THE APPLICATION OF HELICOPTER ROTOR BLADE ACTIVE CONTROL SYSTEMS FOR NOISE AND VIBRATION REDUCTION AND PERFORMANCE IMPROVEMENT

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This paper summarises the actual status of the development of active control systems which took place in rotorcraft industry. Helicopter is a specific kind of airship in which structural, mechanical and aerodynamic complexity appears more than in other aircraft. But it also offers opportunities for application of active control systems. Although contemporary research on smart structures and active control are focused on the reduction of helicopter vibration and noise levels, the developed methodology can be also applicable to augmentation of aeromechanical stability, enhancement of handling qualities, stall alleviation, the minimisation of blade dynamic stresses and rotor head health monitoring. The majority of research effort concerns the improvement of main rotor qualities because of its main role in helicopter aeromechanics.

1. INTRODUCTION

Nowadays in many research institutes and rotorcraft manufacturers the research focused on improvement of helicopter flight qualities and the extension of flight envelope is underway. The problem is more difficult compared to fixed-wing aircraft because of the complexity of phenomena taking place during helicopter flight. High vibratory loads, excessive noise levels, poor flight stability characteristics, aeromechanical instabilities, high dynamic blade stresses are typical for previous and contemporary helicopters. Compared to fixed-wing aircraft, helicopters have higher operating cost, worse ride quality, lower fatigue life of structural components. The primary source of all these problems is the unsteady, complex aerodynamic environment in which helicopter operates. Reduction of vibration level and enhancement of helicopters flying qualities has been an objective of studies [1-116] for several years.

Among various concepts of influencing helicopter rotor properties (Fig.1.1) application of smart structure with active control seems to be the most promising approach. Helicopter rotor blade is an aeroelastic system on which aerodynamic (A), inertial (I) and elastic (E) loads act. For such systems control (C) is applied that leads to aeroservoelastic systems (Fig. 1.2).

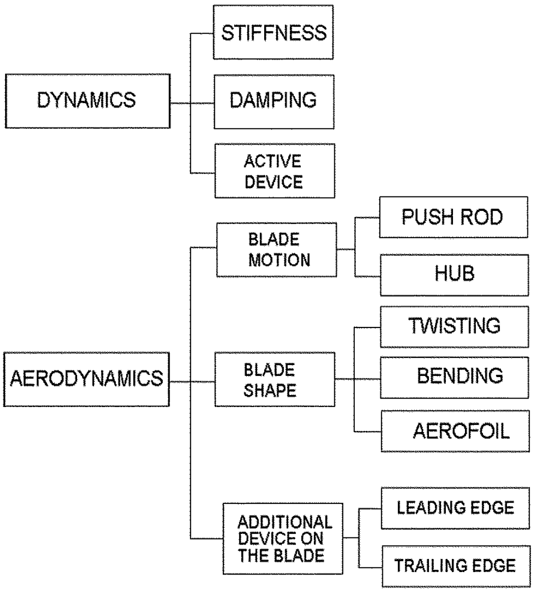

Fig. 1.1. Concepts for influencing helicopter rotor behaviour

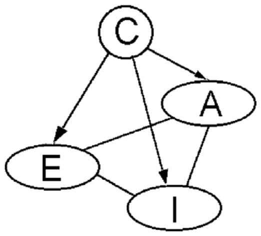

Fig. 1.2. The phenomena of aeroservoelasticity

Smart structure technology is a maturing and its various applications appear in different physical systems. This paper will review the state-of-the-art on the application of smart structures technology to rotor systems.

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2. THE CONTROL OF ROTORCRAFT

There are several types of rotorcraft platforms (Fig. 2.1). They differ by the number of rotors and their placement on the fuselage. The most popular type of rotorcraft is a single rotor helicopter with tail rotor. The main rotor is produces lift, thrust and control moments (Fig. 2.2÷2.3).

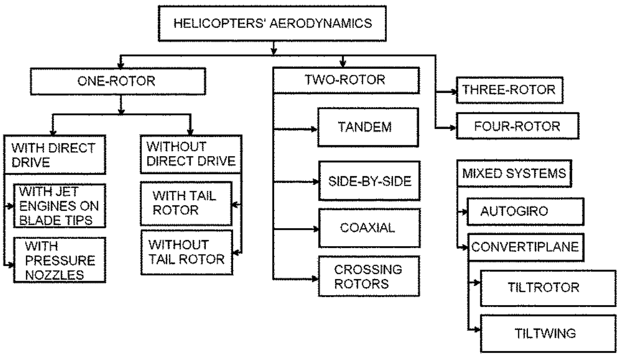

Fig. 2.1. Types of rotorcraft aircrafts

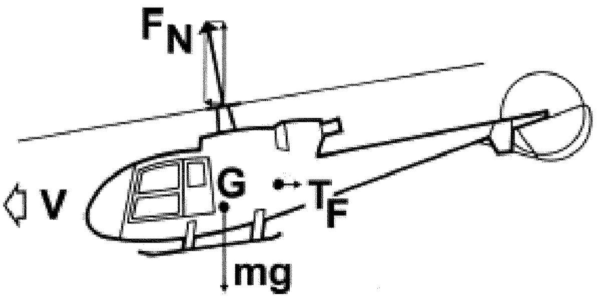

Fig. 2.2. The role of main rotor

2.1. The control of the main rotor using swashplate

The rotor is the system of rotating blades connected together in the hub. The hub allows each blade to rotate individually around three axes [1]. The possibility of blade rotation is assured in different ways. In conventional articulated rotor these rotations are possible due to the system of three hinges which allow pitching, flapping and lagging of rotor blade (Fig. 2.4) [1-3].

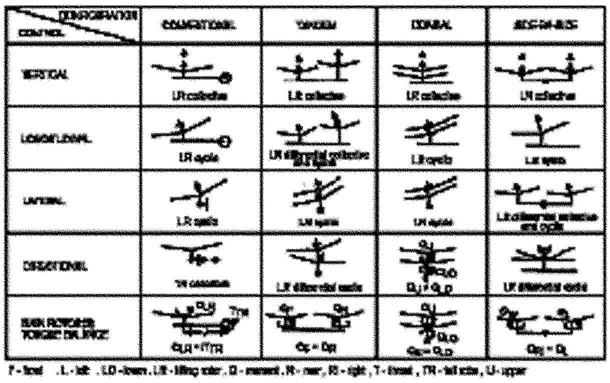

Fig. 2.3. The control of helicopter

In hingeless rotors the structure of the hub provides possibility of the same three rotation angles (Fig. 2.4).

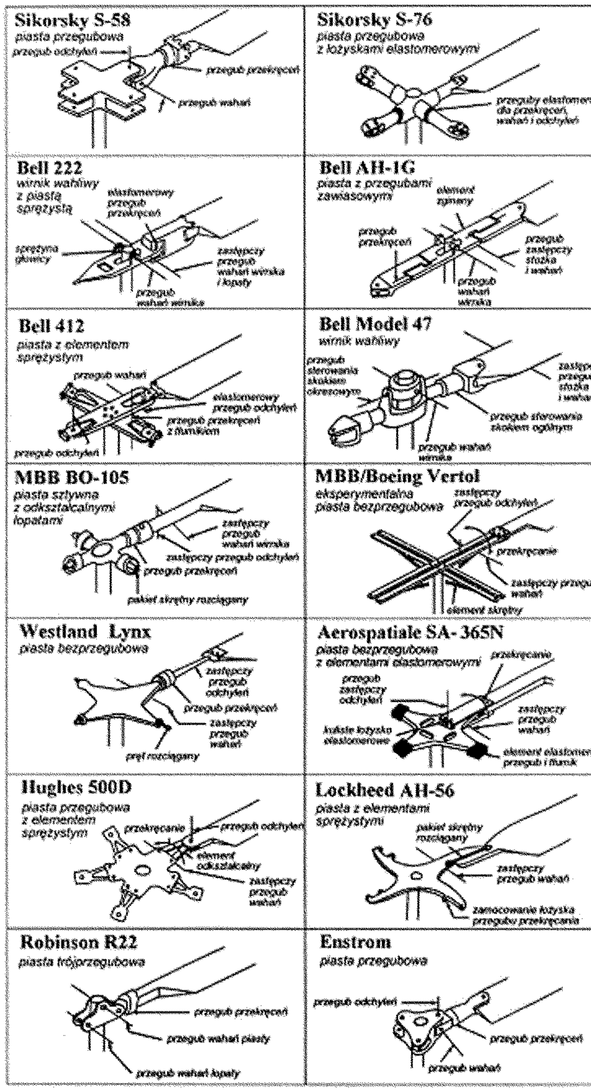

Fig. 2.4. Different types of helicopter hubs

The rotating blade contributes to creating lift, thrust and control moments (Fig. 2.3). Variation of loads is obtained via changes of rotor blade pitch angle using swashplate [4] mechanism, which transfers pilot control inputs to the blades (Fig. 2.5). The collective control causes the same pitch angle of all rotor blades. It allows to change the lift magnitude. The collective control is caused by the swashplate tilt from the position perpendicular to shaft axis, which also causes tilt of the rotor thrust. It is obtained by different pitch of rotor blades as the function of blade azimuth.

Generally rotor blade pitch angle Θ is changed according to the formulae:

$$\Theta = \Theta_0 + \Theta_1 \sin \Omega t + \Theta_2 \cos \Omega t \qquad (1)$$

where:

Θ_0 – collective control,

Θ_1, Θ_2 – cyclic controls.

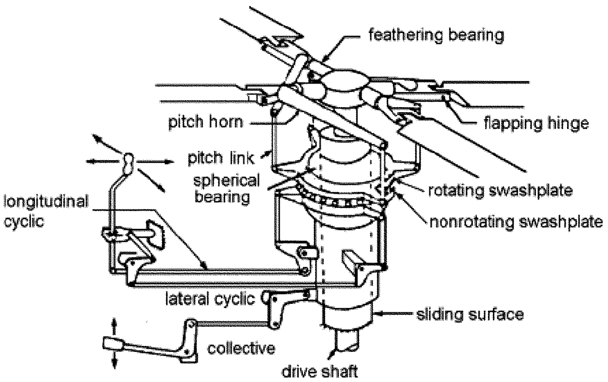

Fig. 2.5. An articulated hub and the swashplate

2.2. Passive control to reduce noise and vibration

There are a few passive methods of blade control to minimise the level of noise and vibrations of helicopter rotor and to improve its flight qualities. For many years the methods were based on aeroelastic blade tailoring and the use of additional passive devices. These measures became more popular when composite rotor blades were put into service.

Aeroelastic blade tailoring is achieved by changes of blade shape and blade dynamic properties. Both methods depend on non real-time changes made not in the flight but in manufacturing. In the first method the changes of:

- blade airfoils,
- the distribution of blade airfoils along the blade,
- blade twist

are selected during the design of rotor blade. The proper rotor blade dynamic properties are obtained by selection of mass distribution and stiffness in the blade along the span and the chord. Such changes are made mainly for specific flight conditions, (for instance for maximal forward flight) and may be not effective for other flight conditions.

Additional passive mechanism such as dumpers [5] are also used for many years. They are places mostly on the rotor hubs. Their effectiveness in the minimising of noise and vibrations of helicopter rotor is not substantial.

2.3. Active control of helicopter

Active (or additional) control is the most promising way of the minimising of the level of noise and vibrations of helicopter rotor and improving its flight qualities [6, 7]. Active control counteracts detrimental aeromechanic phenomena, in the way adjusted for actual flight conditions In smart systems active elements can work both as sensors and actuators.

There are many places where the elements of active control system can be placed. (Fig. 2.5, 2.6). Usually they are applied to rotor blades as actuators (and sensors) where they modify rotor blade geometry and its pitch angle. Sensors of active control system can be mounted also in the fuselage [8], undercarriage, engine, avionics [9]. Such an array of sensors (in HUMS systems) allows monitoring in-flight all important parameters which results in the increase of flight safety and in the simplicity of maintenance.

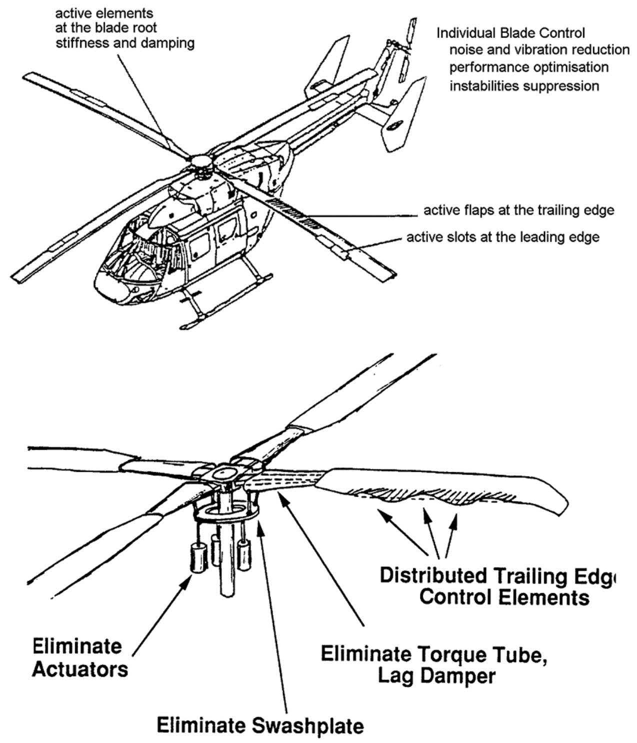

Fig. 2.6. Application of smart structures and active control in helicopter

The first active control systems [10] were used in helicopters to minimising the level of noise and vibrations. Such a system does not counteract adverse conditions but limit their effects. Actuators in these systems are mounted on different parts of fuselage.

2.3.1. High Harmonic Control (HHC)

The first idea of additional control consisted in the modification of the changing of rotor blade pitch angle by adding excitation of pitch angle at frequencies higher than 1/rev. This idea of active control is realised by using additional mechanical system of push rods connected to conventional swashplate causing additional tilt of its plane with higher frequencies. This kind of active control known as High Harmonic Control (HHC) acts on all rotor blades simultaneously; blade pitch angle Θ is described as:

$$\begin{aligned}\Theta &= \Theta_0 + HHC + \\ &+ (\Theta_1 + HHC)\sin\Omega t + \\ &+ (\Theta_2 + HHC)\cos\Omega t\end{aligned} \tag{2}$$

where *HHC* is the modification of rotor blade pitch angle made by active control system.

2.3.2. Individual Blade Control (IBC)

That idea of Individual Blade Control (IBC) is similar to High Harmonic Control – adding to blade pitch frequencies higher then 1/rev. The fundamental difference is that additional changes of blade pitch angle are controlled individually for each blade. In IBC local pitch angle Θ of a blade is described as:

$$\begin{aligned}\Theta &= \Theta_0 + \Theta_1 \sin\Omega t + \\ &+ \Theta_2 \cos\Omega t + IBC\end{aligned} \tag{3}$$

where *IBC*is the modification of rotor blade pitch angle by components of active control system.

Control in HHC and IBC is realised using hydraulic and electromagnetic actuators [11].

2.3.3. Smart rotor

The application of smart systems adapting rotor to actual flight conditions is a new approach.

The rotor loads which result from the influence of elements of additional control system can be divided into two groups (Fig. 1.1):

- dynamic loads (changing of stiffness and damping),
- aerodynamic loads (changing of airfoil shape and adjustments of rotor blades or their parts).

The control of rotor blade dynamic loads may be obtained through:

- application of active elements mounted in the rotor blade [12-14],
- active changes of damping and/or stiffness of rotor hub or blade [15, 16].

Active piezoelectric elements mounted in the inside the rotor blade are used to influencing on the stiffness and damping of that section of the rotor blade.

The aerodynamic loads of rotor blade may be controlled by:

- variation of the pitch angle of rotor blades,
- variation of the rotor blade shape,
- using additional elements mounted in or on the rotor blade.

Changes of the pitch angle of all rotor blades (Fig. 2.7) can be realised by using:

- additional active push rod in rotor blade pitch angle control system,
- additional active elements mounted in inboard blade section [17, 18].

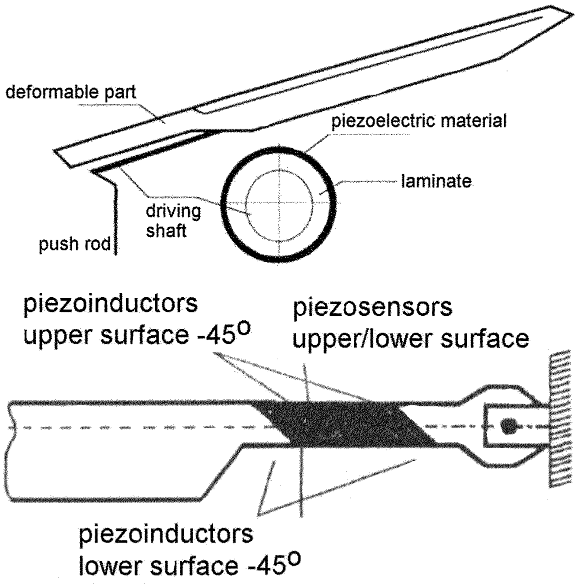

Fig. 2.7. Ideas of changes of pitch angle of rotor blades

Changes of rotor blade geometry can be obtained via changes of [19]:

- blade twist angle,
- blade shape along the span (bending),
- airfoil geometry.

These methods may be realised by using active elements embedded into blade spar (Fig. 2.8).

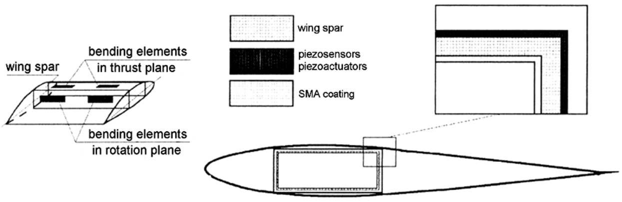

Fig. 2.8. The idea of changes of bending line of blade

The most effective method is changing blade twist angle along the span [20]. It can be obtained by adding twisting shaft inside rotor blade or by using the set of active elements on the surface of rotor blade (Fig. 2.9).

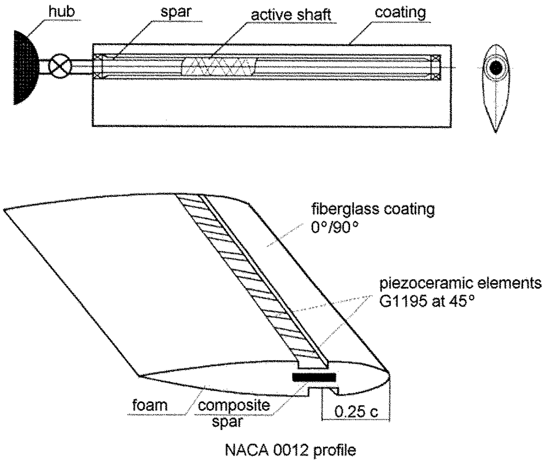

Fig. 2.9. The idea of changes of blade twist angle

Other methods of changing blade airfoil shape are based on application of actuators deforming the trailing part of blade airfoil or the camber line. The actuators are made mostly of piezoelectric elements [21] or shape memory alloys (SMA) [22÷25] (Fig. 2.10).

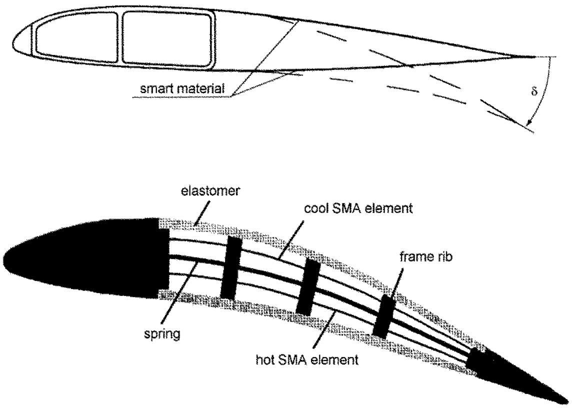

Fig. 2.10. The idea of changes of airfoil geometry

Aactive element can be mounted at the leading or trailing edge of rotor blade. The second concept was described in many papers [26-46], tested in wind tunnel on rotor blade sections, the complete rotor blade and recently was used in helicopter [47] flight tests. The mechanism of actively controlling trailing edge consists of (Fig. 2.11):

- piezoelectric actuator – various types of multilayered piezoelements, piezostack actuators,
- mechanical ‘amplifier’ connected with actuator, multiplying the extension of the actuator,
- the mechanism changing actuator extension into flap deflection,
- flap.

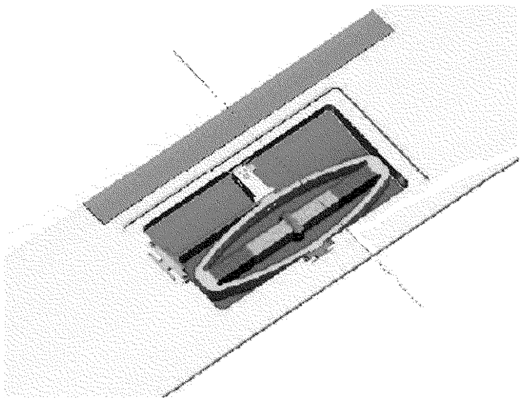

Fig. 2.11. Trailing edge flap with piezoactuator

The selection of the method for blade active control depends on the dynamic properties of the blades. In case of the application of additional control elements, i.e. piezostack actuators with trailing-edge flaps, mounted inside the rotor blade the stiff blade should be used. In case of the application of piezocomposites or piezo-sheets mounted on/in outer layers of rotor blades and causing its twisting or bending the blade should be deformable.

3. SMART MATERIALS

3.1. Piezoelectric materials

In piezoelectric material the strong coupling between mechanic loads and electric voltage exists (Fig. 3.1) [48÷55].

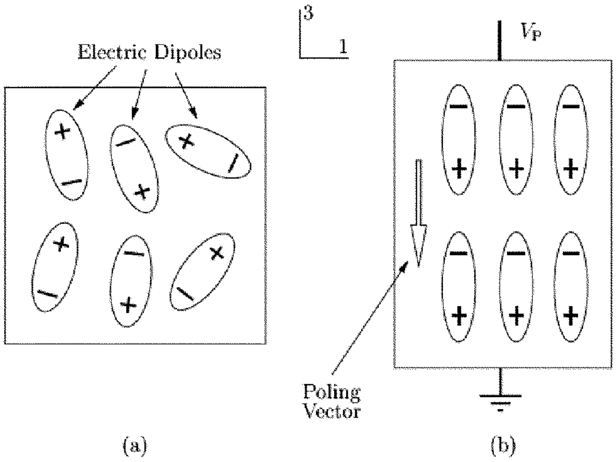

Fig. 3.1. The change upon poling in a piezoelectric material

Piezoelectric materials can generate an electric charge when they are mechanically deformed (and, reciprocally, deform when applied an electric charge) are described (in Greek, the word piezein means to press). In nature some materials exhibit weak piezoelectric properties, i.e. natural quartz or human bone.

However, specially manufactured ceramics exhibit piezoelectric properties in such intensity, that they may find engineering applications.

Fig. 3.2. Various types of piezoactuators

Piezoelectric materials can be appled as piezosensors if it can generate electric voltage when it is subjected to a load (straight piezoelectric effect). It can be also used as piezoactuator, if it can change its volume (especially length in extenders) or shape (in benders) when the electric voltage is applied (reverse piezoelectric effect).

There are many types of piezomaterials and piezoelements in the market. Many of them are made in large quantities, so their prices are not high [54-60] (Fig. 3.2).

3.2. Shape Memory Alloys

A Shape Memory Alloys (SMAs) (also known as memory metals or smart wires) are metallic alloys which can recover permanent strains when they are heated above a certain temperature [56-61].

There are a few types of shape memory materials:

- thermally-responsive,
- ferromagnetic responsive,
- shape memory polymers.

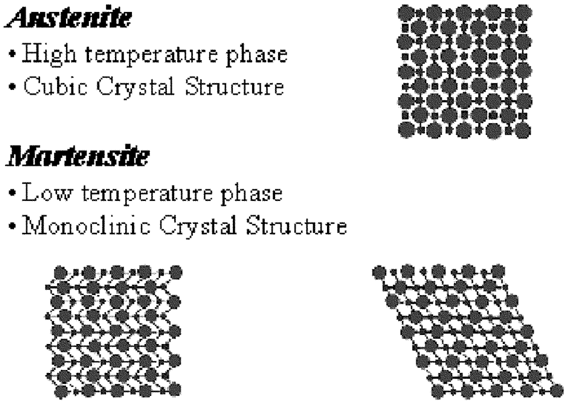

Fig. 3.3. Crystallographic phases of SMAs

The characteristic feature of all SMAs is the occurrence of a martensitic phase transformation (Fig. 3.3). The martensitic transformation is a shear-dominant diffusionless solidstate phase transformation occurring by nucleation and growth of the martensitic phase from a parent austenitic phase. When an SMA undergoes a martensitic phase transformation, it transforms from its high-symmetry, usually cubic, austenitic phase to a low-symmetry martensitic phase, such as the monoclinic variants of the martensitic phase in a NiTi SMA.

The nickel-titanium alloys were first developed in - by the and commercialized under the trade name Nitinol (an acronym for Nickel Titanium Naval Ordnance Laboratories).

The range of applications for SMAs has been increasing in recent years, with one major area is medicine: an example is development of , that exert a constant pressure on the teeth. There have also been studies on using SMA in robotics. Weak point of this technology is energy inefficiency, slow response times, and large .

Metal alloys are not the only thermally-responsive materials, as shape memory polymers have also been developed, having become commercially available in the late 1990's.

There is another type of SMA called (FSMA), that change shape under strong magnetic fields. These materials are of particular interest as the magnetic response tends to be quicker and more efficient than temperature-induced responses.

4. TYPES OF SMART ROTORS

There are two main approaches in building smart rotor [39, 40, 62÷116]:

- blades with piezocomposites causing its twist along the span,
- blades with trailing edge flaps powered by various active actuators (SMA, piezobenders, piezostack actuators).

4.1. Controllable rotor blade twist generated by embedded piezoceramic actuators

Controllable rotor twist can be obtain by:

- piezoactuators embedded in rotor blade,
- using piezocomposites.

The example for the first way is the smart four-bladed rotor model was built for Boeing-ITR tests [63÷65]. The NACA0012 blade was made by laminating 10 mm pre-preg fibreglass cloth plies around a foam core at angles 0°/90° in molds. There were used single-layer and double-layer actuators (PZT-5H manufactured by Morgan-Matroc), which were grouped in banks of five elements at angles of ±45° respectively on the top and bottom surfaces of the blade (Fig. 4.1). During wind tunnel experiments the twist of blade tip of ±0.4° caused by piezo actuation was obtained. That concept was later used in full-scale Sikorsky UH-60 rotor system [65]. Application of piezoelements caused considerable weight increase of 16% of blade weight and bigger tip twist of ±1-2° was measured (caused by piezo actuation).

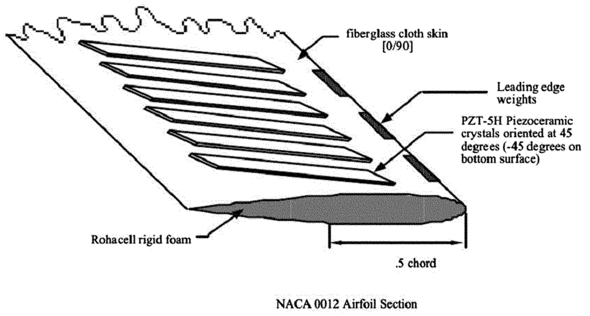

Fig. 4.1. Controllable blade twist generated by embedded piezoceramic PZT-5H actuators

Another concept [66-70] is based on using piezoelectric active fiber composites (AFC) embedded in composite rotor blade structures. The active fiber composite actuator utilizes interdigitated electrode poling (IDE) and piezoelectric fiber composites (PFC), as shown in Fig. 4.2.

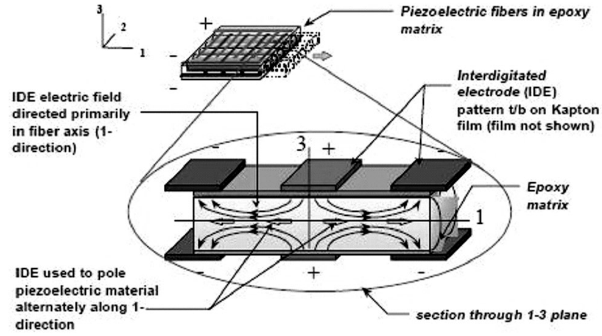

Fig. 4.2. Active Fiber Composite (AFC)

This combination results in a high performance piezoelectric actuator laminate with strength and conformability characteristics greater than that of a conventional monolithic piezoceramic. The high conformability of the actuator package allows it to be embedded easily within nonplanar structures, much like a traditional composite ply.

Boeing, Sikorsky and the Massachusetts Institute of Technology sponsored by the Defense Advanced Research Projects Agency (DARPA) have successfully completed a preliminary hovering flight test of a single model rotor blade incorporating AFC twist actuation (Fig. 4.3÷4.5). Results from this test were used to design a four-bladed 1/6 scale Boeing CH-47D Chinook rotor system (ATR – Active Twist Rotor) to examine the performance of the AFCs under full-scale loads (Fig. 4.6). During tests of rotor model the tip twist of ±1.4° was measured. The application of AFC caused considerable weight increase of 20% of blade weight [66÷70].

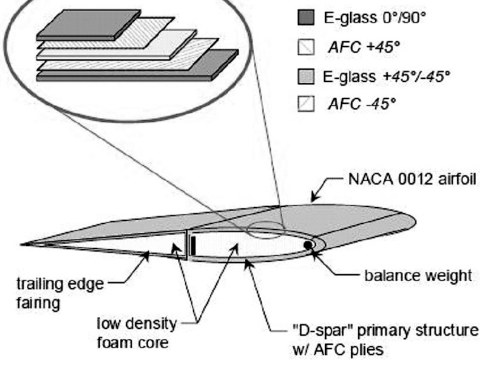

Fig. 4.3. Active Fiber Composite in ATR

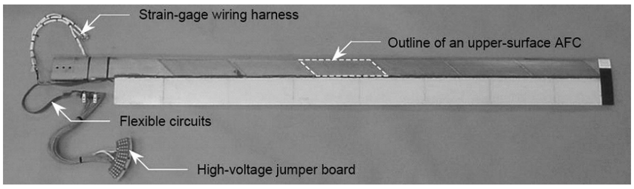

Fig. 4.4. Active Twist Rotor (ATR) blade

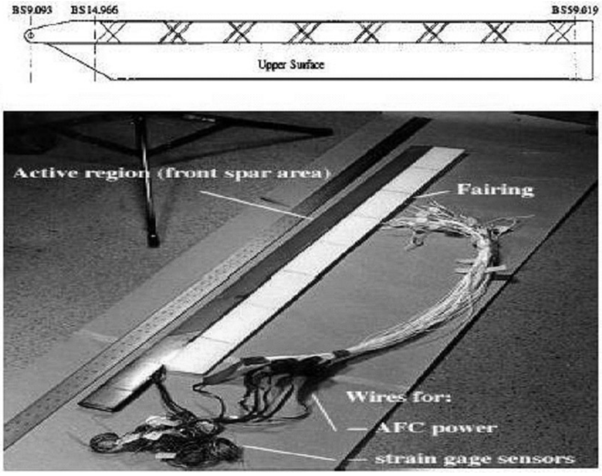

Fig. 4.5. Active Twist Rotor (ATR) blade

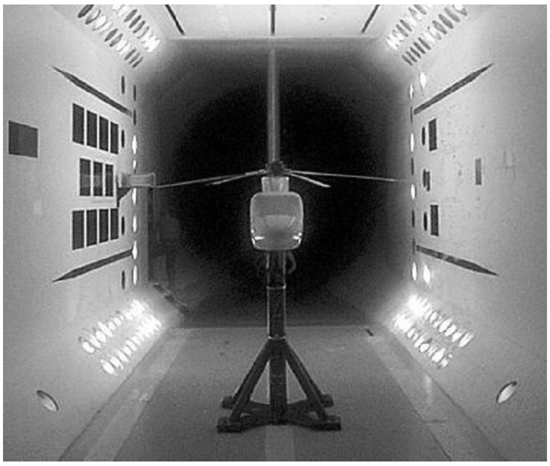

Fig. 4.6. ATR in wind tunnel

4.2. Trailing-edge flaps actuated with piezo bimorphs

Another idea of the trailing-edge flap actuation is the using of a piezo bimorph. It is a bending actuator consisting of piezoceramic (PZT) sheets, bonded on both sides of a very thin brass shim with an electrically conducting adhesive coating. The example of a mechanism with the bimorph clamped at one end is presented in Fig. 4.7.

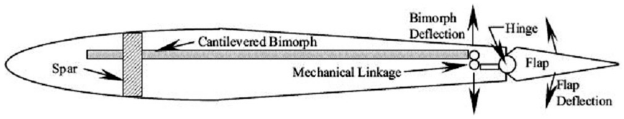

Fig. 4.7. Bimorph actuator in rotor blade section

When equal but opposite electric charges are applied to the PZT sheets, a pure bending of the bimorph occurs. It is a compact actuation device and it generates a small actuation force. The flap is located near the tip of the blade (Fig. 4.8) and is 20% chord wide. The blade uses NACA 0012 airfoil and has the chord of 0.075 m. The rotor is 1.8 m in diameter. Experiments were made on two - or four-bladed scale rotor models (ITR-Boeing simulations) [39, 40, 71].

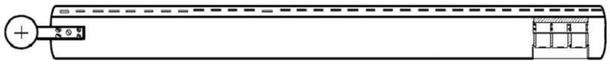

Fig. 4.8. Main rotor blade with flap actuator near the tip

Another system of mechanical hinges and linkages was used to the amplification of the bending of elements at the tip to cause larger flap rotation (Fig. 4.9) [39]. Commercially available two-layered G-1195 bimorphs were used and tested on two-bladed rotor model. The maximum flap deflection amplitude obtained was ±7° for non-rotating rotor and ±1° in case of rotation of 900 rpm in hover.

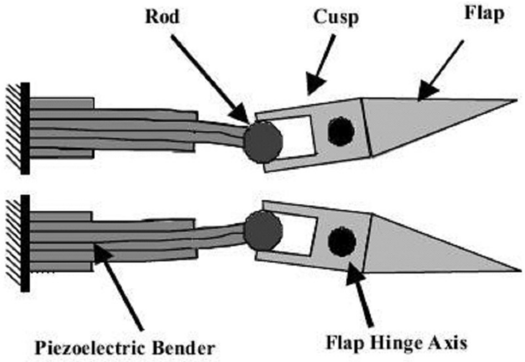

Fig. 4.9. Piezo bimorph flap actuation system

The application of improved clamping of bimorph actuator (Fig. 4.10) allow the increase of the maximum flap deflection amplitude up to ±8° in case of rotation of 900 rpm in hover [72].

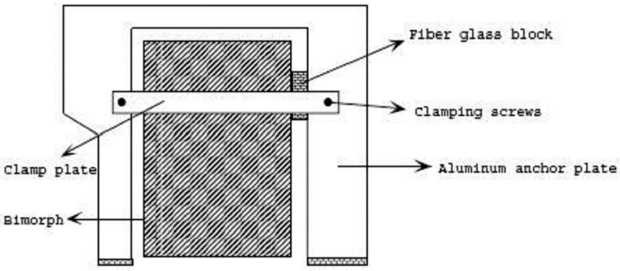

Fig. 4.10. An improved version of bimorph clamping

The increase of the number of piezo layers caused the further increase of the maximum flap deflection amplitude [72].

In case of a 8-layered tapered piezo bimorph actuator, the maximum flap deflection amplitude increased up to ±6° in case of rotation of 2150 rpm in hover.

Such an actuator was used in a four-blade rotor model (Fig. 4.11) with Mach scaled hub of Bell-412 [38, 71, 73÷76]. The rotor was 1.8 m in diameter. This model was tested in a vacuum chamber but it showed the degradation of performance at 2000 rpm. The maximum flap deflection of ± 3.2° was achieved.

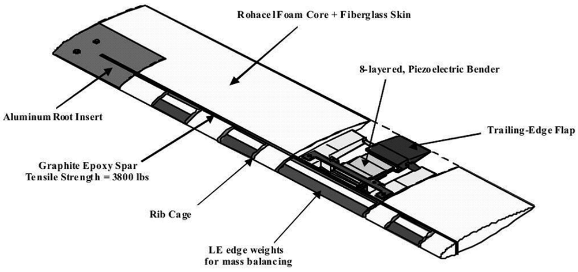

Fig. 4.11. The blade of a four-bladed rotor model (Bell-412)

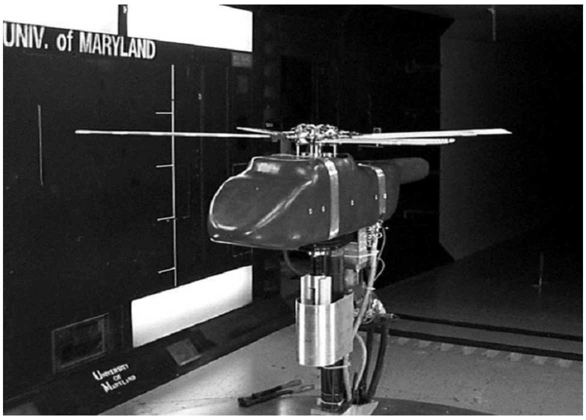

Fig. 4.12. Bell-412 four-blade rotor and fuselage model in the Glenn L. Martin wind tunnel

A two-bladed rotor model with the same hub was tested in hover. This model achieved ±6° to ±10° flap deflections in case of 1850 rpm and over oscillatory thrust [71, 73].

Bell-412 four-blade rotor and fuselage model was tested in the wind tunnel (Fig. 4.12) [74]. Flap deflection of ±4° to ±5° were achieved at 1800 rpm.

4.3. Trailing-edge flaps actuated with piezostack actuators

Piezoceramic stack actuators are often used as a high force and a relatively small displacement devices [48-55]. They are composed of the set of thin piezoceramic layers (sheets) (Fig. 4.13) connected together by conductive adhesive. Voltage is applied to the electrodes on both sides of the stack.

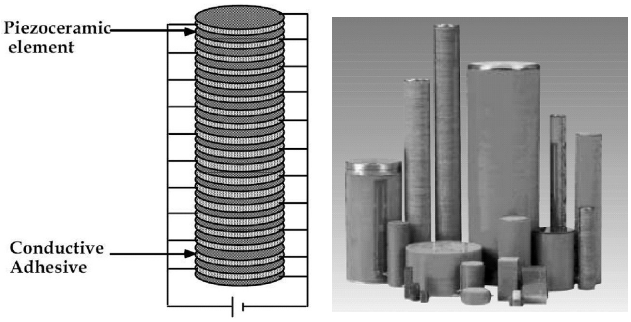

Fig. 4.13. Piezostack actuator (Physik Instrumente)

Because of small displacement of piezostack actuators mechanical amplification is applied. The most common idea in mechanical amplification is the application of an arm.

First device, called L-arm [38, 74-78] was used in wing model (Fig. 4.16÷4.18) which has the chord of 0.2 m and the span of 0.25 m. A single flap has the chord of 0.04 m and the span of 0.1 m. There are two high-voltage (1000 V) piezostack actuators bonded together back to back installed. Their free displacement is 1.5 mm, amplified 10 times. The measured value of free displacement was 10 mm (15 mm calculated). The linear motion of the piezostack actuator was converted to rotary motion of flap using a hinge mechanism. That model was tested in a wind tunnel. The flap amplitude was ±3° when the flow velocity was 0 m/s and ±1.5° when velocity increased to 40 m/s.

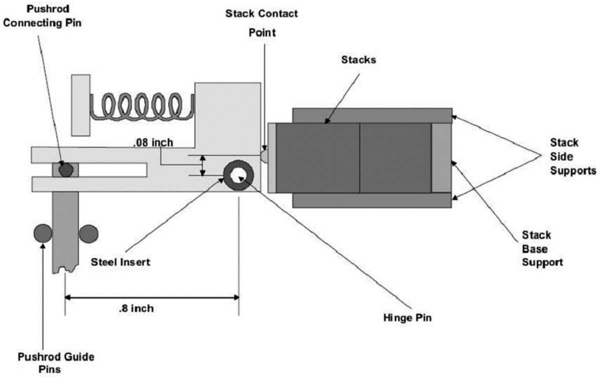

Fig. 4.14. Stack and L-arm arrangement

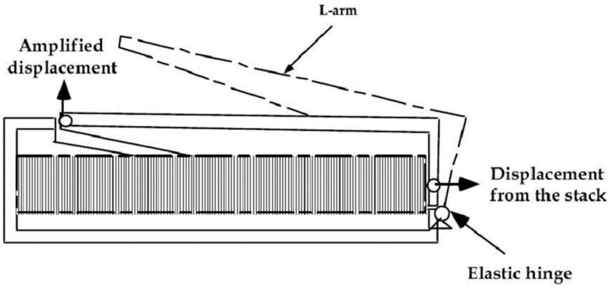

Fig. 4.15. Piezostack actuator with integrated L-arm mechanical amplification

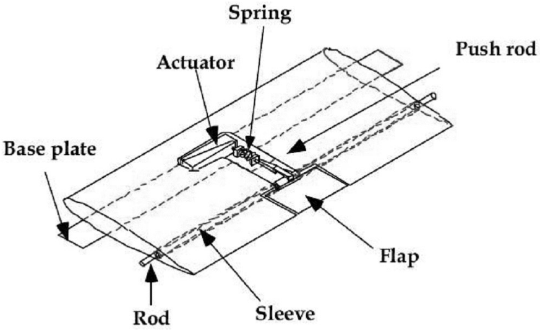

Fig. 4.16. Wing with trailing-edge flap and L-arm amplification

The amplification mechanism was designed for Boeing MD-900 Explorer [79-81]. It was based on 5 stack actuators and a new double-lever (L-L) amplification mechanism (Fig. 4.17) which was the developed version of L-arm amplification. A wing section model of chord 0.3 m and span 0.3 m with the flap of span 0.1 m and chord 0.075 m was built (Fig. 4.18, 4.19). The maximum flap amplitude was from ±4° to ±20° depending on excitation frequency at the flow velocity of 40 m/s [81].

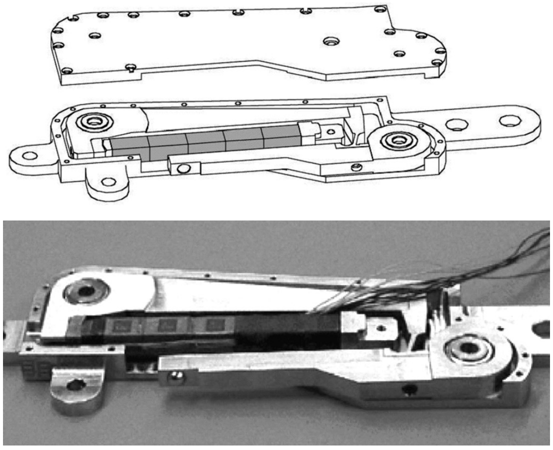

Fig. 4.17. L-L amplification mechanism

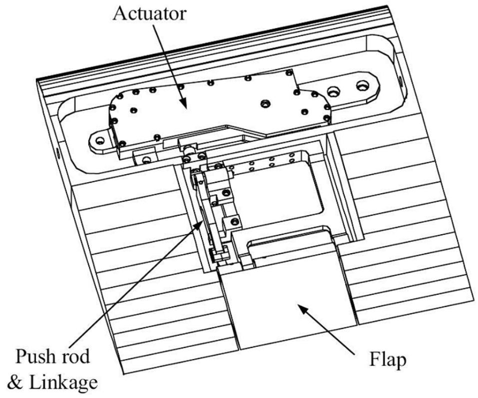

Fig. 4.18. Wing section with trailing-edge flap and L-L piezostack amplification system for Boeing MD-900 Explorer

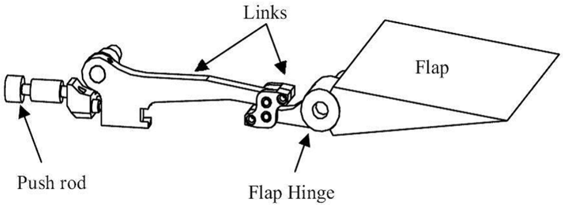

Fig. 4.19. The actuator/flap push-rod attachment

The other amplification mechanism [82, 83] was designed for Boeing MD-900 Explorer five-blade rotor system of 11 m in diameter. This actively controlled rotor was used for vibrations, noise and performance tests. The new amplification system was based on 4 piezostack actuators (piezoceramic/lead magnesium niobate stack, low-voltage, co-fired PMN:PZ by Xinetics). The large deflection was supplied by bi-axial arrangement of two long stack columns operating in push-pull mode in conjunction with L-shaped lever and flexural mount (Fig. 4.20). The expected flap amplitude of ± 4° at excitation frequency 40 Hz was not realised.

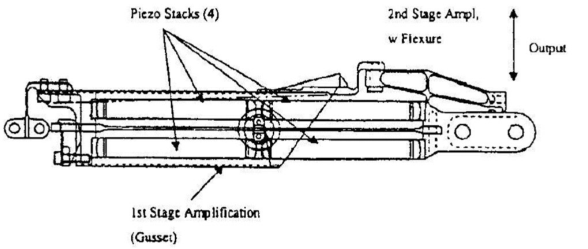

Fig. 4.20. Bi-axial piezostack flap actuator

The next type of discrete trailing-edge servo-flap actuator called X-frame actuator (Fig. 4.21÷4.23) was designed for the 1/6th Mach scale rotor model of Boeing CH-47D Chinook [84÷87].

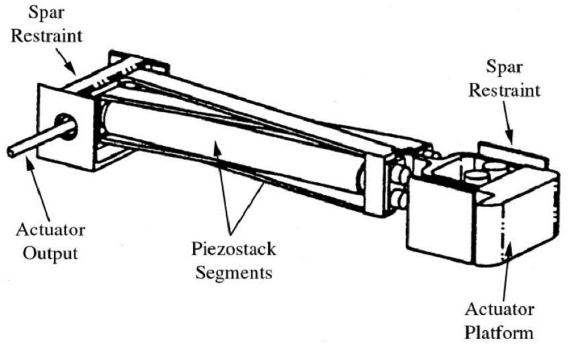

Fig. 4.21. X-frame actuator

The actuator consists of two active high-voltage piezostacks and two criss-cross frames. Amplification is achieved via shallow angle arrangement. During tests at the tip Mach 0.63 and 8° collective pitch, oscillatory flap deflections ±2.4° were achieved for excitation voltage of ±1000 V. The actuator was tested in full-scale rotor system of MD-900 Explorer and scaled rotor model of Eurocopter EC-135.

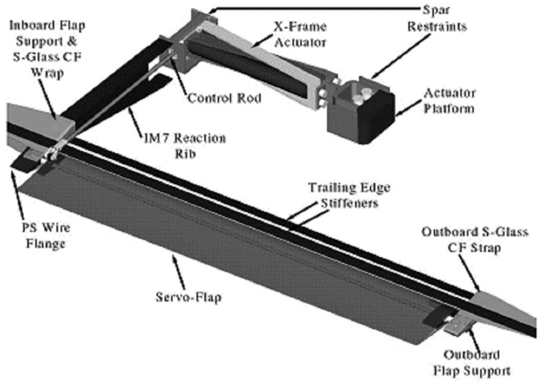

Fig. 4.242 The schema of control system with X-frame actuator

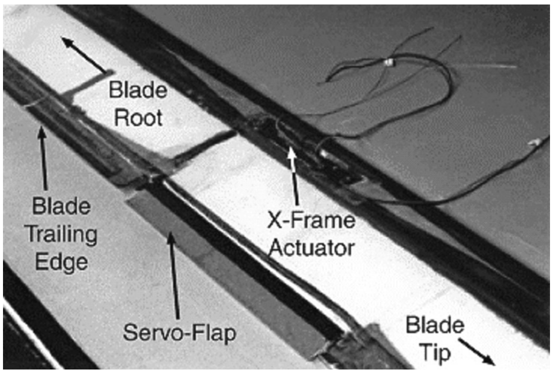

Fig. 4.23. X-frame actuator in CH-47D rotor blade

Similar mechanism composed of piezostack actuator was also used in [88, 89] to control leading-edge flap.

Similar mechanism was used by ONERA and Eurocopter during their experiments. They used low-voltage (200 V) piezostack Cedrat actuator APA (Amplified Piezo Actuator) series (APA230, APA500L, APA750X) [45÷48]. These actuators have the shape of composite frame (elliptical) (Fig. 4.24) which allows to be centered easier than X-frame or L-L frame actuators.

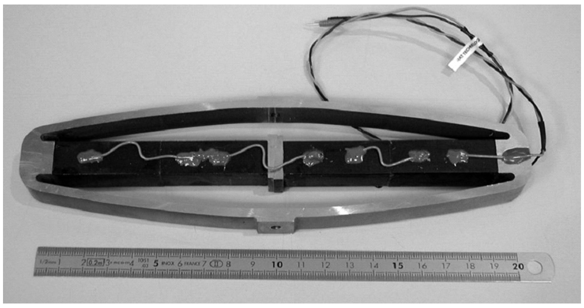

Fig. 4.24. Amplified Piezo Actuator (APA) actuators from Cedrat

The segment of Rotor ŕ Pales Actives (RPA) blade (Fig. 4.25÷4.28) was built. During experiments the flap deflections of -2.5°+3.5° were measured.

Fig. 4.25. The Rotor ŕ Pales Actives (RPA) blade with flaps actuated by APA

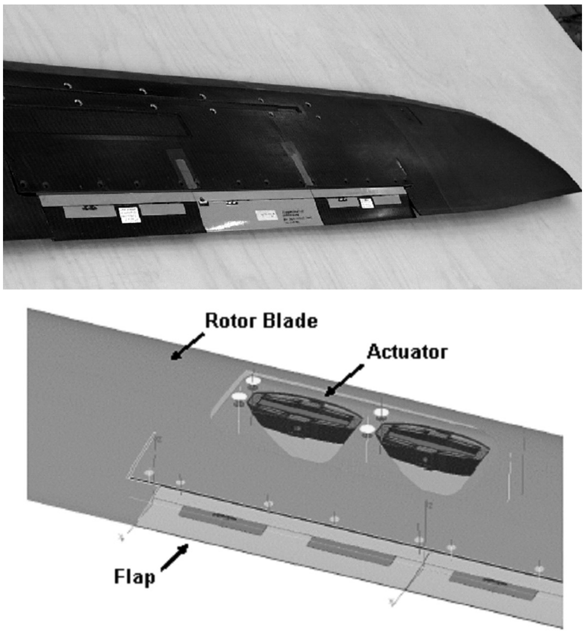

Fig. 4.26. The Rotor ŕ Pales Actives (RPA) blade with flaps actuated by APA

Recently full-scale rotor (Fig. 4.27, 4.28) was build by Eurocopter and tested in hover stand and in flight (Eurocopter BK-117).

Fig. 4.27. Eurocopter BK-117 smart rotor in test stand

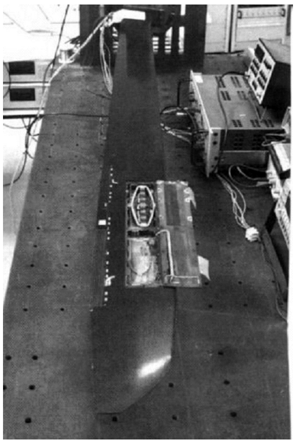

Fig. 4.28. Eurocopter BK-117 with smart rotor

4.4. Trailing edge flap actuated with magnetostrictive actuators and extension-torsion coupled composite tube

The idea of using the extension-torsion coupled composite tube [90, 91] working in conjunction with magnetostrictive actuator was also tested. (Fig. 4.29).

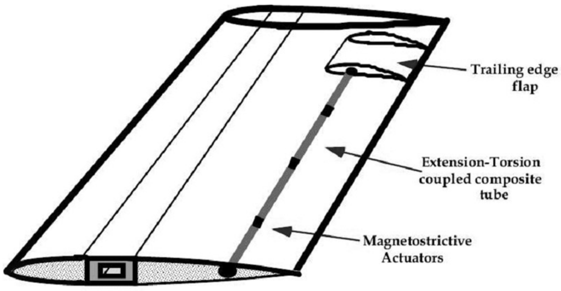

Fig. 4.29. Rotor blade with trailing edge flap actuated with magnetostrictive actuators and extension-torsion coupled composite tube

The extension-torsion coupled composite tube was subjected to an axial force generated by a magnetostrictive actuator that induces the twisting of the tube. The extension-torsion coupled composite beam was built by wrapping angle plies resulting in an antisymmetric ply lay-up with respect to the beam axis. To utilise the extension-torsion coupling of the composite tube, the magnetostrictive actuator must be attached to the tube in such a way that both twist and axial strain is permitted freely (Fig. 4.30). During tests Kevlar-epoxy tube / piezoelectric stack systems of 0.5 m length generated ±5.2° of flap deflection. Such a system can be used for vibration control but because of poor overall structural efficiency of extension-torsion coupled tubes appears less useful than other actuation systems.

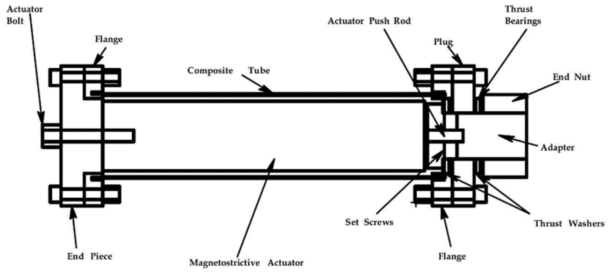

Fig. 4.30. Schema of composite tube and magnetostrictive actuator assembly

4.5. Trailing edge flap actuated with piezoceramic actuators and tailored bending-torsion coupled composite beam

A piezo-induced bending-torsion coupled composite beam was also used for trailing-edge flap deformations (Fig. 4.31) [92] or twisting the blade tip (Fig. 4.32) [93÷95].

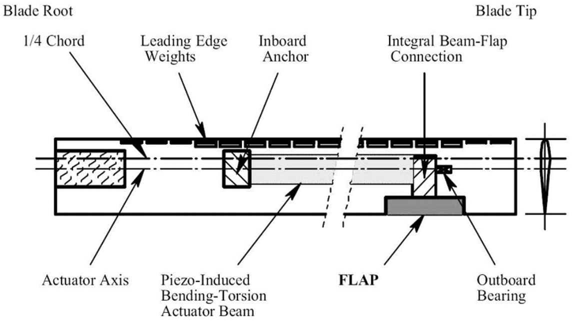

Fig. 4.31. Trailing edge flap actuated with piezoceramic actuators and tailored bending-torsion coupled composite beam

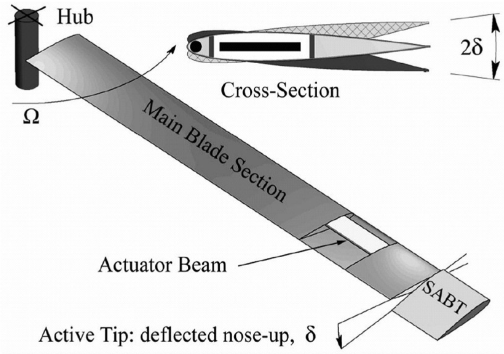

Fig. 4.32. Blade tip actuated with bending-torsion actuator

The beam is divided into the number of spanwise segments with reversed bending-torsion coupling for each successive segment. the same piezoceramic actuators are bonded on each beam segment on the top and bottom surfaces resulting in an equivalent bimorph unit (Fig. 4.33). An excitation generates a sinusoidal spanwise bending, where as induced twist is additive in the spanwise direction.

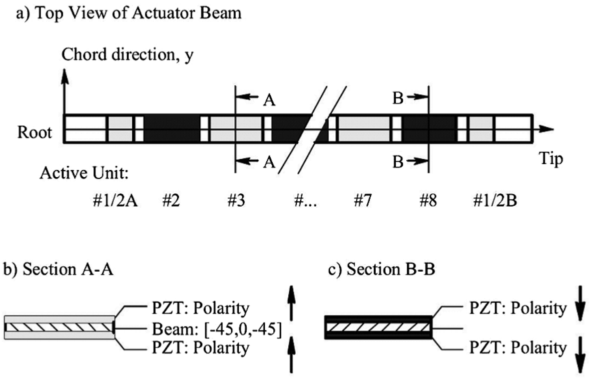

Fig. 4.33. Composite bending-torsion beam

A 2-bladed Mach-scaled rotor model with blades with flaps at 90% of radius was tested and the maximum flap deflection of ± 4° was achieved.

A 4-bladed Mach-scale rotor model with hub of Bell-412 [94, 95] with 10% tip was tested. For an 125 V actuation the measured tip deflection was between ±1.2° and ±1.6° (Fig. 4.34).

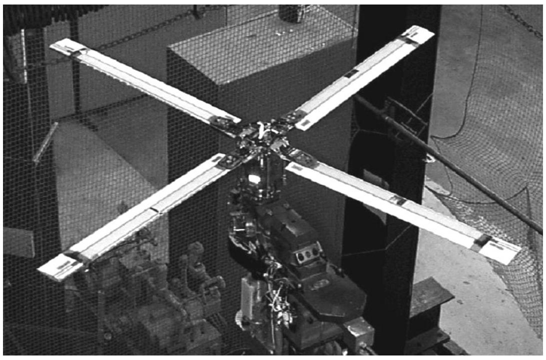

Fig. 4.34. A 4-bladed Mach-scale rotor model with hub of Bell-412 with 10% tips

4.6. Shape Memory Alloys actuators

Shape Memory Alloys (SMA) can generate the biggest forces from all smart materials but they work with the frequencies of order of 1 Hz which limits their application to the static case. The strains can be quite large, i.e., in case of moderate increase of Nitinol temperature up to 120°F the deflection can be even 6% [96÷101].

The potential application of SMA in aerospace systems may be to adjust trailing-edge trim-tab of a helicopter rotor for in-flight tracking.

Few concepts of using of SMA were investigated. Two SMA rods deflecting a blade airfoil (Fig. 2.10, Fig. 4.35) were used: the first one as actuator, and the second one as a restoring spring. There were the concept of using SMA plates (Fig. 4.36) [102, 103] or beams [104÷108].

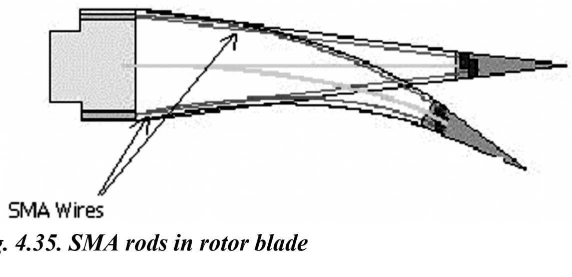

Fig. 4.35. SMA rods in rotor blade

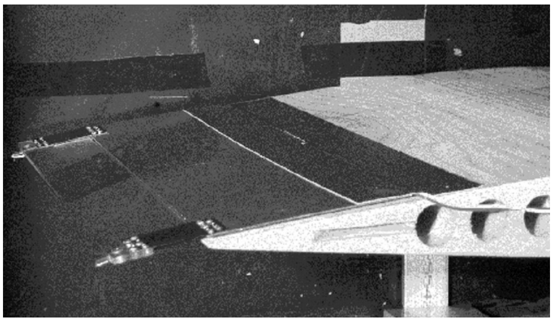

Fig. 4.36. SMA plates on rotor blade

Using SMA wires the segment of rotor blade with controlled trailing-edge flap was built. The flap was deflected by the system of from 2 to 5 Nitinol wires of diameter 0.005 m (Fig. 4.37, 4.38). During the tests the tab deflections of 20° were obtained in wind tunnel when a inflow was 40 m/s [109÷111].

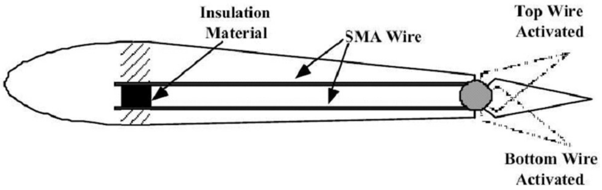

Fig. 4.37. Blade with SMA wires

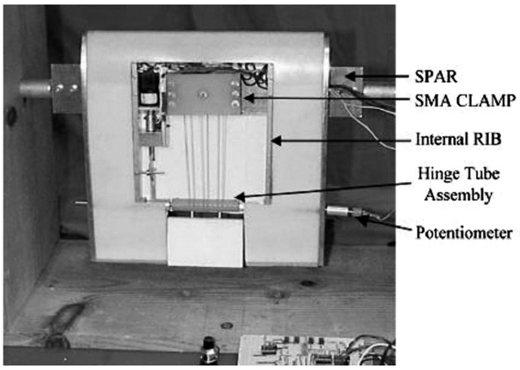

Fig. 4.38. The segment of rotor blade with 3 SMA wires

SMA Trim Actuator (SMART) was used for actuating of trailing-edge flap on Boeing MD-900 Explorer (Fig. 4.39) [112÷116]. It was used to adjust trailing-edge trim-tab on a helicopter rotor for in-flight blades tracking. Also a doubled X-frame piezostack actuator deflecting a trailing-edge flap was used for blade active control for noise and vibration (Fig. 4.40).

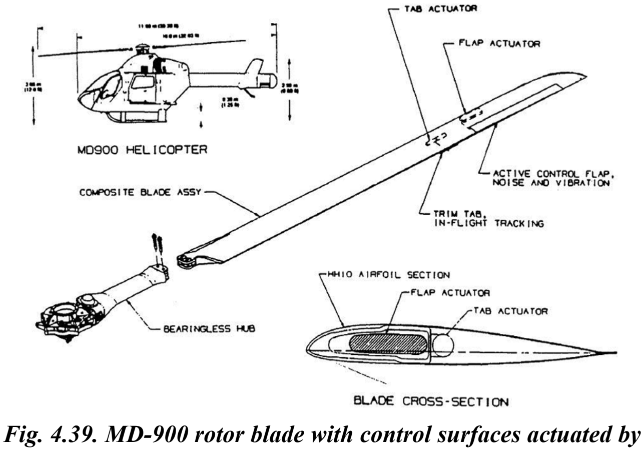

Fig. 4.39. MD-900 rotor blade with control surfaces actuated by SMART and X-Frame

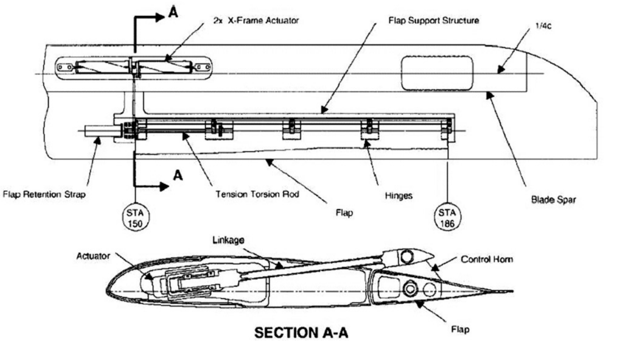

Fig. 4.40. Doubled X-frame actuator controlling a trailing-edge flap in MD-900 rotor blade

The trim-tab was located at 72% radial position and was deflected by SMA torsional actuator developed by Memry (Fig. 4.41). The locking mechanism was designed to keep the tab in position without power to the actuator. It was designed to undergo ±7.5° in steps of 0.25°.

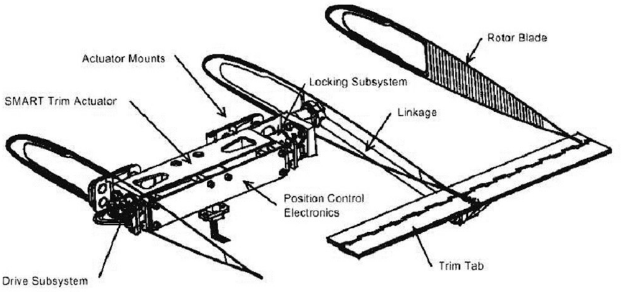

Fig. 4.41. SMART Trim Actuator used for deflecting of trim-tab

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ZASTOSOWANIE UKŁADÓW AKTYWNEGO STEROWANIA ŁOPAT WIRNIKA NOŚNEGO ŚMIGŁOWCA W REDUKCJI HAŁASU I DRGAŃ ORAZ POPRAWY OSIĄGÓW

Streszczenie

W artykule przedstawiono możliwości wykorzystania aktywnego sterowania łopat wirnika nośnego śmigłowca do redukcji hałasu i drgań oraz poprawy osiągów. Prace w zakresie opracowywania nowych, cichych i efektywnych pod względem osiągów aerodynamicznych i sterowania wirników nośnych śmigłowców są prowadzone praktycznie przez większość ośrodków badawczych oraz wytwórców śmigłowców na świecie. Własności wirnika nośnego w największym stopniu decydują o parametrach eksploatacyjnych całego śmigłowca: osiągach, manewrowości, poziomie drgań i hałasu, jakości sterowania, itd. Jednym ze sposobów poprawy osiągów wirnika nośnego jest zastosowanie układu aktywnego sterowania łopat wirnika nośnego śmigłowca. Badania nad takimi rozwiązaniami są obecnie prowadzone przez przemysł lotniczy na świecie (Eurocopter, Boeing) (rys. 1). Są one także tematem projektów w ramach europejskich programów badawczych (FRIENDCOPTER). Układy aktywnego sterowania są konstruowane z wykorzystaniem różnorodnych materiałów inteligentnych, które działają jako czujniki i/lub siłowniki, co pozwala na szybkie dostosowanie sterowania do zmieniających się warunków pracy sterowanego układu. Najczęściej stosowane materiały piezoelektryczne są wbudowywane w konstrukcję łopaty jako moduły z piezosiłownikami lub piezokompozyty. W zależności od sposobu zabudowy wielkością sterowaną jest kąt wychylenia klapki lub odkształcanie segmentu łopaty w celu zmiany jego kąt skręcenia. W zależności od miejsca zamocowania materiałów inteligentnych aktywne sterowanie dotyczy całej łopaty lub tylko jej zewnętrznej części.

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ПРИМЕНЕНИЕ СИСТЕМ АКТИВНОГО УПРАВЛЕНИЯ ЛОПАСТЕЙ НЕСУЩЕГО ВИНТА ВЕРТОЛЕТА ДЛЯ УМЕНЬШЕНИЯ ШУМА И КОЛЕБАНИЙ, А ТАКЖЕ УЛУЧШЕНИЯ ХАРАКТЕРИСТИК

Резюме

В статье представлена возможность использования активного управления лопастей несущего винта для уменьшения шума в колебаний, а также улучшения характеристик. Работы в области разработки новых, тихих и эффективных в отношении аэродинамических характеристик и направления несущих винтов вертолетов проводятся практически в большинстве исследовательских центров и вертолетостроительных заводов в мире (1-5). Свойства несущего винта в наиболешей степени определяют эксплуатационные параметры вертолета в целом: характеристики, маневренность, уровень колебаний и шума, качества управления и т.д. Одним из способов улучшения характеристик несущего винта является применение активного управления лопастей несущего винта. Исследования таких решений проводятся в настоящее время в мировой авиапромышленности (Eurocopter, Boeing), фиг. 1. Они являются также темой проектов в рамках европейских исследовательских программ (FRIENDCOPTER). Системы активного управления разрабатываются с применением разнообразных интеллигентных материалов, которые действуют как датчики и/или сервомотор, что дает возможность быстро приспособливать управление к изменяющимся условям работы управляемой системы. Наиболее часто применяемые пьезоэлектрические материалы встраивают в конструкцию лопасти как модули с пьезосерводвигателями либо пьезокомпозиты. В зависимости от способа встройли управляемой величиной является угол отклонения щитка либо деформация сегмента лопасти с целью изменения его угла скрутки. В зависимости от места крепления интеллигентных материалов активное управление касатся целой лопасти или только её внешней части.