aim of this design is to reduce vibrational and noise problems. Analogous works have been performed by Bernhard et al. [2], [3] and Chen et al. [4]. The same problems are addressed, using similar techniques as long as the actuation of the edge of the helicopter blade (active part) is concerned. It is very important to mention here that all these approaches could not produce adequate blade twisting, which could be used to obtain collective and cyclic control of the helicopter, to eventually get rid of the heavy blade control mechanism that is part of the rotor.

In this direction the work of Barrett et al.[5] had to offer some innovative aspects. Based on existing technology developed by Barrett [6], [7], high blade twist angles were achieved. This type of piezoelectric

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actuator was used for the cyclic control of a small helicopter blade, while the collective control was performed using another mechanism. The approach showed clearly that piezoelectric actuators can be used for displacements that exceed those needed for vibration and noise suppression. This study proved also that it is possible to reduce the amount of moving parts a helicopter rotor needs in order to be functional, by the intelligent use of piezoelectric actuators.

The work done in the RMA departs from piezoelectric actuators, based on existing technology. They are used for cyclic and collective pitch control of a helicopter blade, planned to be used on a small UAV helicopter. The radius of this blade, being about 0.8 m, makes the issue of piezoelectric actuation even more demanding. However, one expects to profit from the weight decrease a piezoelectric rotor incorporates such that the payload can be increased.

The aim of the research work presented here is initially not to optimize aerodynamic rotor and blade performance, but to focus more on the smart actuation mechanism. However, the airfoil selection is of critical importance. In order to reduce as much as possible the aerodynamic loads exerted on the piezoelectric actuators, a symmetric airfoil seems to be a good choice. A good compromise between high lift, low pitching moment and high drag divergence Mach number performance is found to be the NACA 0012 airfoil. One can still improve performances using camber and with the use of an evolutive profile, though, this would complicate blade construction. Moreover, such a profile should be selected carefully in order not to increase piezoelectric actuator load. Therefore, the selection of the NACA 0012 airfoil for the rotor blades seems to be the most interesting at this time.

The actuators have been analyzed using coupled mechanics finite element solvers developed especially for this purpose. Two different solvers were implemented: A CLPT solver using electromechanically coupled constitutive formulation and a layerwise solver using thermal-electrical-mechanical coupled constitutive formulation. In the work of Giannopoulos et al. [8] the formulation is presented, however, the most important parameters will be presented here as well. Finite element analyses are verified through experiments on real actuators.

2.0 DESIGN OF PIEZOELECTRIC ACTUATORS

2.1 Design Parameters

The design of the actuators is based on a series of parameters. It is evident that an actuator with maximum possible displacement and blocking force has to be elaborated. The same piezoelectric actuator can perform as displacement actuator (no force applied), as a force actuator (no displacement permitted) and also perform in an intermediate state providing both displacement and force. If the two limits are known, it is possible to know the performance of the actuator in all possible intermediate states since it is a linear combination of force and displacement. Preliminary calculations were performed where the force that is necessary to actuate the structure in cyclic mode was calculated on the basis of the maximum angular acceleration for actuation frequency of 13 Hz. However, the polar moment of inertia of the helicopter blade was not known a priori. Based on the mass characteristics of the blade a CAD model was developed and an estimation of the polar moment of inertia was possible.

The dynamic response of the actuator is essential considering possible resonance phenomena. Opposite to what could be expected, the resonance in this structure is not something to be avoided, since the actuator displacement can be maximized. In other words, the piezoelectric actuator performing in resonance, maximizes the amount of electrical energy that can be transformed to mechanical energy which is of particular interest for the application presented in this work. The lack of data for the blade does not permit to have an accurate prediction for the resonance frequency of the whole system in advance. The fact that piezoelectric materials are excellent dampers reduce the amplitude of the vibration in resonance which prevents the structure from failing.

To conclude, the requirements imposed were for a minimum rotational velocity of 700 rpm, diameter of the rotor 1.6-2.0 m and a NACA 0012 profile with chord length 70 mm. The cyclic actuation peak to peak amplitude should be 15^o. With these characteristics, the lift that the rotor can produce is in the area of 100 Nt, which is considered as adequate for this class of UAV's.

2.2 Preliminary Designs

The class of actuators used in the present work are based on the existing technology of bimorph actuators. Two layers of PZT actuators are attached on a aluminum substrate ([5]) using an adhesive film and the whole structure is cured at an elevated temperature. This is done in order to increase the precompression in the piezoelectric layers and avoid depoling. However, for the present application a simple bimorph is not adequate due to low stiffness and natural frequencies. In order to overcome this, it was considered that multilayer actuators should be considered. Such structures are much stiffer with higher natural frequencies and increased blocking forces.

In order to design a piezoelectric actuator it is necessary to have accurate data on both displacements and blocking forces. The displacement provided by a piezoelectric actuator can be multiplied using a mechanism, however this is at the expense of blocking force. Creating a wider bimorph actuator it is possible to increase the force actuation keeping the displacement in the same levels. It is evident that the actuator should perform as both force and displacement actuator which means that the maximum force required for the cyclic actuation should be lower than the blocking force of the actuator. In figure 1 the combinations of force and displacement calculated using different models as well as the experimental verification are presented.

Taking into account the above mentioned requirements it was decided that a continuous wide actuator with 4 layers (2 piezoelectric layers in each side of the aluminum substrate) should be realized. A detailed analysis on the design chosen is presented in the following paragraphs. The piezoelectric material used is the PZT 5H with thickness of 0.191 mm and the adhesive film is the Hysol 9689. The properties for the piezoelectric and aluminum materials are presented in table 1. It has been assumed that the adhesive material reassures perfect bonding and that its influence in the stiffness of the structure is negligible. Thus it has not been included in any of the FE models.

Table 1: Properties for aluminium and piezoelectric materials

Aluminum	Piezoceramic
Elastic (GPa)	
E=67	$E_1=E_2=62$
G=27	$E_3=53$
v=0.3	$G_{12}=30.6$
	$G_{23}=G_{13}=25.6$
	$v_{12}=0.25$
	$v_{13}=v_{23}=0.49$
Piezoelectric (m/V)	
	$d_{31}=-320x10^{-12}$
	$d_{32}=-320x10^{-12}$
	$d_{33}=650x10^{-12}$
Electric (F/m)	
$\varepsilon_{11}=3.1x10^{-11}$	$\varepsilon_{11}=1.31x10^{-8}$
$\varepsilon_{22}=2.66x10^{-11}$	$\varepsilon_{22}=1.31x10^{-8}$
$\varepsilon_{33}=2.66x10^{-11}$	$\varepsilon_{33}=1.16x10^{-8}$
Thermal (m/mK)	
$\alpha=23.1x10^{-6}$	$\alpha=0.9x10^{-6}$
Density (kg/m3)	
2700	7600
Thickness (μm)	
70	191

2.3 Finite Element Analysis

2.3.1 CLPT and Ansys Analysis

The structure being thin (a/h>50), it is possible to use CLPT theory in order to perform a finite element analysis of the actuators. The structure examined is 70 mm long, 50 mm wide made out of 4 piezoelectric layers. In order to have an accurate finite element analysis, electromechanicaly coupled constitutive formulation has been implemented. This is shown in equations 1, 2.

$$\sigma_i = C_{ij}S_j - e_{ik}E_k \tag{1}$$

$$D_l = e_{lj}S_j + \varepsilon_{lk}E_k \tag{2}$$

In equations 1, 2, σ_i is the stress tensor, C_{ij} is the elasticity tensor, S_j is the strain tensor, e_{ik} is the electromechanical coupling tensor, E_k the electrical field vector, D_l the electric displacement vector and finally ε_{lk} the electric permitivity tensor. As it is shown in [8] and [9] coupled formulation provides higher accuracy and must be considered instead of equivalent strain approaches in order to model the existence of active materials.

Based on the above mentioned formulation, a linear 4-node plate element was developed as well as the corresponding finite element solver using Matlab. This solver was used in order to calculate both the maximum free displacement of the actuator as well as the maximum blocking force. In addition the stress profiles were calculated for all layers and are compared with the corresponding ones obtained from other calculation methods.

A finite element model was also created in Ansys using the Solid 5 coupled field element for the representation of the active materials and the Solid 45 for the representation of the aluminum layer. The formulation of the Solid 5 element is based on the formulation shown in equations 1,2, however, 3D mechanics are applied and thus in thin plates it is possible to have artificial stiffening. Another important parameter is that in the 3D analysis the complete stiffness matrix is introduced which has a major impact on the calculation of the blocking force. For the calculation of the stroke of the actuator the stiffness plays a very small role.

The structure was further analyzed using a coupled mechanics layerwise solver that it has been developed explicitly for the analysis of smart structures in the department of Civil and Materials Engineering of the Royal Military Academy. In [8] the details are presented.

The main feature of the layerwise theory is that in a multilayer structure each layer is treated seperatelly which is not the case for an equivalent single layer theory like CLPT. In fact it is an hybrid 3D theory where the integration in order to derive the stiffness matrix takes place in 2 stages and the in-plane and through the thickness terms are decoupled. This accounts for a lower number of integration points in general, which means lower computational cost while at the same time it is possible to have different approximation functions for in-plane and out of plane. This is the case in the present work. The through the thickness approximation takes place using a linear shape function while the in-plane approximation is taking place using quadratic shape functions (8-node quadratic plate element). More details one can find in [10]. Additionally the coupling mechanics introduced in this solver are extended to the thermal field as well. In equations 3,4,5 the full thermal-electrical-mechanical coupled field is depicted.

$$\sigma_i = C_{ij} S_j - e_{ik} E_k - \lambda_i \theta \tag{3}$$

$$D_l = e_{lj} S_j + \varepsilon_{lk} E_k + p_l \theta \tag{4}$$

$$\varsigma = \lambda_i S_i + p_l E_l + \alpha \theta \tag{5}$$

The advantage of this formulation with respect to an electromechanically coupled FE solver is more pronounced in the case that the piezoelectric structure performs in a high temperature environment and especially when it performs in sensory mode as well as in the case of high temperature gradients inside the structure (high difference in the temperature levels on each of the free surfaces).

In table 2 the results of the different calculation methods are presented. One can clearly see that all models are close to the predictions and agree with the experimental values as far as displacements are concerned. However, this is not the case for the blocking force and this is due to the fact that the later depends on the elastic properties that are different for the 3D analyses and the CLPT analysis. The experimental results and the first resonance frequency for the actuator show clearly that 3D theories are applicable and give quite accurate results. Although the difference between experiment and 3D theories seems to be high for the blocking force, finally this is not the case. In the FE analysis all the nodes of the free edge of the actuator are restricted and thus the blocking force incorporates also the effect of the piezoelectric actuation in the transverse direction. The experimental procedure took place using a load cell which pointed in the middle of the free edge of the actuator and as a consequence the effect in the transverse direction is not measured.

Table 2: Free displacement, blocking force and first resonance frequency for a multilayer actuator

	Free Disp.	Bl. Force	Res. Freq.
Ansys	1.938	3.588	99.542
LW	1.9818	4.1059	97.565
CLPT	2.1427	2.7935	83.14
Actual	2.327	3.198	97.96

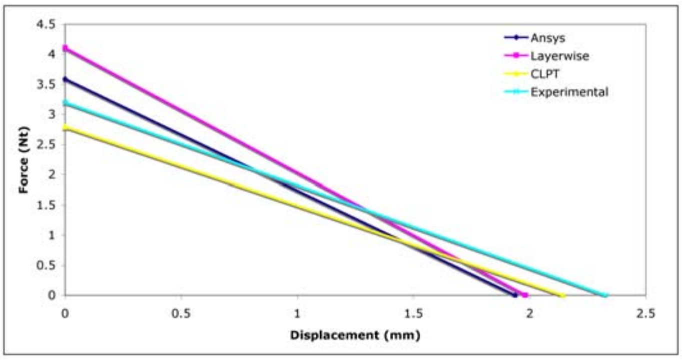

Figure 1: Force/displacement combinations.

Piezoelectric actuators of this type suffer from fatigue problems. After a certain amount of cycles cracks appear and finally the actuator is not capable of performing the actuation. Together with depoling, these are the most severe problems that have to be addressed in a piezoelectric actuator. Due to the thermal expansion coefficient mismatch between the PZT layers and the aluminum substrate and due to the elevated temperature curing cycle, high compressive stresses are developed in the piezoelectric layers that counteract the tensile stresses developed during actuation and reduces the risk of depolarization. In figure 2 the stresses in the longitudinal direction are presented for the maximum permitted actuation voltage (240 volts). It is clear that the thermal stresses are dominant and change dramatically the stress levels in the structure. Without thermal stresses the middle aluminum layer should experience very low stresses while the outer piezoelectric layers very high tensile and compressive stresses.

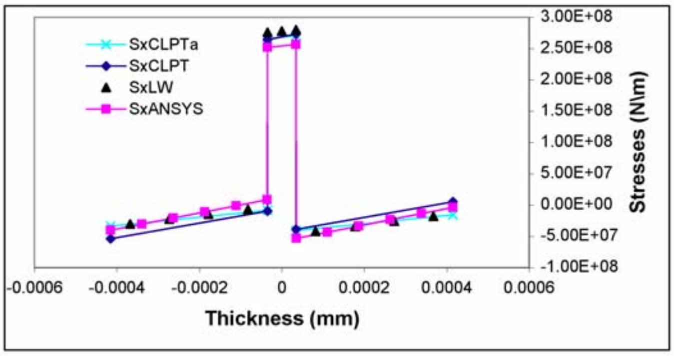

Figure 2: σ_x stress levels.

3.0 CONSTRUCTION OF PIEZOELECTRIC ACTUATORS

The piezoelectric bimorph actuators are constructed using continuous layers of PZT 5H material with dimensions (73x73x0.171 mm) which are cut to the desired shape. The layers are attached using the Hysol 9689 adhesive film as well as conductive glue in order to have electrical continuity. The middle aluminum foil acts as ground electrode. With respect to figure 4 the only difference is that the same voltage is applied in the outer surfaces of the actuator and the ground is connected in the middle alluminum layer. The stacking sequence is shown clearly in figure 3.

PZT
Adh
PZT
Adh
Alu
Adh
PZT
Adh
PZT

Figure 3: Stacking sequence of the multilayer actuator.

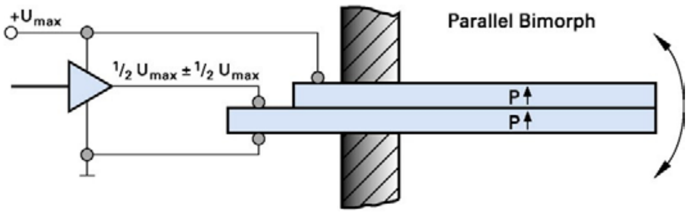

Figure 4: Electrical connectivity for a parallel bimorph.

The curing of the adhesive film takes place at the temperature of 177°C for 1h. Vacuum techniques are used and an overpressure of 0.3 bar is applied throughout the whole curing procedure. This parameter is critical in order to reassure the perfect bonding between all the layers and to reduce the amount of adhesive material between the layers. The thicker the adhesive layer, the worst is the performance of the actuator in terms of displacement. Higher curing temperatures could be even more adequate taking into account the precompression that can be exerted to the piezoelectric material. However, higher temperatures will lead to depolarization of the piezoelectric layers.

4.0 DESIGN, CONSTRUCTION AND IMPLEMENTATION OF THE SMART ACTUATION SYSTEM

4.1 General Aspects

The mechanism to host the smart actuator was designed taking into account that the potential of the piezoelectric actuators should be fully exploited in the actuation of the blade. The actuator was thus isolated from any kind of structural loading, like centrifugal forces. It was decided that it should not be an integral part of the structure since in that case it would carry structural loads that reduce the amount of available actuation.

In order to reduce the amount of friction three bearings were used. Two roller bearings in order to take all the forces due to the lift and drag and one thrust bearing for the centrifugal forces that reach the value of 750 Nt at 700 rpm. To reduce as much as possible this load certain parts of the support system are made from aluminum. The design is presented in figure 5, and the detail with the 3 bearings in figure 6 and the system in its final form is shown in figure 7.

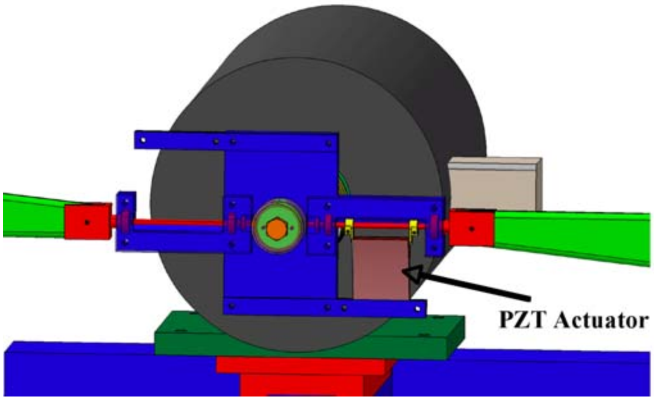

Figure 5: Design of the smart support system.

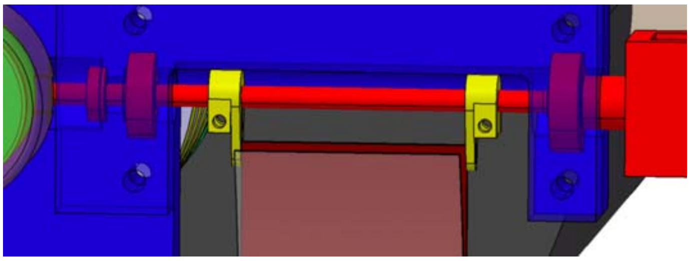

Figure 6: Detail of the bearings.

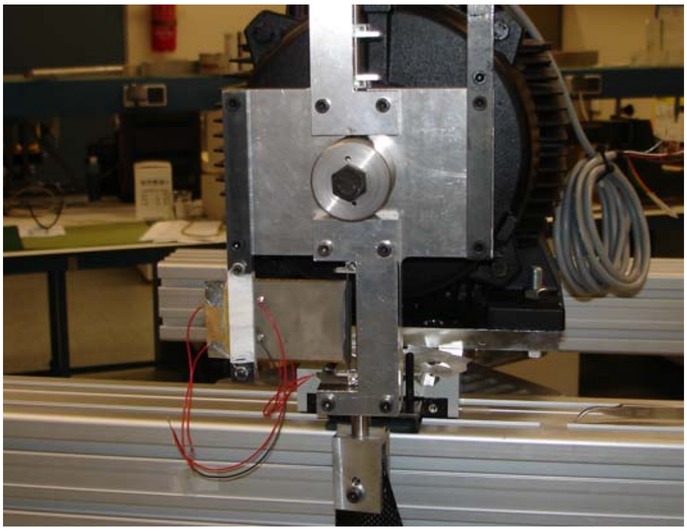

Figure 7: The smart support system realized.

4.2 System Identification

4.2.1 Testing Setup

The piezoelectric actuators need to perform in dynamic mode. The first natural frequency is very high with respect to the operational frequency(12-13 Hz) but this analysis took place without taking into account the influence of the blade together with the bearings. This changes off course dramatically the dynamic performance of the system. It is thus evident that at this stage it is very important to investigate the resonance frequency of the whole system.

A testing setup, in order to perform the dynamic analysis of the system was elaborated. Using a PCMCIA input/output card from National Instruments, the linear sinesweep signal that was generated in Matlab, was transmitted to a high voltage amplifier and finally to the piezoelectric actuator. The angle of attack of the blade was measured using a non conductive laser sensor with a dynamic bandwidth up to 22 kHz. However, due to the fact that a rotational movement is measured using a linear displacement device (in fact a non-contact LVDT), there is a small error that is introduced in the measurements. Taking into account that the angle of the blade will never exceed 20^o from peak to peak, the error remains small.

The system identification is necessary in order to consider in a later step a closed loop controller for the position of the blade. It will be thus possible to eliminate any hysteresis imposed by the piezoelectric actuators. This hysteresis prevents from having an accurate control of the direction that the helicopter would take at a certain input from the operator. The significance of the closed loop controller is exactly there; to avoid having the operator compensating manually the difference between the desired and the actual response.

At this stage the rotor is not put in rotation. This will take place in a next series of tests. However, due to the design of the smart actuator support system shown in figure 5 the characteristics of the system are not expected to change dramatically. Thus the results presented here can be considered as representative for the performance of the system.

4.2.2 Sinesweep Excitation

As it has been mentioned already, the importance of the first resonance frequency is essential for the performance of the system. In order to clearly identify this, a linear sinesweep signal was generated using Matlab and was sent to the actuator through the high voltage amplifier. The gain of the amplifier was set to 30 V/V. The amplitude of the signal was set to 1 volt and the frequency sweeping was performed in a time period of 10 seconds from 0 to 50 Hz. The sampling rate was set to 1kHz which is adequate for the frequencies scanned. In figure 8 the signal sent to the high voltage amplifier represented in the frequency domain is depicted.

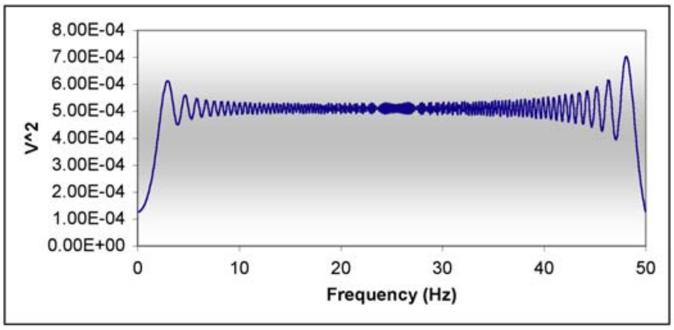

Figure 8: Auto spectrum for input signal.

The aim of the experimental procedure is to identify the behavior of the system and that in fact is related with the transfer function of the system. In figure 9 the transfer function of the system is presented and in 10 the corresponding phase shifting is depicted. It is clear that the resonance occurs at the area of 13 Hz. It is also evident that for any frequency between 11-15 Hz the actuation is maximized and this defines the rotational speed of the rotor. The piezoelectric actuator does not fail since the damping of the system is such that prevents the actuator from reaching excessive displacement levels as well as due to the fact that piezoelectric layers are excellent dampers.

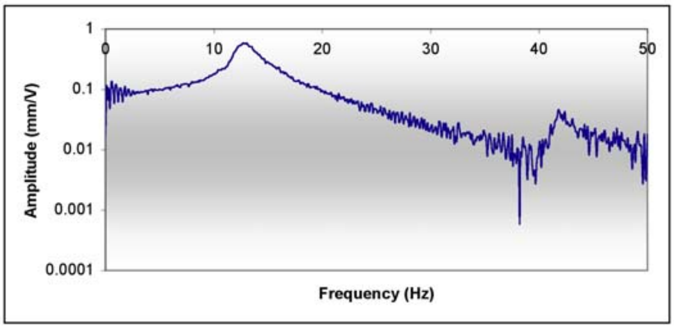

Figure 9: Transmissibility amplitude for 1 volt input (before amplification).

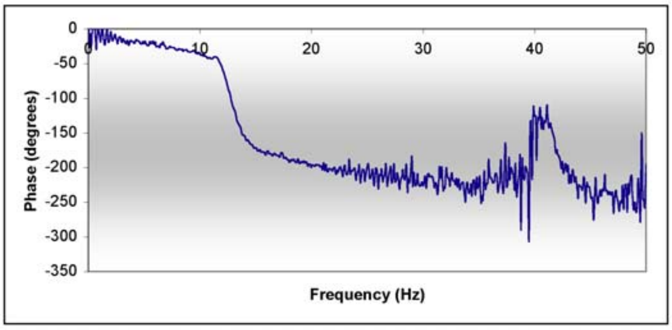

Figure 10: Phase shifting for 1 volt input (before amplification).

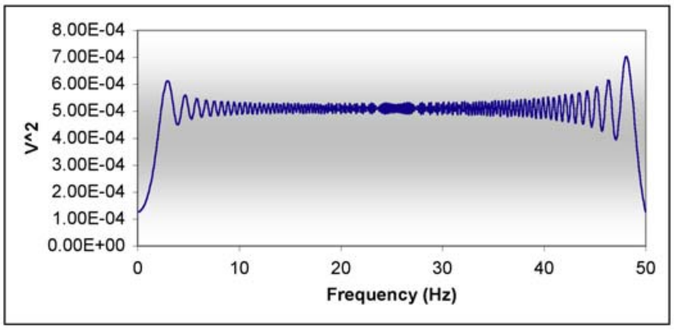

Figure 11: Auto power spectrum for the acquired signal.

From figures 9 and 10 it is shown that for the frequency domain between 30 and 50 Hz some unexpected phenomenae occur. The peak around 40 Hz is probably due to tolerances in the assembly of the structure and not due to electrical noise, since a low pass filter has been applied during the signal acquisition. Finally in figure 11 the auto spectrum for the acquired signal is depicted showing again clearly the resonance frequency and the power output of the actuator at this frequency. In figure 12 the amplitude coherence of the acquired signal with respect to the signal sent to the actuator is presented as an indication of the quality of the experimental procedure.

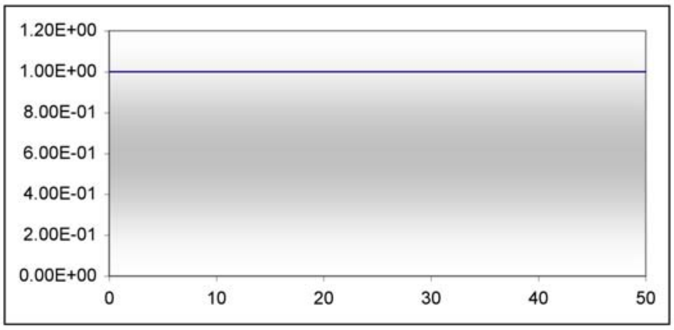

Figure 12: Amplitude coherence.

This procedure took place using different voltage amplitudes. The results as it was expected are identical. In figure 13 the transfer function is presented for voltage amplitude of 2 volts (before amplification).

The significance of knowing exactly the resonance frequency is very important. The actuation requirements for cyclic control can be achieved at much lower voltages. This is an important parameter taking into account that the necessary electronics to create high voltages are complicated, heavy and in many cases there is the fear of interference with other devices.

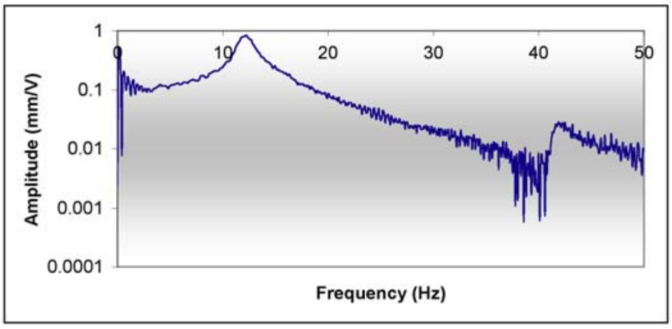

Figure 13: Transfer function for 2 volts input (before amplification).

5.0 CONCLUSIONS

The main target of the present work is to give an overview of the design, implementation and testing of a smart actuated helicopter blade. Finite element methods were used in order to design the actuators in terms of displacements and blocking forces. The stress levels due to thermal effects are depicted showing their influence in the functioning of the structure. The design that was elaborated for the support of the piezoelectric actuators helped to reduce the loads that pass to the actuator, reducing in the same time friction and thus maximizing the performance of the actuator.

The testing procedure showed clearly that multilayered bimorph actuators have the capacity to be used in such applications. Taking advantage of the resonance frequency is something that should be considered since the voltage required for the actuation is highly reduced. The inherent damping characteristics of the piezoelectric material do not permit excessive displacements that could reach failure levels. However, electronic devices capable of handling high reactive loads should be considered.

Future work will be focused on performing tests on the rotor while the rotor is put in rotation. Forces in different axes will be measured in order to investigate the capability of the piezoelectric actuator in real conditions. Aerodynamic forces is possible to impose high loads on the actuators and thus reduce the amount of available actuation.

6.0 ACKNOWLEDGEMENTS

The authors of the present work would like to thank Dr. Jean Marie Ndambi Mulambula for his help on the dynamic identification of the system as well as the Mechanics Department of the Royal Military Academy for their excellent work and support of this project.

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SYMPOSIA DISCUSSION – PAPER NO: 11

Author's Name: G. Giannopoulos

Question (B. Baron):
What are the fatigue characteristics of PZT material?

Author's Response:
Preliminary studies have shown that fatigue life is limited but the precompression in the PZT layers improve the life of the actuators.

Question (P. Hendrick):
Would it be possible to apply this PZT actuation system for a rotor of a smaller RUAV tuning at higher RPM, say 2000 RPM? If yes, what do you need to change to the system/blades?

Author's Response:
It is possible by reducing the size and the inertia of the blade . For micro and mini UAVs it can go even higher.