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ACTUATORS FOR SMART APPLICATIONS

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ABSTRACT

Actuator manufacturers are developing promising technologies which meet high requirements in performance, weight and power consumption. Conventionally, actuators are characterized by their displacement and load performance. This hides the dynamic aspects of those actuation solutions. Work per weight performed by an actuation mechanism and the time needed to develop this mechanical energy are by far more relevant figures. Based on these figures, a selection process was developed. With time and energy constraints, it highlights the most weight efficient actuators. This process has been applied to the Gurney flap technology used as a morphing concept for rotorblades. Three control schemes were considered and simulations were performed to investigate the mechanical work required. It brought forward piezoelectric stack actuators as the most effective solution in the case of an actively controlled rotorblade. The generic nature of the procedure allows to use it for a wide range of applications.

INTRODUCTION

Hydraulic actuators have been used for a long time in aeronautic applications for their reliability and performance over a large number of cycles. However, their size and weight limit their integration in applications like smart helicopter blades. Piezoelectric stack actuators used to be a good alternative. Manufacturers such as Physik Instrumente have recently developed new types of actuators achieving high performance per unit mass. These new actuators are linear step actuators and linear ultrasonic actuators [1, 2]. Unlike piezoelectric stack actuators, which provide large forces but limited stroke, these achieve large strokes

with limited forces. These new technologies use piezoelectric elements to transmit force by mean of friction to a moving rod that leads the final motion. They are of great interest for shape-morphing applications in the scope of the Green Rotorcraft Project from the European Clean Sky Joint Technology Initiative [3]. This project aims at improving rotorcraft transportation. The work is carried out on multiple aspects: fuel consumption reduction, increased efficiency, improved global transport quality improvement and rotorcraft noise reduction. In order to wisely use those actuation technologies, a selection process has been developed. It allows to match an actuator type to an actuation strategy and has been applied to a rotorblade with Gurney flaps.

ACTUATOR TYPES

In this study, the actuator selection has been restrained to the three following types of actuators: linear stepped actuators, linear ultrasonic piezoelectric actuators and piezo electric stack actuators. They are more suitable for light weight and high performance applications. 200 actuator references were used from the following manufacturers: Physik Instrumente, Piezo Mechanik, New Scale Technology and Smart Materials.

Linear piezoelectric stepped actuators

Linear stepped actuators are using piezoelectric elements to sequentially clamp a moving rod to a main piezoelectric longitudinal element that extends and contracts to communicate motion to the rod as shown in Fig. 1 [4]. Depending on the type of actuator, it is possible to hold the rod against the element and consequently have a holding force due to friction while no power is provided to the actuator anymore. The force provided is constant

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over the full stroke. The stroke can be as long as the rod. The limitation of those actuators is the motion velocity. Therefore, they will not be able to deliver their full stroke at high frequencies.

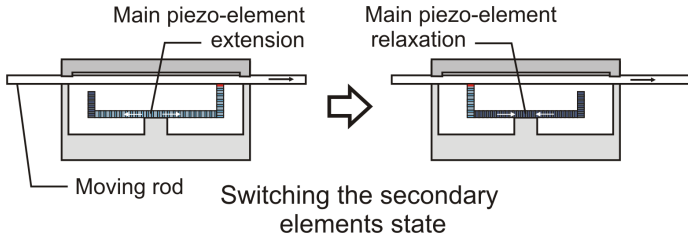


FIGURE 1. SKETCH OF THE WORKING PRINCIPLE OF A PIEZOELECTRIC STEPPED ACTUATOR.

Ultrasonic piezoelectric actuators

Ultrasonic linear actuators use friction forces generated by a block of piezoelectric material on a moving rod [5]. This piezoelectric block is subjected to orthogonal vibration modes to achieve an elliptical motion of all the surface elements as shown in Fig. 2. A slider is pressed on the piezoelectric block which can move forward and backward depending of the applied modes. Again, as friction forces are applied, there is a residual holding force with no driving power. The stroke can be as long as the slider length. This actuator can achieve large velocities but the forces are less significant than these applied by linear stepped actuators. The force applied is constant over the full stroke of the motion.

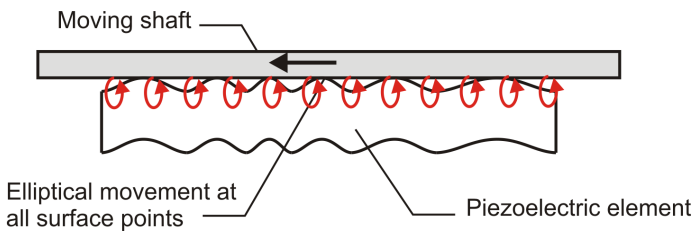


FIGURE 2. SKETCH OF THE WORKING PRINCIPLE OF A PIEZOELECTRIC ULTRASONIC TRAVELLING WAVE ACTUATOR.

Piezoelectric stack actuator

Piezoelectric stack actuators are composed of many layers of piezoelectric elements [6]. When a voltage is applied, the el-

ements contract and the tip of the actuator moves back as shown in Fig. 3. The stroke is very limited but the forces generated are large. A symmetric stroke can be achieved by pre-stressing the stack, applying a compressive force. The velocities achieved are also very large, which makes the stack actuator suited for high frequency applications. The control of this type of actuator is more difficult because the stack actuator force is not constant over its tip displacement. The stack actuator has a characteristic curve defined by its free displacement and blocking force. Depending on the loads applied on the actuator and its stiffness, the working point will be different. For comparison purposes here, the stroke and the force developed by the stack actuator will be half of the free displacement and respectively half of the blocking force.

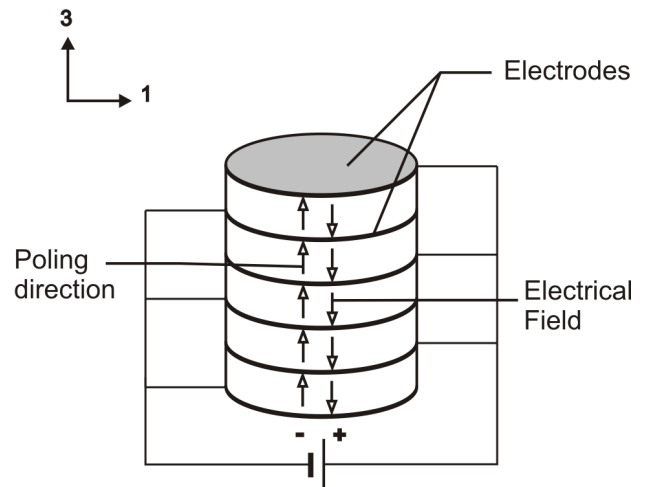


FIGURE 3. SKETCH OF PIEZOELECTRIC ELEMENTS ASSEMBLED INTO A PIEZOELECTRIC STACK ACTUATOR.

ACTUATOR COMPARISON
Actuator Performance

The performance of actuators are usually displayed in displacement versus force as provided by the manufacturers data sheets [4–6]. The graph displayed in Fig. 4 shows the spread of these two figures over many orders of magnitudes for the various types of actuators. Furthermore these figures do not give any idea about the efficiency of the actuator according to its weight, nor its actuation speed. Other criteria are therefore indispensable to accurately compare technologies that are so different. The work per weight ratio that is available within a defined duration is by far more relevant when investigating the dynamics and the efficiency of these actuators. The graph displayed in Fig. 5 shows that this figure is only spread over two orders of magnitude for all

the actuators considered. Furthermore, the performance of each actuator can be calculated for any duration. Thus it is straightforward to compare actuators weight-efficiency according to the time required for one stroke. Power efficiency can also be compared by calculating the work available per Watt of power consumed.

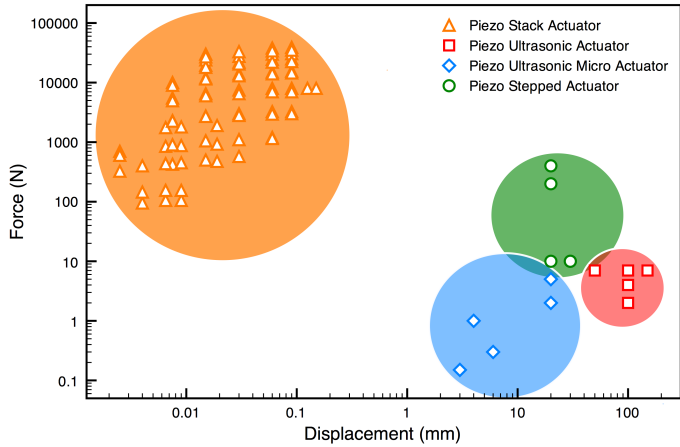


FIGURE 4. GRAPH SHOWING THE FORCE VERSUS DISPLACEMENT FOR VARIOUS TYPES OF ACTUATORS.

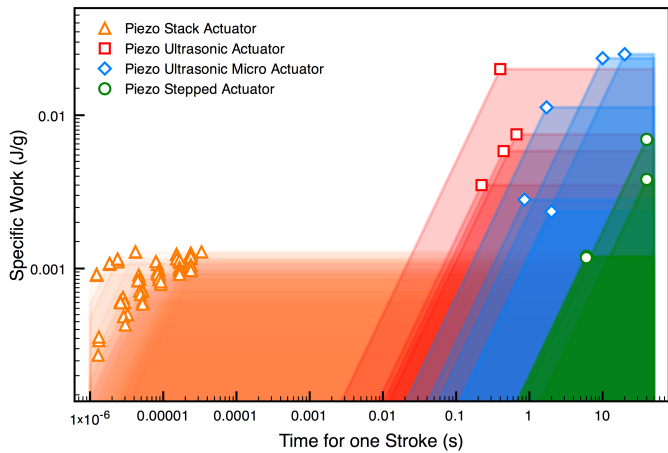


FIGURE 5. GRAPH SHOWING THE WORK PER WEIGHT VERSUS THE TIME REQUIRED TO ACHIEVE MAXIMUM DISPLACEMENT FOR FOUR TYPES OF ACTUATORS.

From the graph presented in Fig. 5, it is possible to ob-

serve the various types of actuators and their weight efficiency at a specific actuation speed. The time needed for one stroke is directly related to the maximum frequency performed by an actuation system. For frequencies below 0.06 Hz (i.e equivalent to one stroke completed within 8 seconds), the piezoelectric micro ultrasonic actuator is the best choice. From 0.06 Hz to 50 Hz, the piezoelectric ultrasonic actuator is the most efficient solution. Finally, for frequencies higher than 50 Hz, the stack actuator is the most capable choice.

Establishing The Selection Process

A selection process has been set up using the relevant figures mentioned in the previous section. Fig. 6 displays this selection process.

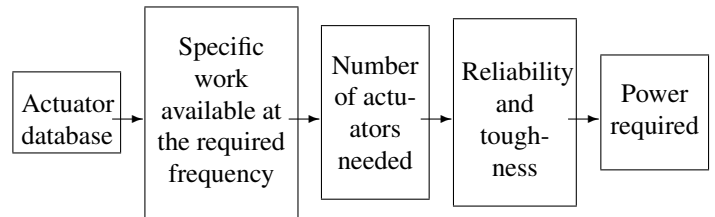


FIGURE 6. ACTUATOR SELECTION DIAGRAM.

It can be applied to any application constrained by the weight efficiency of the actuator and its capacity to deliver mechanical energy within a specific duration. Piezoelectric ultrasonic micro-actuator actuators are very weight efficient, but cannot deliver much force because they are small. Thus the number of actuators needed for an application needs to be carefully considered. The next step involves the reliability and the environmental constraints. Finally the power consumed by each actuation system is calculated to select the most efficient solution. This selection process is mainly based on the energy delivered by an actuation system. Further design constraints on dimensions and on the connections to the final mechanism need to be added according to the application considered.

THE GURNEY FLAP: A MORPHING CONCEPT FOR HELICOPTER BLADES

Morphing Concepts for Rotorblades

Morphing the blade of an helicopter can increase its efficiency, adapting the aerodynamic performances of the blade profile to various flight conditions or to the airspeed variations encountered by the blade during its rotation. The first concept involves having various configurations for various flight conditions. High lift configuration for take-off, landing and hovering versus low drag configuration for efficient cruising with defined speed and altitude [7]. The second concept is an adaptive blade

that changes its profile during its revolution. This concept can not only improve the efficiency of the helicopter aerodynamics but also the maximum allowable speed. When operated at frequencies higher than the blade passing frequency, it can even damp some of the vibrations generated by the blade rotation which makes the third concept [8–11]. The actuation frequency and control scheme will be determined according to the chosen configuration.

The Gurney Flap Mechanism

A Gurney flap is a small flap, usually a few percents of the chord length of the profile as shown in Fig. 7. Deploying a Gurney flap is aerodynamically equivalent to increasing the profile curvature: it increases the lift with only a small drag penalty [11–13]. This morphing system does not require heavy and complex mechanisms to be actuated. Early concepts involve a simple bender to achieve the deployment motion [11, 14].

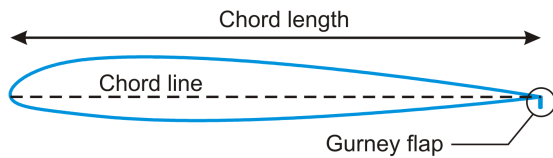


FIGURE 7. SKETCH OF THE NACA 23012 PROFILE WITH A 2% LONG GURNEY FLAP AT THE TRAILING EDGE.

Control Strategies For The Gurney Flap

For each of the three morphing concepts, three main control strategies have been distinguished.

Flight configuration Deploying the Gurney flap when there is a change in the flight conditions such as switching from take-off mode to cruising mode.

Active revolution control Deploying and folding back the Gurney flap at a specific position during the revolution over a precise angle range. When the helicopter travels, there is an air-speed difference between the advancing and the retreating blade. In order to keep the helicopter in a straight forward motion, the pilot increases the pitch for the retreating blade to even the lift. The maximum speed and the helicopter stability is limited by how much it is possible to balance the lift between the advancing and retreating blade. Periodic deployment on the blade retreating side increases the lift and improves the stall behavior [11].

Active vibration damping Vibrations are a typical disturbance during an helicopter flight. They generate discomfort and noise. The vibration frequency is linked to the blade passing frequency. The main vibration modes concern four and eight times the blade passing frequency. An active damping of those frequencies is allowed by actuating the Gurney flap at similar frequencies as the disturbance frequencies [9].

Specific constraints on actuation time and on required mechanical power are necessary for each of these control strategies.

APPLYING THE SELECTION PROCESS FOR THE GURNEY FLAP

The following part will investigate the constraints on the time and on the mechanical energy for the selection process of actuators for the Gurney flap. The blade specifications for this application has been taken from the Green Rotorcraft project baseline definition and are presented in Tab. 1 [15].

TABLE 1. BLADE DIMENSIONS AS DEFINED IN THE BASELINE OF THE GREEN ROTORCRAFT PROJECT.

Blade radius	8 m
Rotational velocity	26.26 rad/s
Profile reference	NACA 23012
Profile chord length	0.65 m

Gurney Flap Dimensions

The dimensions of the Gurney flap have been chosen according to the studies found in the literature. Studies on the Gurney flap length have concluded that a Gurney flap with a length equal to 2% of the profile chord length would show a good balance for the improvement of rotorcraft blade aerodynamics [7].

Time Constraints

The time required for the actuation system to deploy is related to the chosen control strategy necessary for the specific morphing concept. For the control strategy concerning the change of flight configuration, there is not really a time limit. The modification of the profile can be achieved over many blade revolutions. The control scheme for the active revolution control strategy requires a fast deployment so that the modified profile can be efficient over a wide angle on the retreating side before

being folded back. The deployment should be completed within 10 degrees of the blade sweeping. This gives a maximum deployment time of 6.6 ms according to the rotational speed as defined in the baseline blade definition. The configuration regarding vibration damping requires an actuation cycle at a frequency that is at least four times the blade passing frequency [9]. The blade passing frequency is equal to 4.2 Hz. Therefore the minimum cycle frequency is 16.8 Hz and the time to achieve half a cycle is 30 ms.

Energy Constraints

The mechanical work that is needed for the three control strategies is more or less the same. However this mechanical work has to be delivered within the times previously calculated. The various actuator technologies are not all efficient at delivering the same mechanical work within the same duration. A flow simulation was performed to determine an upper bound to the mechanical energy required for the Gurney flap deployment. The results were used as input for the actuator selection process.

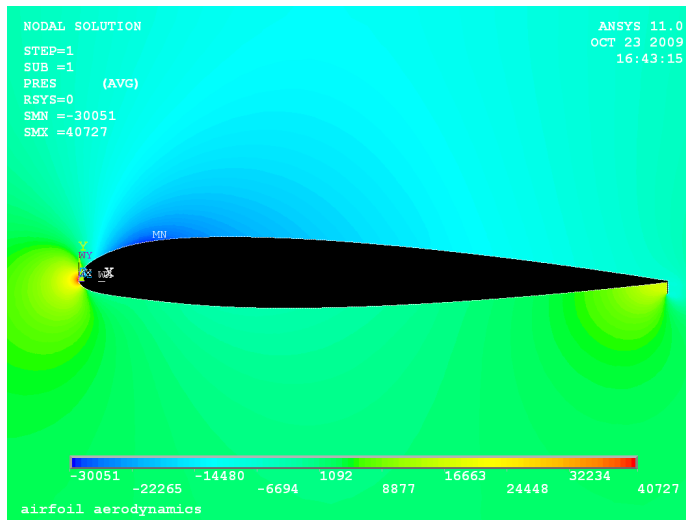


FIGURE 8. PRESSURE DISTRIBUTION AROUND THE PROFILE WITH A FULLY DEPLOYED GURNEY FLAP.

A steady state CFD simulation was performed on a single blade using the ANSYS finite element package. The pressure around the Gurney flap was computed for various angles of the Gurney flap for a profile angle of attack of 20 degrees. Fig. 8 shows the pressure distribution around the NACA23012 profile with a Gurney Flap. The airspeed chosen is the airspeed at the tip of the blade not considering any motion of the rotorcraft. This speed is 214 m/s. The speed encountered by the actual system is very likely to be lower because it would not be mounted at

the end of the blade. Complex phenomena such as blade vortex interaction are not taken into account in this preliminary analysis. The aim is to get an upper bound for the actuator selection.

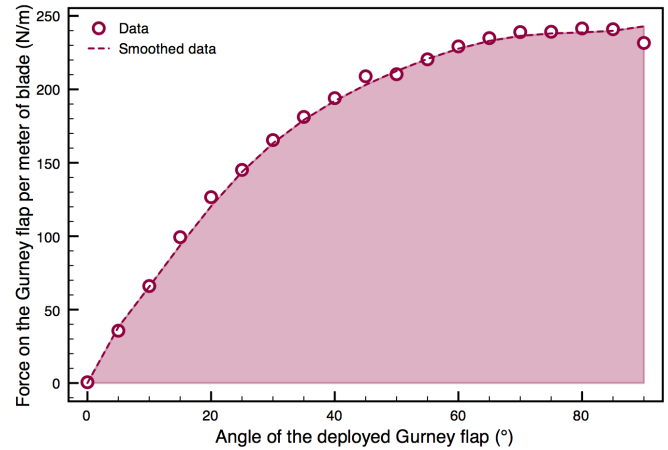


FIGURE 9. FORCE APPLIED ON THE GURNEY FLAP PER METER OF WINGSPAN VERSUS ITS DEPLOYMENT ANGLE

The force applied by the airflow on the flap is calculated from the pressure distribution for each deployment angle considered as shown in Fig. 9. After integration, the mechanical energy required to deploy the Gurney flap counter the airflow is 3.6 Joules, assuming the deployment of the flap by means of rotation around the wing tip. This value has been used for the selection of the actuators of this specific application.

Results

The three control strategies mentioned in the Gurney flap concept part have been examined. Neglecting the dynamic effects of the Gurney flap deployment, the energy estimation for the three cases is the same. The selection is therefore done on the required deployment time where Fig. 5 is used to determine the most weight-efficient solution and on the number of actuators required. The results are presented in Tab. 2.

Flight configuration The best actuator for this is the piezoelectric stepped linear actuator which is capable of delivering a large mechanical energy per weight but is not capable of delivering that mechanical work within a short time.

Active revolution control Although being a promising technology, ultrasonic piezoelectric actuators cannot deliver as

TABLE 2. TABLE PRESENTING THE ACTUATION SOLUTION SELECTED AFTER APPLYING THE SELECTION PROCESS.

Concept	Motion duration	Extra weight per meter of blade	Maximum power per meter of blade
Flight configurations	20 s	0.6 kg	24 W
Active control	6.6 ms	1.9 kg	112 W
Vibration control	30 ms	1.9 kg	448 W

much work in a short time as stack actuators. Stack actuators appear to be the most capable solution here.

Active vibration damping In this case again, the stack actuator is the best solution besides a less demanding time constraint. The power is more important than for the active revolution control concept because the power consumed by a stack actuator depends on the number of cycles performed by the actuator per blade revolution.

FUTURE WORK AND CONCLUSION

A database was created with actuator references from Physik Instrumente, Piezo Mechanik, New Scale Technology and Smart Materials. The next step consists in the research of mechanisms to convert the mechanical work available by the selected actuators into actual motion. The first design has considered the Gurney flap as a conventional flap. Other options involve mechanisms for a cross-flow deployment [11, 14]. Although the forces required to deploy the Gurney flap are greatly reduced, it is impossible to place the Gurney flap close to the trailing edge of the profile to fully benefit of the Gurney flap aerodynamic enhancement [13]. Additional constraints will rise, especially on the dimensions of the actuators and on the stresses they are going to experience depending on their position within the blade.

The construction of a demonstrator is scheduled within the Green Rotorcraft project. The actuator mechanism needs to be adapted to fit within the demonstrator. Designing such a mechanism will show the relevance of the actuator selection.

The stack actuators highlighted as the best solution for the most demanding control strategy could also be used for the other ones. It is possible to envision a combination of control strategies

to enhance the aerodynamic performance while fine tuning the profile for specific flight conditions.

Advanced control of the Gurney flap would allow not only an increase of the performance of the rotor blade but also a fine tuning of the aerodynamic performance for various flight conditions.

The selection process and the actuator database used for this example could be applied to any application requiring an efficient actuation solution.

ACKNOWLEDGMENT

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