Chapter 25

Smart Actuation for Helicopter Rotorblades

A. Paternoster, R. Loendersloot, A. de Boer and R. Akkerman

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/51438

1. Introduction

The first helicopter to successfully achieve stable hovering flight and decent forward flight performances was demonstrated in 1935 and is attributed to Louis Breguet and René Dorand [22] as shown in Figure 1. Their patent details the two coaxial counter-rotating blades which resulted in an unprecedented level of performance, stability and safety for a rotorcraft [7]. This success was soon matched by other helicopter pioneers. Henrich Focke at the Focke Wulf Company and Juan de la Cierva within the Weir company demonstrated the hovering capabilities of a side by side rotor configuration in 1936 and 1938 respectivelly [3, 22, 47]. In 1940 Sikorsky flew a single rotor helicopter configuration with three auxiliary tail rotors to negate the counter-torque effect [22, 51] as shown in Figure 2. Sikorsky refined his design and produced a significant number of helicopters during the war, some of which were used during World War II in the Pacific [22]. After the war, this configuration was widely adopted by the emerging industry. Today almost every helicopter uses this single-rotor configuration.

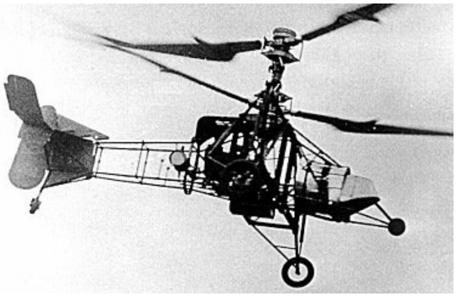

Figure 1. Picture of the Breguet-Dorand helicopter.

These successes and the birth of the modern helicopter are the results of the convergence of technology, knowledge and experience. Before Breguet and Sirkorsky flights, many aircraft enthusiasts and pioneers built contraptions that merely hopped a few meters. Successful machines came when mature engine and mechanical technologies met scientific

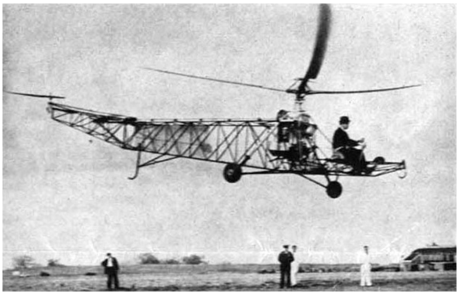

Figure 2. Picture of Sikorsky VS300 prototype.

study and a good understanding of the specificity of helicopter aerodynamics. In the 1930s, engines were refined by the booming aircraft industry. They were delivering unprecedented power-to-weight ratios [47], enabling helicopters to sustain more efficiently hovering flights. The counter-torque effect was tackled in many ingenious ways. Breguet used two counter-rotating shafts on the same axis to balance the torques. Other concepts used two and even quad-rotor configurations to balance this effect [3, 22, 34]. Patents show the level of engineering that was achieved to overcome the complexity of the various designs. Nevertheless, compelling forward flight performance came when the airflow asymmetry on the rotorblades was balanced.

When hovering, each blade experiences the same distribution of incident airflow velocity. This distribution is linear and proportional to the blade radius and the blade rotation. The lift generated by each blade can be estimated using the lift formula

$$L = \frac{1}{2}\rho v^2 A C_l \quad (1)$$

where L is the lift force on the rotorblade profile, ρ is the density of the air, v is the velocity of the airflow on the profile, A is the surface of the profile considered and C_l is the lift coefficient. The lift coefficient is function of the pitch angle of the blade. Assuming the helicopter is hovering, the pitch angle and the airspeed distribution are the same regardless of the position of the blade relative to the helicopter. The lift force of each blade is obtained from the integration of the lift formula along the length of a helicopter blade R

$$L = \int_0^R \frac{1}{2}\rho C_l (\omega r)^2 c dr \quad (2)$$

where c is the chord length of the blade profile and ω, the rotational velocity of the blade. After integration, we obtain

$$L = \frac{1}{6}\rho c C_l \omega^2 R^3 \quad (3)$$

As soon as the helicopter goes forward an extra velocity component is added to the velocity profile [6, 48]. We can distinguish the retreating side where the blade motion points in the opposite direction of the helicopter motion and the advancing side where the blade motion is in the same direction as the helicopter motion alike shown in Figure 3. Therefore, the incident airflow speed is increased on the advancing side and reduced in the retreating side. This asymmetry causes a difference in the lifting capabilities of the two helicopter sides. The lift for a blade in the retreating side becomes

$$L = \int_0^R \frac{1}{2}\rho C_l (\omega r - v_n)^2 c dr \tag{4}$$

where v_n is the component of the helicopter velocity normal to the blade and ω is the rotational velocity of the blade. After integration, we obtain

$$L = \frac{1}{2}\rho c C_l \left(\frac{1}{3}\omega^2 R^3 - \omega v_n R^2 + v_n^2 R\right) \tag{5}$$

The difference between equations 3 and 5 gives the loss of lift Δ on the reatreating side due to the helicopter overall motion

$$\Delta L = \frac{1}{2}\rho c C_l \left(v_n^2 R - \omega v_n R^2\right) \tag{6}$$

The quadratic relation between the loss of lift on the retreating side and the helicopter forward motion velocity shows the importance of this phenomenon. Reverse flow is another important consequence of the forward motion of the helicopter. It happens where the helicopter speed is larger than the velocity of the blade due to its rotation. At high speeds, this region can cover a significant portion of the blade, meaning most of the lift is generated by the outer part of the blade. A cyclic control input was the key to balance the lift. Breguet-Dorand aircraft as well as Cierva and Sikorsky helicopters used a swashplate to vary the pitch of each blade during its revolution [8, 22, 51, 52]. Modifying the pitch of the blade changes the angle of attack and thus the lift for various positions of the blade around the helicopter. The angle of attack is increased on the retreating side and decreased on the advancing side. The lift is therefore evened on the two sides of the helicopter. Other early rotorcrafts pioneer considered a change of the twist of the blade or the deployment of flaps at the trailing edge of the blade to control on the lift [22, 43].

Today, all helicopters use cyclic pitch control for tuning the lift as the blades rotate. But lift can only be maintained by improving the angle of attack up to the stalling point of the blade profile. The maximal speed of a rotorcraft is therefore limited to the amount of lift the rotorblade can develop on the retreating side. In the case of rotorblade, the stall is dynamic, due to the unsteady nature of the flow. The vertical motion of the blade along with time-dependent pitching moments allows the angle of attack of the blade to exceed the quasi-static stalling angle of the profile. This favourable effect is followed by the development of vortexes close to the leading edge which can move towards the trailing edge causing large downward pitching moments [6, 22, 48]. Consequently, the rotor performance and the stability of the aircraft are reduced.

To further improve the helicopter blade performance, adaptive blade concepts are studied. The aim is to adapt the aerodynamic characteristics of the blade to maximise performance on both the advancing and the retreating side of the blade and improve the stall performance for large angles of attack. These systems range from morphing and changing the shape of a full blade profile to smaller devices acting on the boundary layer of the airflow to control its separation.

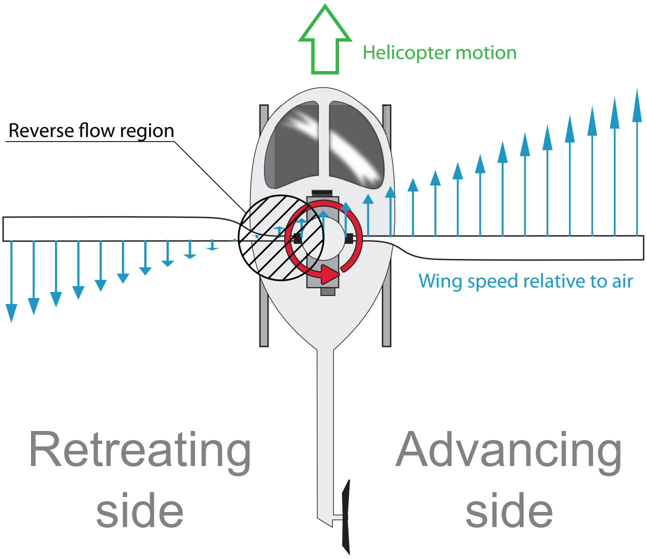

Figure 3. Helicopter in forward flight.

2. Capabilities of smart systems in rotor blades

Smart-blades can greatly enhance the performances of modern helicopters. Local modifications of the aerodynamic characteristics of a blade profile provide an optimised performance across the full blade revolution. The control of such systems conditions its capabilities and usage. In the introduction, focus was made on the lift characteristics of the retreating side. Most concepts improve directly the lift of the profile at fixed angle of attack. Other systems increase the efficiency of the helicopter improving the stall behavior of the profile or by reducting the vibration on the rotor. Vibrations decrease an helicopter blade efficiency, influence the dynamic stall and generate noise. The latter is a great concern for helicopter operating in a urban environment.

2.1. Flaps

Flaps on helicopter blades are not designed as a primary control surface like in airplanes. They act as a secondary control to improve the efficiency of the rotorblade by modifying the lift of the profile and by reducing vibrations on the rotor.

2.1.1. Active trailing edge flaps

Active trailing edge flaps are flaps situated at the trailing edge that actively modify the rotorblade performance. A schematic of a trailing edge flap for a helicopter blade taken from Koratkar [28] is shown in Figure 4. Although research has been conducted to study the possibility to use them for control in a swashplateless configuration [49], most of the studies focus on their ability to reduce the vibrations of helicopter blades [1, 15, 18, 27, 28, 35, 62]. The angle of the flap directly relates to a change of the bending of the blade during rotation

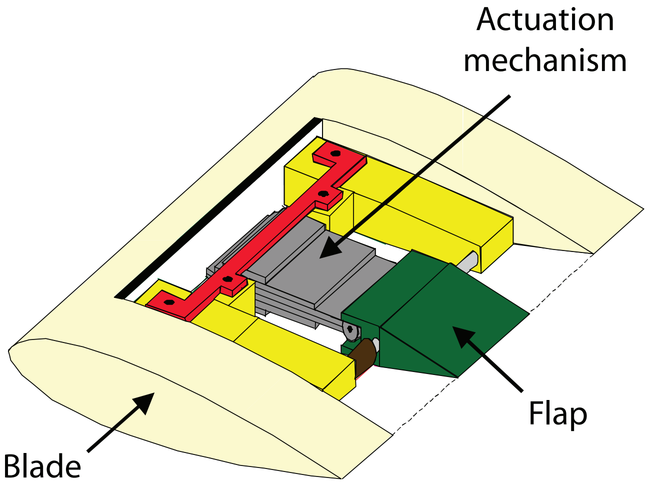

Figure 4. Schematic of a trailing-edge flap and its actuation system (adapted from Koratkar paper [28]

[18, 28]. The position of the flaps along the rotor has a great influence on the final performances of the mechanism. Although the optimum positioning of the flap depends on the application objective, studies show that multiple flaps achieve a better vibration reduction that a single flap [18, 27, 62]. These flaps only need a few degrees of deflection to affect the system dynamics [15, 28]. Loads on the helicopter rotor are function of the rotational frequency of the blade. The largest loads happens at 1, 2, 3 and 4 times the rotational frequency of the blade [6]. Therefore the flaps need to be actuated at similar frequencies to cancel undesired vibrations. With multiple flaps, the phase between the flaps is another key element. Under a suitable control authority, literature shows that the vibratory loads on the rotor can be reduced up to 80% [15, 18].

The amount of noise generated by helicopters is another important issue, especially because many helicopter missions involve flying over dense populated area. Noise generated by the helicopter blade comes mainly from the interaction between one blade and the vortexes generated by the previous blade [69]. This phenomenon is called blade-vortex interaction (BVI). Decreasing the effects of blade-vortex interaction can not only lead to a reduction in the noise emitted but also to a decrease in the power requirement. Active trailing edge flaps are actively studied to limit this effect by an individual control on each blade [1, 18, 69]. Controlling the trailing edge flap at 2 cycles per revolution (hereafter indicated as 2/rev) shows potential for consequent noise reduction [1].

2.1.2. The Gurney flap

The Gurney flap is a small flap deployed at 90 degrees at the edge of the trailing edge of the rotorblade, as shown in Figure 5. Typically its length is 2% of the chord length of the blade profile. The Gurney flap modifies the flow at the blade trailing edge and induces a low pressure zone which brings the separation point closer to the trailing edge [53]. The result is an increase of the lift over a large range of angles of attack with a small drag penalty [38, 53, 59,

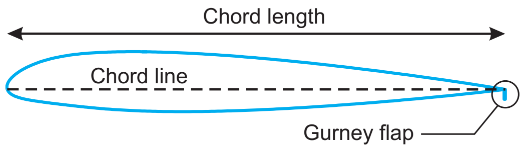

Figure 5. Sketch of a Naca 23012 profile with a 2% Gurney flap.

68]. Although the Gurney flap induces pitching moment, it provides a beneficial improvement of the efficiency of the rotorblade profile for the hovering situation [68]. In forward flight, the Gurney flap provides the blade with additional lift on the retreating side to balance the lift distribution [59]. For large forward velocity, the Gurney flap improves the airfoil behaviour in light stall conditions, which increases directly the flight envelope of a helicopter [68]. The behaviour of the Gurney flap is related to its length and placement. Studies about the length of the Gurney flap show an increase in drag and pitching moments with increasing lengths [38, 53, 63, 68]. Depending on the application, the Gurney flap length is limited to the point where these disadvantages outweigh its benefits in lift and stall characteristics.

Furthermore, the Gurney flap can have a positive effect on blade-vortex interaction. Similarly to a trailing edge flap, the Gurney flap acts on the blade mechanical behaviour [68]. Actuating the Gurney flap at 2/rev with suitable control would lead to a decrease in vibration and noise in a similar way than active trailing edge flaps [69].

2.2. Morphing blades

The idea behind morphing blades is to change the aerodynamic characteristics of the blade by a continuous change in its shape. This approach is inspired by the way birds and flying animals are modifying their wings to adapt to the various situations they encounter while flying. Most of these solutions involve a stiff structure that supports the loads and a flexible skin to keep the outer surface of the rotorblade without discontinuities.

2.2.1. Variable droop leading edge

The concept behind the nose drop is to advance the front part of the profile at an angle. It increases the profile as well as the curvature, as shown in Figure 6. The variable droop leading edge is used to alleviate the dynamic stall by ensuring that the flow passes smoothly over the leading edge for high angles of attack [32]. Although the lift is increased during the downward motion of the leading edge [32], the maximum lift is reduced by 10% [13, 21, 37]. More significantly, the drag and pitching moments are reduced by 50% [13]. The variable droop leading edge concept provides a decrease in helicopter vibrations and loads due to the suppression of dynamic stall within the retreating blade region. However, the helicopter maximum speed is reduced due to a decrease in lift when the droop nose is deployed. Therefore, the variable droop leading edge is studied in combination with the Gurney flap to negate the lift reduction [14]. This concept can also be applied to reduce the noise generated by a helicopter [9].

Figure 6. Sketch of the VR-12 profile used for wind tunnel testing at NASA Research Center from Lee paper [32].

2.2.2. Camber change

Changing the camber of a profile increases its lift for the same chord length [54]. The benefit is a larger flight envelope of the helicopter by improving the lift on the retreating side of the rotorcraft in the same way than the Gurney flap concept. Once again harmonic actuation at 2/rev could reduce the noise and the vibratory loads on the rotor, improving the rotor performance [18, 20]. Most studies on this concept consider the plane as the main application, envisioning morphing flaps as a main control surface [39].

2.2.3. Active-twist

Among early helicopter prototypes, some developer considered cyclic twist control [43] for changing the lift of the rotating blades. The idea behind active twist is to modify the twist and the torsional stiffness of rotating blade not only to improve the lift and the global helicopter performance but also to actively damp vibrations. Early experiments on active twist involved changing the twist of the helicopter blade at the root of the blade [2]. Later experiments used a distributed actuation actuation system to modify the blade twist [46, 50, 58, 66]. In a similar manner to the active trailing edge, the placement and the number of actuators modify the amount of vibration that are reduced. Thakkar study shows that up to 69% of reduction in vibrations can be achieved with the actuation of two sections [58]. Wind tunnel tests on a helicopter model demonstrated a 95% reduction in vibrations [66]. In the tests, each of the four blades mounted on the helicopter model was equipped with 24 actuators bonded onto the skin of the blade. Although only up to 1.4 degree of change in the pitching angle of the blade was achieved, torsional vibrations at 3/rev and 5/rev were successfully damp. In addition, the noise generated by the blade-vortex interaction can be reduced by up to 90% using an appropriate control of the blade twist [5].

2.2.4. Extended trailing edge

The amount of lift a profile can deliver depends on its chord length. For the same geometry, the lift is proportional to the blade surface area as shown in equation 1. Therefore, extending the chord length of a profile increases the lift generated. Studies on an extended trailing edge active blade have shown an increase in the lift without significant increase in the lift-to-drag ratio [36].

2.3. Active flow control

Active flow control devices take another approach to improve the lift on a profile. Instead of modifying the airfoil geometry to act on the flow, they directly modify the air flow by re-energising the boundary layer on the top of the profile with a high speed jet. Such a flow is called a synthetic jet. The objective is to bring the separation point closer to the trailing-edge and therefore improve laminar flow over a larger portion of the airfoil [23]. Actuators for this application are placed inside a cavity which has a tiny opening [26] or a full slot perpendicular to the flow direction on the top part of the profile [67]. Figures 7 and 8 show these two types of synthetic jet actuator.

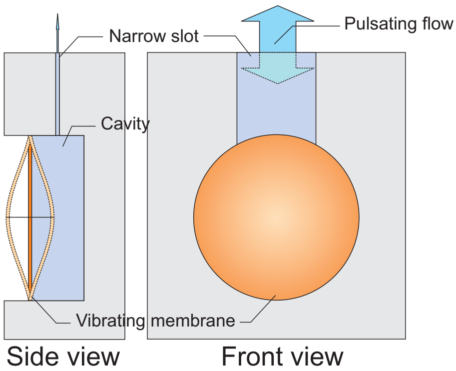

Figure 7. Sketch of a slot synthetic jet system.

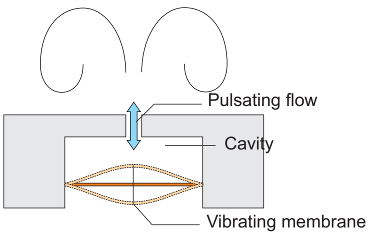

Figure 8. Sketch of a synthetic jet system with a circular orifice.

Wind tunnel experimentations have shown that synthetic jets improve the aerodynamic performance when driven at a specific frequency [23]. Much better performance is obtained when the actuation mechanism is combined with sensors arrays before and after the position of the synthetic jet system [57]. The sensors monitor the instabilities that will trigger the flow transition and actuate the synthetic jet system so that it damped the instabilities delaying further the transition. The actuation frequencies are in the kHz range and are related to the airflow speed [10]. Most of the literature focuses on fixed wind tunnel test [10] but simulations show a potential increase in the maximum lift of an airfoil by 34% with an increase in the maximum stall angle of a profile [17]. These characteristics make synthetic jets system very promising for improving the characteristics of a profile for helicopter applications.

3. Challenges for smart-systems inside helicopter blades

Smart-systems need to answer challenges specific to the integration in helicopter blades. The combination of these challenges make smart-blade concepts very difficult to design.

3.1. Weight and space constraints

The weight and space are the main constrains in helicopter blades. Helicopter blades are designed to handle large centrifugal loads. The structural material takes most of the section of a rotorblade. Carbon fibre composites provide strength in the direction of the blade and reinforced layers give the blade impact resistance. The only space available is in the tail of the profile. Therefore, it is very difficult to integrate a system directly in the rotorblade skin for structural reasons. Concerning the weight, not only it cannot increase much, but its distribution in the profile should not affect the chordwise balance of the blade. Therefore, any weight added behind the aerodynamic centre needs to be compensated by an extra mass in the leading edge. For the whirl tower test of the SMART active flap rotor, weight was added in the leading edge to maintain the blade balance [55]. This constraint makes distributed and light systems like the active twist very relevant to maintain the distribution of mass along the profile chord. In comparison, the variable droop leading edge requires a very heavy mechanism to deform the leading edge of the profile that would change completely the weight distribution around the aerodynamic centre [29].

3.2. Mechanical constraints

Mechanical constraints are significant in a helicopter blade. The centrifugal loads are by far the main issue. The centrifugal loads come from the large rotational speeds of the blade. The centrifugal acceleration a is calculated with the following formula

$$a = \omega^2 r \tag{7}$$

where ω is the rotational speed of the blade in rad/sec and r is the position along the length of the blade. An 8m rotorblade rotating at 250rpm will generate close to 560g of acceleration at the tip. Because of the aerodynamics of an helicopter blade, the active system needs to be integrated near the tip of the blade where the centrifugal acceleration is the largest. The centrifugal loads resulting from the acceleration depend on the mass of the actuation system. Thus, a very light system does not lead to large loads. Some small actuation systems are very small and robust. The "Squiggle" linear drive motor, developed by NewScale technology, features a shock resistance of 2500g [40, 64]. For larger mechanisms most of the designs limit the load transfer along the blade [42, 55, 60]. Hence the design can be approximated to a bi-dimensional structure that is extended along the blade axis. For distributed systems that use patch actuators bonded onto the structure, like the active-twist technology developed by DLR, the actuators are being supported by the blade structure [46]. The main concern with these actuators is related to the deformation of the blade during its rotation. The peak strain

Active concept	Actuation frequency	Lifetime
Retreating side actuation	1/rev	66,460 hours
BVI noise	2/rev	33,230 hours
Vibrations	4/rev	16,615 hours
Flow control	2kHz	278 hours

Table 1. Comparison of the life time of an 10^9 cycles actuation mechanism in a 250rpm rotor blade system for various active control concepts. For the Active flow control system, the system is in operation only on the retreating side of the helicopter.

at the surface of the blade must not exceed the maximum strain of the actuator that will lead to breaking or debonding.

In addition to centrifugal loads, helicopter blades are subjected to large vibrations. In the most common configuration, helicopter blades are attached to the rotor by a joint that allows rotations with three degrees of freedom. The motions of the blade relative to the joint are defined as flapping, leading-lagging and feathering. Each of these motions are associated with one degree of freedom. While the blade is rotating the cyclic loads excite each degree of freedom causing vibrations at frequencies that are multiples of the blade rotational frequency [6, 48]. As a consequence, the design of a mechanism must address the resulting loads. Moreover, these loads constrain the use of mechanical elements like hinges or friction surfaces that will tend to jam and fail.

3.3. Reliability and environmental constraints

Any mechanism built in a commercial aircraft must comply to a set of rules to ensure the reliability of the system after a large number of actuation cycles, as well as the safety and the integrity of the aircraft in the event of a failure. Helicopter blades in a general purpose helicopter are designed for 10,000 flight hours [30]. Although composite blade design can handle even more loading cycles, manufacturers specify helicopter blades to be maintained and replaced on a much shorter basis [25, 30]. Actuation mechanisms for the active blade need to have a design life superior to the blade design life and have to maintain performances through their operational life. In aircrafts, hydraulic and pneumatic mechanisms are widely used due to these concerns. They are especially utilized for moving control surfaces that must satisfy a reliability requirement of 10^{-9} failure per hour and their performance is hardly affected even after a large number of cycles. It is only recently that electrical mechanisms have reached equivalent levels of safety and have been used to control control-surfaces in aircraft [4].

The reliability of the actuation system is also depending a lot on the application type. For alleviating the lift asymmetry on the retreating side, the mechanism performs a cycle once per revolution. This figure is to be compared with an actuation system for actively cancelling vibrations that need to operate at 2/rev and 4/rev or even at 5/rev in the case of torsional frequencies [18, 66]. Table 1 shows the various expected life time for a mechanism that has been design for 10^9 cycles in the case of various active blade concepts for a 250 rpm rotor system.

Although all the cases satisfy the 10,000 hours of operating life, the vibration damping case shows that a high quality actuation system certified for 10^9 has an operating life close to that of the blade. Therefore, it would be very difficult to qualify an actuation system for damping vibration at 6/rev. For flow control devices, very much higher quality actuators are required to be certified for active flow control.

Finally, helicopters need to operate under a large range of environmental conditions. Blades are certified to perform over a large temperature range: from high altitude freezing conditions to high temperatures and with very high moisture content. It is therefore very difficult to design a fail-safe mechanism in these conditions, especially on small helicopters which do not have a de-icing system. Furthermore, some specific environments subject helicopter components to very difficult conditions such as sea and desert environments where corrosion and erosion are important matters.

3.4. Failure

In addition to being designed to exceed the life time of the blade, the active blade actuation system must also be developed not to influence the performance of the helicopter in the event of a failure. For distributed systems like the active-twist, if the patch actuators are not working, they will not reduce the performance of the blade profile. On the contrary, for the Gurney flap, the variable droop leading edge and the trailing edge active blade concept, in the event of a jamming, the blade profile will be modified during the full rotation of the rotor blade. Hence, care must be taken to make sure the helicopter is stable and able to be controlled with a modified profile. Furthermore, in the event of a power failure, the mechanism must go back to its initial state. This can be done by prestressing the mechanism or making sure that the aerodynamic loads are sufficient to bring the mechanism back to its inactive state.

3.5. Power requirement

To operate an actuator in a rotorblade, power needs to be transfered from the helicopter to the blades. Electrical, pneumatic and hydraulic power can be provided to a rotating blade by the use of specialized rotor mounts which add to the complexity of the rotor hub [24]. The type and the amount of power that can be drawn for an actuation system is a serious limitation to some active system. Large helicopter blades include a de-icing system for high altitude flight. Such a system draws up to 1kW of electrical power that is transfer to each blade. This gives a good estimation of the power available for an electrical actuation system.

3.6. Complexity of the system

Developing smart systems for helicopters is tremendously complex due to the number and the variety of the domains involved. For designing an active helicopter rotorblade, knowledge is required not only in aerodynamics and mechanics, but also in control, material science and electronics. Simulating for validating a concept, selecting of a suitable actuation technology and defining an application demand skills in all these domains. In order to move from research and laboratory experiments to flying prototypes and commercial products, the European union has created a Consortium within the Clean Sky Joint Technology Initiative to bring various research partners together. The Green Rotorcraft Consortium, among its lines of research, manages the evaluation of the Gurney flap technology to improve helicopter performance and noise reduction with both academic and industrial partners [16].

4. Piezoelectric actuators for smart-rotor blade systems

Many actuation technologies are available to actuate every smart blade concepts. Among them, piezoelectric actuators have a tremendous potential to meet and exceed the various requirements of these specific applications. This section focuses on piezoelectric actuators and their potential for the actuation of active systems for helicopter blades.

4.1. Piezoelectricity

Piezoelectric materials are materials that have the property to convert mechanical energy into electrical energy. When such a material is subjected to a strain, an electrical charge is created inside the material. This property is called the direct piezoelectric effect. Additionally, when the material is subjected to an electrical field, it deforms according to the electrical field magnitude. This is called the converse piezoelectric effect. A piezoelectric material is characterized by the piezoelectric strain constant d_{ij} which relates the strain to the electrical field. The subscript i indicates the direction of the applied electrical field and the subscript j indicates the direction of the deformation. Prior to be used, the piezoelectric material is poled. Conventionally the poling direction is along the vertical axis (3-axis) as shown in Figure 9. When an electrical field is applied in the poling direction, the material is contracting in that direction and extending in other directions (1- and 2-axis). Changing the direction of the electrical field will result in a contraction along the 1- and 2-axis and extension along the vertical axis. To quantify these piezoelectric effects, the direct and shear strains are related to the electrical field by the following constants: $d_{31} = d_{32}$, d_{33}, $d_{25} = d_{15}$. Equation 8 is the equilibrium equation that relates the electrical field E to the strain and shear components of the material (ε and γ) when no mechanical constraint is applied on the material.

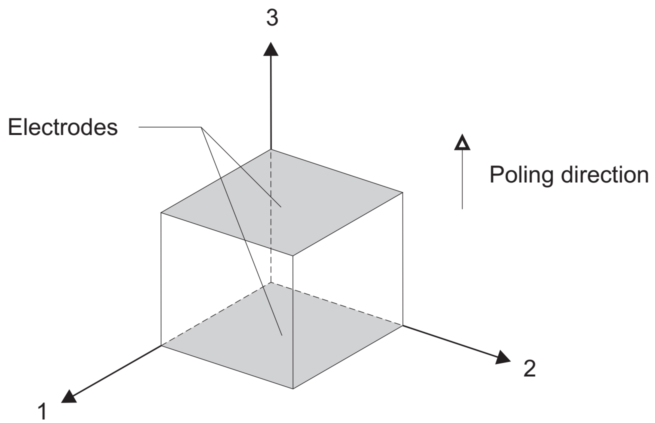

Figure 9. Axis reference system for piezoceramic components.

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{pmatrix} = \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{25} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \times \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \tag{8}$$

Name	d_{31}(m/V)	d_{33}(m/V)	e_{33}	CT(°C)	ρ(kg/m^3)	S_{33}(m^2/N)
PZT-SP4	-1.23e-10	3.1e-10	1300	325	7500	1.81e-11
PZT-5A1	-1.85e-10	4.4e-10	1850	335	7500	2.07e-11
PZT-5H	-2.74e-10	5.93e-10	3400	193	7500	2.083e-11
PZT-PSt-HD	-1.9e-10	4.5e-10	1900	345	7500	2.1e-11
PZT-PSt-HPSt	-2.9e-10	6.4e-10	5400	155	8000	1.8e-11
PZT-PIC-255	-1.8e-10	4.0e-10	1750	350	7800	2.07e-11
PZT-PIC-151	-2.1e-10	5.0e-10	2400	250	7800	1.9e-11

Table 2. Table of some piezoceramic materials. PZT-SP4 and PZT-5A1 are from Smart-Material Company. PZT-5H is taken from Chopra review on actuators [15]. PZT-PSt-HD and PZT-PSt-HPSt are from Piezomechanik Company. Finally, PZT-PIC-255 and PZT-PIC -151 are from Physic Instrumente Company [45].

Consequently, the knowledge of the 3 constants d_{31}, d_{33} and d_{15} is sufficient to fully characterize the electromechanical properties of a piezoelectric material. A deformation along the 1- and 2-axis which is characterized by the d_{31} coefficient is called the d_{31} effect and a deformation along the 3-axis is called the d_{33} effect as the d_{33} coefficient characterizes this deformation as shown in Figure 10.

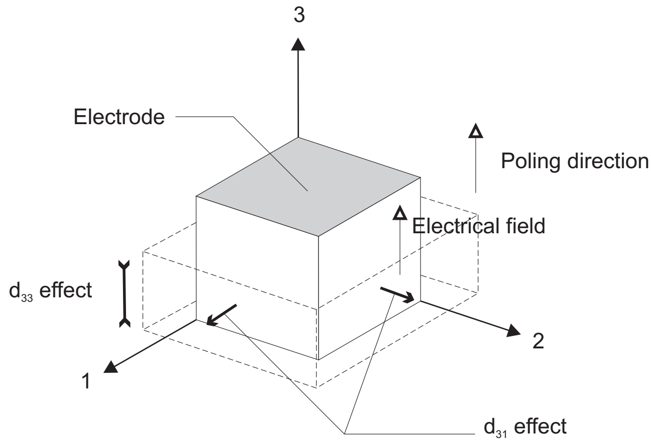

Figure 10. Piezoelectric effects for an electrical field applied in the poling direction.

4.2. Types of piezoelectric actuators

Although some polymers can exhibit piezoelectric characteristics [61], most piezoelectric actuators are based on piezoceramics. Piezoceramic materials have been widely studied and used since the second world war to manufacture ultrasonic transducers. Table 2 lists some piezoceramics available from manufacturers.

4.2.1. d_{31} effect actuators

Piezoceramic actuators using the d_{13} effect are based on the fact that a through-thickness electrical field will contract the material's width and length. The components manufactured using this principle are consequently laminates of fine piezoceramic sheets. Electrodes are bonded on the upper and lower faces of the piezoceramic patch. Applying a voltage through the patch's thickness causes a contraction in the plane of the patch as shown in Figure 11. These can be easily bonded or embedded inside a structure, thanks to their low weight and volume. Thus, they are mainly used to manufacture unimorph and bimorph structures.

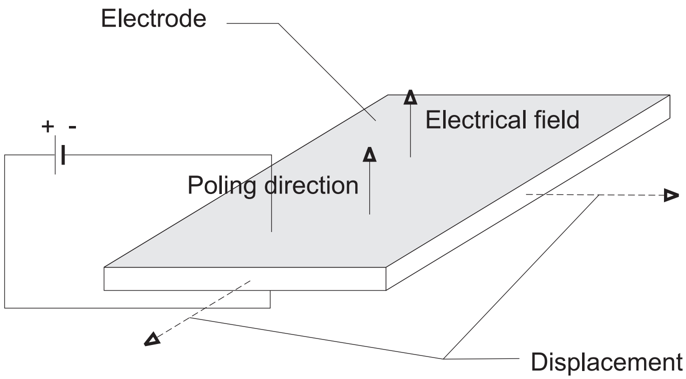

Figure 11. Principle of a piezoelectric laminar actuator

4.2.2. d_{33} effect actuators

Piezoceramic actuators using the d_{33} effect are based on the fact that a through-thickness electrical field will modify the material's thickness. Within piezoceramics, the d_{33} coefficient is always more important than the d_{31} coefficient, therefore using the d_{33} effect is preferable. Consequently, there are many types of actuators that try to take advantage of the larger d_{33} coefficient using various geometries.

- Stack actuator
  Stack actuators use the d_{33} effect to achieve deflection. They consist of multiple layers of piezoceramic plates separated by electrodes as shown in Figure 12. This configuration allows long elements to be made for higher displacement capabilities while high voltage is not needed to obtain high electrical fields if the piezoceramic layers are small enough between two electrodes. Stack actuators are capable of delivering higher forces than laminar actuators as they are fully using the highest strain coefficient available.
- Macro Fibre Composites (MFC) & Active Fibre Composite (AFC)
  Long piezoceramic components have better displacement capabilities. Active Fibre Composite (AFC) consists of piezo ceramic fibres embedded into a protective polymer substrate and poled into the fibre direction to use the highest strain coefficient. Interdigitated electrodes bonded onto the fibres ensure high electrical fields. The voltage required by these components depends on the fibre diameter and the distance between electrodes. Compared with laminar actuators, these components require less voltage to achieve the same force and displacement. Macro Fibre Composite exploit the same principles as AFC, except that they are made of fibres having an improved contact with electrodes, which plays an important role in the electrical field magnitude inside the material. Furthermore, those actuators are much more flexible than a strip made of the same material.

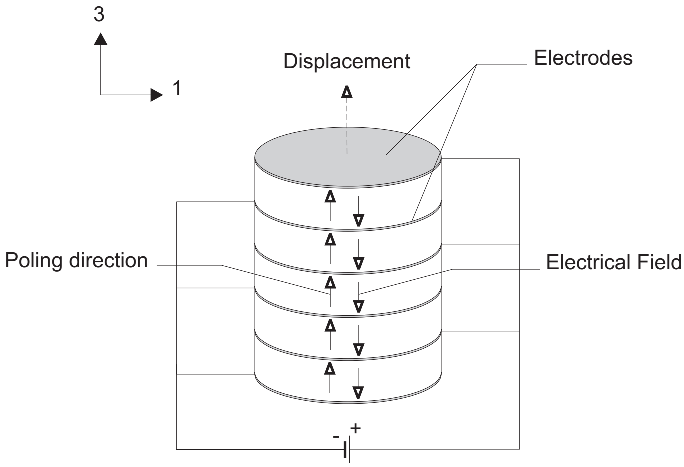

Figure 12. Principle of a piezoceramic stack actuator.

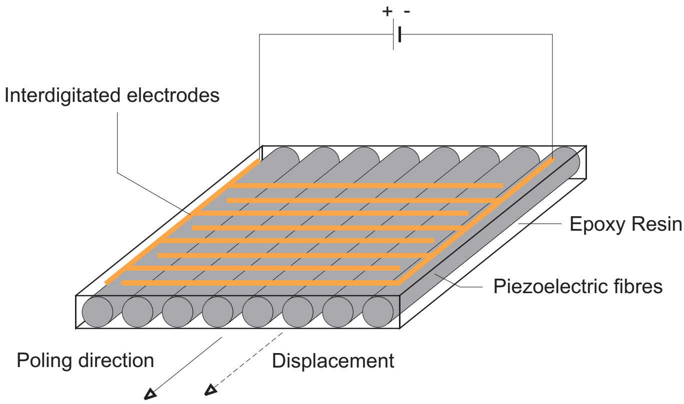

Figure 13. Sketch of an Active Fibre Composite (AFC) actuator.

4.2.3. d_{15} effect actuators

The d_{15} effect is a shearing effect. The material shears in the 3-1 or 3-2 plane when an electrical field is applied in the 1-axis or 2-axis respectively, perpendicular to the poling direction as shown in Figure 14.

The d_{15} shearing effect can be used to manufacture a tube actuator that twists when actuated as shown in Figure 15. Centolanza has discussed the manufacturing of an induced shear actuator and its testing [12]. Kim has tested the same component with feedforward control and pointed out fatigue and heating issues [27]. Their conclusions are that such an actuator is a promising option and more studies of the piezoceramic material would improve their models accuracy.

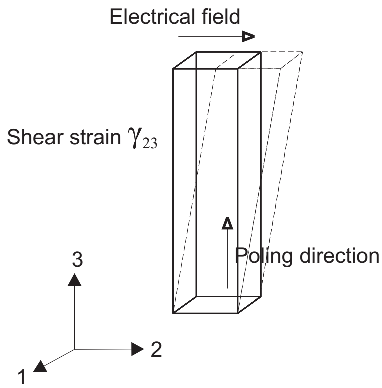

Figure 14. d_{15} effect in piezoceramics.

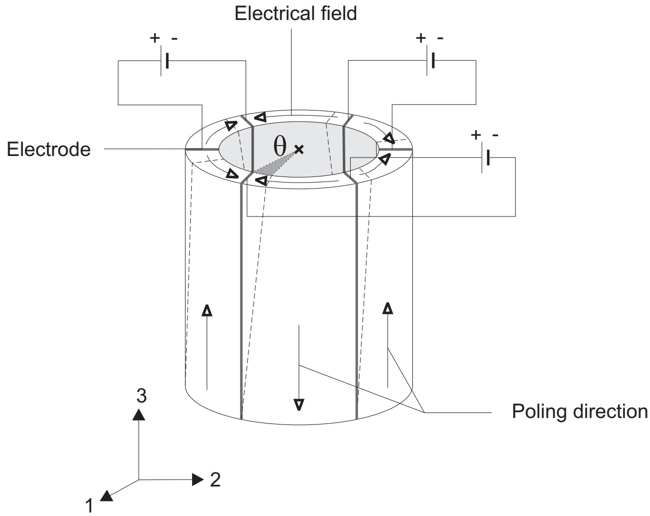

Figure 15. Twisting motion for the d_{15} effect in a shear tube actuator.

4.3. Performances

4.3.1. Block force and free displacement

The performance of piezoelectric actuators is evaluated in block force and free displacement. The block force is the maximum force the piezoelectric actuator can deliver when clamped. The free displacement is the displacement achieved by the actuator when no force is applied on it. These two parameters depend on the values of the piezoelectric strain coefficient, the electrical field inside the material and the geometry of the actuator. For a d_{31} patch actuator the free displacement Δ and the block force F_{block} can be directly derived from the Equation 8.

$$\Delta = d_{31} L \frac{V}{t} \tag{9}$$

where d_{31} is the piezoelectric strain coefficient, L the length of the actuator, V the applied voltage and t the distance between the two electrodes.

$$F_{block} = \frac{d_{31}AV}{S_{11}t} \tag{10}$$

where A is the cross-section area of the actuator, t the distance between two electrodes and S_{11} the compliance in the plane of the actuator.

Piezoelectric actuators provide large blocking forces but only very low displacements. Therefore, typical mechanisms that involve piezoelectric components contain systems to amplify the displacement of the actuator. The amplification can be achieved by the use of level arms or by the integration of the piezoelectric component in a structure providing that amplification. Cedrat Technologies develops these systems based on stack actuators [11, 44].

4.4. Bandwidth

The first widespread use of piezoelectric actuators was for manufacturing acoustic sources for sonar because of their large actuation frequency bandwidth. Overall, piezoelectric actuators have a very small actuation time and can achieve large motion speed and acceleration. Cedrat Technologies manufactures actuators with a response time below 1ms [11]. Moreover, the typical resonance frequency for piezoelectric actuators is in the kHz range, leaving a very comforting margin for structural applications [11, 45].

4.5. Power consumption and voltage

The power consumption of piezoelectric actuators depends on the type of actuation. Integrated inside an electrical circuit, a piezoelectric actuator behaves like a capacitor. Under harmonic actuation, the energy required to charge the piezoelectric actuator can be recuperated in the system for the next charge. When fast positioning is required, the electrical components which drive the piezoelectric actuator must be able to provide large currents. For the discharge, the circuit and its components must be able to dissipate quickly the energy stored in the piezoelectric. Therefore, active systems using harmonic actuation only need around 100W in operation, while a fast actuation system requires close to 1000W of power depending on the actuation profile. However, the main problem is not the amount of electrical power required but the time during which the power is required.

4.6. Reliability and operational environment

Piezoelectric actuators are very reliable and can perform a large number of cycles under good operating conditions. For instance piezoelectric stack actuators manufactured by Physik Instrumente feature 10^9 cycles [45]. Cedrat technologies is developing high end actuators with 10^{10} cycles before failure [11]. Furthermore, piezoelectric actuators can operate in very harsh environments. Physik Instrumente provides piezoelectric stack actuators capable of operating in cryogenic environments [45]. Moreover, piezoelectric actuators can operate at high temperatures as long as the Curie temperature is not reached. The Curie temperature is the temperature at which the piezoelectric material looses its electro-mechanical coupling and this temperature is usually higher than 200°C as shown in Table 2.

4.7. Applications

The relevance of piezoelectric actuators for active blade systems comes from the large specific work they can output [41] while being small and easily integrable. Moreover their reliability makes them suitable for safely powering mechanisms in smart blade concepts.

Many actuation systems for the active trailing-egde rotorblade are actuated using amplified stack actuators [33, 44, 56]. Other designs use piezoelectric patch actuators bonded onto a beam [28] or piezoelectric shear actuators built as a torsional actuator as shown in Figure 15 [12].

Some studies on the design of airfoils with controllable camber involve stack actuators inside a structure that convert and amplify the motion into a change of curvature of the airfoil [19, 20].

For the deployment of the Gurney flap at the trailing edge, bimorph piezoelectric actuation mechanisms are being studied [59], as well as more complex structures to amplify the displacement of piezoelectric patch actuators and MFCs [42]. AFC and MFC actuators have also been tested successfully for the active-twist application [65]. They provide distributed strain over all the rotorblade surface to successfully twist the blade under operating conditions [46, 50].

Research on flow control systems has considered piezoelectric diaphragms to deliver enough airflow speed for synthetic jets and achieve proper flow control [31, 67].

5. Conclusion

Today's helicopters are the results of some tremendous work and collaborations in mechanical engineering and aeronautics. The first successes came from inventors that could understand the complexity of a rotating lift surface while designing advanced mechanical mechanisms. To further improve today's helicopters, research is focussing on active blade systems to adapt the aerodynamic properties of the blade to the local aerodynamic conditions. Two aspects are especially studied: enhancing the lift on the retreating side and alleviating the large vibrations in the rotor. Both these aspects will provide improvements on the helicopter performances. Besides the efficiency of the rotor system, the objective is to push the flight envelope of these aircrafts and to make them faster, smoother and quieter.

Many active concepts are being studied but they all face a large number of challenges to be successfully integrated within a helicopter blade. The rotation speed generates critical loads on the blade and any system within it. With the helicopter blade being the component providing both lift and control in a helicopter, any mechanism influencing its behaviour is required to be durable, reliable and safe. Actuation of the active system is the most critical aspect of a smart adaptive blade. Piezoelectric actuators have the potential to provide compelling actuation for these systems. They are actively tested for many of these concepts. Their toughness, size and reliability make them especial candidates for delivering the required mechanical power.

The key aspect of helicopter progress remains in the collaboration between partners from various domains, combinig different skills and expertise, to answer these challenges and develop tomorrow's aircrafts.

Acknowledgements

This project is funded by the European Union in the framework of the Clean Sky program - Green Rotorcraft.

Author details

Paternoster A.
Chair of Applied Mechanics, Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands
Chair of Production Technology, Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands

Loendersloot R. and de Boer A.
Chair of Applied Mechanics, Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands

Akkerman R.
Chair of Production Technology, Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands

6. References

[1] Altmikus, A., Dummel, A., Heger, R. & Schimke, D. [2008]. Actively controlled rotor: aerodynamic and acoustic benefit for the helicopter today and tomorrow, *34th European Rotorcraft Forum*, Liverpool.
[2] Barrett, R. & Stutts, J. [1997]. Design and testing of a 1/12th-scale solid state adaptive rotor, 491.
[3] Bennett, J. [1944]. Helicopter and Gyroplane, *US patent 2,344,967* .
[4] Bennett, J., Mecrow, B., a.G. Jack, Atkinson, D., Sheldon, S., Cooper, B., Mason, G., Sewell, C. & Cudley, D. [2005]. A prototype electrical actuator for aircraft flaps and slats, *IEEE International Conference on Electric Machines and Drives, 2005.* pp. 41–47.
[5] Booth, E. & Wilbur, M. [n.d.]. Acoustic Aspects of Active-Twist Rotor Control, *Journal of the American Helicopter Society* 49(1): 8.
[6] Bramwell, A., Done, G. & Balmford, D. [2000]. *Bramwell's Helicopter Dynamics*, Elsevier.
[7] Breguet, L. [1933]. Revolving Supporting Surfaces, *US Patent 1,919,089* .
[8] Breguet, L. [1935]. Flying machine having revolving supporting surfaces, *US Patent 1,986,709* .
[9] Breitbach, E. & Büter, A. [1996]. The main sources of helicopter vibration and noise emissions and adaptive concepts to reduce them, *Journal of Structural Control* 3(1-2): 21–32.
[10] Cattafesta, L., Song, Q., Williams, D., Rowley, C. & Alvi, F. [2008]. Progress in Aerospace Sciences Active control of flow-induced cavity oscillations, *Progress in Aerospace Sciences* 44: 479–502.
[11] CedratTechnologies [2012]. CEDRAT TECHNOLOGIES: Innovation in Mechatronics, *www.cedrat-technologies.com* .
[12] Centolanza, L., Smith, E. & Munksy, B. [2002]. Induced-shear piezoelectric actuators for rotor blade trailing edge flaps, *Smart Materials and Structures , February* .

[13] Chandrasekhara, M. [2007]. Compressible dynamic stall vorticity flux control using a dynamic camber airfoil, *Sadhana* 32(1-2): 93–102.
[14] Chandrasekhara, M. [2010]. Optimum Gurney flap height determination for lost-lift recovery in compressible dynamic stall control, *Aerospace Science and Technology* 14(8): 551–556.
[15] Chopra, I. [2002]. Review of State of Art of Smart Structures and Integrated Systems, *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Seattle, WA, AIAA Journal* 40(11).
[16] CleanSky [2012]. Clean Sky Joint Technology Initiative, *http://www.cleansky.eu* .
[17] Duvigneau, R. & Visonneau, M. [2006]. Simulation and optimization of stall control for an airfoil with a synthetic jet, *Aerospace Science and Technology* 10(4): 279–287.
[18] Friedmann, P., de Terlizzi, M. & Myrtle, T. [2001]. New developments in vibration reduction with actively controlled trailing edge flaps, *Mathematical and Computer Modelling* 33(10-11): 1055–1083.
[19] Gandhi, F. & Anusonti-Inthra, P. [2008]. Skin design studies for variable camber morphing airfoils, *Smart Materials and Structures* 17(1): 015025.
[20] Gandhi, F., Frecker, M. & Nissly, A. [2008]. Design Optimization of a Controllable Camber Rotor Airfoil, *AIAA Journal* 46(1): 142–153.
[21] Geissler, W. & Trenker, M. [2002]. Numerical investigation of dynamic stall control by a nose-drooping device, *Technical Report C*.
[22] Gordon Leishman, J. [2006]. *Principles of Helicopter Aerodynamics*.
[23] Greenblatt, D. & Wygnanski, I. [2000]. The control of flow separation by periodic excitation, *Progress in Aerospace Science* 36.
[24] Haber, A. & Jacklin, S. [2002]. Development, manufacturing, and component testing of an individual blade control system for a UH-60 Helicopter Rotor, *American Helicopter* .
[25] Head, E. [2012]. Blade Trouble | Vertical - Helicopter News.
[26] Hong, G. [2006]. Effectiveness of micro synthetic jet actuator enhanced by flow instability in controlling laminar separation caused by adverse pressure gradient, *Sensors And Actuators* 132(2006): 607–615.
[27] Kim, J.-S., Wang, K. & Smith, E. [2007]. Development of a resonant trailing-edge flap actuation system for helicopter rotor vibration control, *Smart Materials and Structures* 16(6): 2275–2285.
[28] Koratkar, N. & Chopra, I. [n.d.]. Wind Tunnel Testing of a Mach-Scaled Rotor Model with Trailing-Edge Flaps, *Journal of the American Helicopter Society* 47(4): 263–272.
[29] Kota, S., Ervin, G. & Osborn, R. [2008]. Design and Fabrication of an Adaptive Leading Edge Rotor Blade, *American Helicopter Society Annual Forum* .
[30] Kwon, J.-H., Hwang, K.-J., Kim, S.-S., Kim, P.-J. & Kim, C.-S. [n.d.]. Fatigue life evaluation in composite rotor blade of multipurpose helicopter, *Proceedings 6th Russian-Korean International Symposium on Science and Technology. KORUS-2002 (Cat. No.02EX565)*, IEEE, pp. 15–20.
[31] Lee, C., Hong, G., Ha, Q. & Mallinson, S. [2003]. A piezoelectrically actuated micro synthetic jet for active flow control, *Sensors And Actuators* 108(April 2003): 168–174.
[32] Lee, S. & McAlister, K. [1993]. Characteristics of deformable leading edge for high performance rotor, *AIAA Journal* 35.
[33] Lee, T. & Chopra, I. [2001]. Design of a piezostack driven trailing-edge flap actuator for helicopter rotors, *Smart Mater. Struct.* 10: 15–24.
[34] LePage, L. [1936]. Flight on rotating wings, *Journal of the Franklin Institute* 222.

[35] Lim, I.-G. & Lee, I. [2009]. Aeroelastic analysis of rotor systems using trailing edge flaps, *Journal of Sound and Vibration* 321(3-5): 525–536.

[36] Liu, T., Montefort, J., Liou, W., Pantula, S. R. & Shams, Q. a. [2007]. Lift Enhancement by Static Extended Trailing Edge, *Journal of Aircraft* 44(6): 1939–1947.

[37] Martin, P., McAlister, K. & Chandrasekhara, M. [2003]. Dynamic Stall Measurements and Computations for a VR-12 Airfoil with a Variable Droop Leading Edge, *Technical report*.

[38] Maughmer, M. & Bramesfeld, G. [2008]. Experimental Investigation of Gurney Flaps, *Journal of Aircraft* 45(6): 2062–2067.

[39] Monner, H. [2001]. Realization of an optimized wing camber by using formvariable flap structures, *Aerospace Science and Technology* 5: 445–455.

[40] NewScaleTechnologies [2012]. New Scale Technologies - precision motion for micro imaging and vision systems, *http://www.newscaletech.com/* .

[41] Paternoster, A., DeBoer, A., Richard, L. & Remko, A. [2010]. Actuators for Smart Applications, *Proceedings of the ASME 2010 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, Asme.

[42] Paternoster, A., Loendersloot, R., de Boer, A. & Akkerman, R. [2011]. Geometric Optimisation of Hinge-less Deployment System for an Active Rotorblade, *Proceedings of the ASME 2011 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, ASME.

[43] Pescara, R. [1923]. Screw propeller of helicopter flying machines, *US Patent 1,449,129* .

[44] Petitniot, J., Rochettes, H.-M. & Leconte, P. [2002]. Experimental assessment and further development of amplified piezo actuators for active flap devices, *Actuator*, number June, pp. 10 – 12.

[45] PhysikInstrumente [2012]. PI Leader in: Precision Nano-Positioning & Piezo Engineering, NanoAutomation, Piezo Stage, Hexapod, PZT, Piezo Actuator, Transducer: Sub-Nanometer Resolution, Metrology, Photonic Packaging Automation, Piezo Linear Motor, Steering Mirror, Translation, *http://www.physikinstrumente.com/* .

[46] Riemenschneider, J., Opitz, S., Schulz, M. & Plaß meier, V. [2010]. Active Twist Rotor for Wind Tunnel Investigations, *Proceedings of the ASME 2010 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, Vol. 2010, ASME, pp. 371–378.

[47] Rosen, K. [n.d.]. A Prospective: The Importance of Propulsion Technology to the Development of Helicopter Systems with a Vision for the Future. The 27th Alexander A. Nikolsky Lecture, *Journal of the American Helicopter Society* 53(4): 31.

[48] Saunders, G. [1975]. *Dynamics of helicopter flight*, Wiley-Interscience.

[49] Shen, J. & Chopra, I. [2004]. A Parametric Design Study for a Swashplateless Helicopter Rotor with Trailing-Edge Flaps, *Journal of the American Helicopter Society* 49(1): 43.

[50] Shin, S., Cesnik, C., Wilkie, W. & Wilbur, M. [2008]. Design and Manufacturing of a Model-scale Active Twist Rotor Prototype Blade, *Journal of Intelligent Material Systems and Structures* 19(12): 1443–1456.

[51] Sikorsky, I. [1943]. Helicopter and Controls therefor, *US Patent 2,318,260* .

[52] Sikorsky, I. [1947]. Helicopter rotor, *US Patent 2,627,929* .

[53] Singh, M., Dhanalakshmi, K. & Chakrabartty, S. [2007]. Navier-Stokes Analysis of Airfoils with Gurney Flap, *Journal of Aircraft* 44(5): 1487–1493.

[54] Stanewsky, E. [2001]. Adaptive wing and flow control technology, *Progress in Aerospace Sciences* 37(7): 583–667.

[55] Straub, F., Kennedy, D. & Stemple, A. [2004]. Development and whirl tower test of the SMART active flap rotor, *SPIE Conf. on Smart* .

[56] Straub, F., Ngo, H. T., Anand, V. & Domzalski, D. [2001]. Development of a Piezoelectric Actuator for Trailing Edge Flap Control of Full Scale Rotor Blades, *Smart Materials and Structures, Vol. 10, No.* 1: 101088/0964–1726/10/1/303.

[57] Sturzebecher, D. & Nitsche, W. [2003]. Active cancellation of TollmienâĂŞSchlichting instabilities on a wing using multi-channel sensor actuator systems, *International Journal of Heat and Fluid Flow* 24(4): 572–583.

[58] Thakkar, D. & Ganguli, R. [2007]. Induced shear actuation of helicopter rotor blade for active twist control, *Thin-Walled Structures* 45(1): 111–121.

[59] Thiel, M. [2006]. *Actuation of an active Gurney flap for rotorcraft applications*, PhD thesis, The Pennsylvania State University.

[60] Thiel, M. & Lesieutre, G. [2009]. New Actuation Methods for Miniature Trailing-Edge Effectors for Rotorcraft, *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, number May.

[61] Vinogradov, A., Schmidt, V., Tuthill, G. & Bohannan, G. [2004]. Damping and electromechanical energy losses in the piezoelectric polymer PVDF, *Mechanics of Materials* 36(10): 1007–1016.

[62] Viswamurthy, S. & Ganguli, R. [2004]. An optimization approach to vibration reduction in helicopter rotors with multiple active trailing edge flaps, *Aerospace Science and Technology* 8(3): 185–194.

[63] Wang, J., Li, Y. & Choi, K.-S. [2008]. Gurney flap-Lift enhancement, mechanisms and applications, *Progress in Aerospace Sciences* 44(1): 22–47.

[64] Watson, B., Friend, J. & Yeo, L. [2009]. Piezoelectric ultrasonic micro/milli-scale actuators, *Sensors And Actuators* 152: 219–233.

[65] Wickramasinghe, V. & Hagood, N. [2004]. Material characterization of active fiber composites for integral twist-actuated rotor blade application, *Smart Materials and Structures* 13(5): 1155–1165.

[66] Wilbur, M., Mirick, P., Yeager, W., Langston, C., Cesnik, C. & Shin, S. [n.d.]. Vibratory Loads Reduction Testing of the NASA/Army/MIT Active Twist Rotor, *Journal of the American Helicopter Society* 47(2): 11.

[67] Yang, A., Ro, J., Yang, M. & Chang, W. [2009]. Investigation of piezoelectrically generated synthetic jet flow, *Journal of Visualization* 12(1): 9–16.

[68] Yee, K., Joo, W. & Lee, D.-H. [2007]. Aerodynamic Performance Analysis of a Gurney Flap for Rotorcraft Application, *Journal of Aircraft* 44(3): 1003–1014.

[69] Yu, Y., Gmelin, B. & Splettstoesser, W. [1997]. Reduction of helicopter blade-vortex interaction noise by active rotor control technology, *Progress in Aerospace* 33(97): 647–687.