EXPERIMENTAL INVESTIGATION OF AN ACTIVE TWIST MODEL ROTOR BLADE WITH A LOW VOLTAGE ACTUATION SYSTEM

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ABSTRACT

Smart materials that are directly embedded in the rotor blade structure are an attractive concept for active blade control. Operating as solid state actuators they can generate a twist deformation of the rotor blade without any friction and wear. A promising approach is the use of anisotropic piezoelectric strain actuators embedded in the rotor blade skin. Especially in Europe and the US this concept has been intensively investigated over the past years. A major drawback of all configurations studied so far is the high operation voltage of up to 2000V of state of the art piezoelectric actuators. Within the Green Rotorcraft Project of the European Joint Technology Initiative Clean Sky a new approach with a low voltage piezoelectric actuation system operating at 120V is investigated to demonstrate the feasibility of this technology.

A first major step in this direction was done by conducting a centrifugal test with a model rotor blade. The objective of the centrifugal test was to demonstrate the performance of the actuation system and the structural concept under centrifugal loads by showing that the expected twist deformation can be achieved at the nominal rotation speed and different actuation frequencies. For the centrifugal tests a comprehensive test matrix was derived starting with the measurement of the static peak to peak twist displacement with increasing rotation speed from 280 RPM up to the nominal rotation speed of 1043 RPM for a mach scaled model rotor followed by a measurement of the tip twist at different excitation frequencies from 1/rev up to 6/rev. Since the full scale rotor is operated at significant lower rotation speeds the results of the model rotor blade are also significant for a full scale blade.

The main characteristics of the blade were taken from the well-known BO 105 model rotor blade. The BO-105 model blade features a C-spar made of unidirectional glass fiber, a glass fiber skin and a foam core. It has a radius of 2m and a chord of 121mm. The new actuation system was successfully integrated into the glass fiber skin of the model rotor blade. All actuators endured the manufacturing process in an autoclave at a temperature of 120°C and a pressure of 6 bar. To allow a comparison of state of the art actuators with the new low voltage actuation system the blade was equipped with two different kinds of actuators. It was demonstrated that the new actuation system is capable to operate under high centrifugal loads. In comparison to state of the art actuators (operation voltage -500…1500V) the new actuation system (operation voltage -20..120V) exhibits higher active twist performance per active area.

1 INTRODUCTION

The superposition of flight speed and the rotational speed of the main rotor leads to asymmetric flow conditions between the advancing and retreating side. This asymmetric the flow condition in the rotor disk is growing with increasing flight speed. At the advancing side the flow reaches transonic and critical velocities resulting in local shock waves which are a major source of noise in high-speed forward flight. At the retreating side flow separation and stall occur. Flow separation as well as shock waves are of high dynamic nature and induce vibrations.

In low speed flight as well as descent flight, rotor noise and vibration are mainly caused by blade vortex interactions (BVI). In contrast to fixed-wing aircrafts for which tip vortices are moving downstream away from the wing, those created by helicopters remain in the vicinity of the rotor for several revolutions. This causes multiple blade vortex interactions when rotor blades encounter previously generated tip vortices or pass them very close. Consequently, the velocity field around the blades is changing and the altered angle of attack generates unsteady airloads on the blades which originate noise and vibration.

A reduction of noise and vibration is most effective when the disturbing forces are attenuated at their origin e.g. by an individual control of the blades. A promising approach is the use of anisotropic piezoelectric strain actuators embedded in the rotor blade structure, capable of generating a direct twist deformation of the rotor blade. In comparison to approaches using flaps, which generate an aerodynamic moment to deform the blade, the complexity of the actuation system is rather low. Since no moving parts are involved there is no friction and wear. This is of special importance in a helicopter environment with high centrifugal forces. The same applies for the fact that no heavy mechanical components have to be installed inside the blade causing high loads on the rotor blade structure. In addition to that the active twist concept guarantees a very smooth surface of the blade whereas flaps have distinct edges producing additional vortices and sources for noise and vibration.

2 STATE OF THE ART IN ACTIVE TWIST BLADES

The first active twist rotors using piezoceramic materials to actuate the blade were presented by Chen and Chopra from the University of Maryland. From 1993 to 1996 they built and hover tested a series of 1/8th Froude scaled model rotors. The rotor blade skins incorporated piezoceramic plates using the transversal piezoelectric d_{31}-effect[1]. They achieved twist angles of 0.3° in a hover test.

In 1995 a team joining scientists from Boeing, Penn State University and MIT started research in the field of active rotors. After proving the concept with a 1/16th Froude scale model rotor, they investigated the capability of active twist of two 1/6th Mach scale rotors (Active Material Rotor AMR). At this moment it was not sure whether the generation of structural twist or the twist generation via flaps is favorable, the first phase of this project included the design, manufacturing and testing of both design principles. At the beginning of the project the active twist concept was rated as the high risk approach whereas the flap design was considered to have low risk. This direct comparison by the same team of engineers developing both concepts side-by-side pointed out many advantages of the active twist concept. Actually the active twist concept turned out to be the low risk approach. Because of the encouraging results the active twist concept was applied to a modern planform and airfoil rotor blade. The active twist blades were actuated by interdigitated piezo fiber composites integrated in the spar of the rotor blade and achieved active twist angles of 2.8° in a hover test [2].

In 1999 a joint venture from NASA, Army and MIT built and tested an active twist rotor (ATR) with a structural design similar to the Boeing model rotor. This rotor was conceived for testing in heavy gas medium, in the NASA Langley Transonic Dynamics Tunnel. This rotor is so far the only one which is wind tunnel tested under forward flight conditions. The twist was generated via Active Fiber Composite piezoelectric actuators embedded into the rotor blade spar[3][4][5].

In 2004 Boeing investigated the possibility of scaling the results of the Mach-scaled rotor to a full scale rotor blade. The main focus of this investigation was laid on production and manufacturing approaches concerning the incorporation of the piezoelectric actuators and a robust and reliable wiring to provide the necessary power to the actuators. A 1.8m CH-47D blade section with 24 layers of active fiber composites embedded in the spar laminate was build and successfully tested. It was shown that a full scale active twist blade with a meaningful actuation capability and acceptable natural frequencies can be built within the weight limit of a passive blade[6].

Motivated by these promising results and the potential benefits, the German Aerospace Center (DLR) started to work on active twist blades with improvements in actuation technology and alternative structural concepts to bring this technology a further step forward[7],[8],[9]. First experiments to demonstrate the performance of an active twist model rotor blade under centrifugal loads showed an active twist angle of about 4°[10]. Several generations of active twist blades with different planforms and airfoils have been built and successfully tested[11]. The purpose of this work is to prove the feasibility of a new low voltage actuation system for active twist rotor blades.

3 ACTUATION TECHNOLOGY

Actuators and sensors on the basis of smart materials are essential parts of active rotor systems. As integral structural components these materials can also provide load carrying capabilities at the best. Due to several advantages, piezoceramic materials are most commonly used as smart materials for active rotor systems. The reasons for the popularity of piezoceramic materials are on the one side of technical nature but there are also some “practical” reasons. On the technical side it’s especially their ability to operate at high frequencies and the high stiffness of the material (typical 60 GPa), what is of special importance when used as actuators. In addition to that it is relatively easy to activate the material by a simple electrical field. The "practical" reasons are primarily the good availability and the reliable quality of the material. Piezoceramic materials are produced on an industrial level and a growing number of manufactures offer different types and shapes. Also the price is quite moderate in comparison to more exotic materials. The main disadvantage of piezoceramic materials is their inherent brittleness. Whereas it is no problem to apply high compression loads, tensile loads must be avoided at any time. Therefore the processing and structural integration of this sensitive material has to be done very carefully to avoid damages.

An appropriate solution for this problem is the use of so called "piezo composites"[15]. Piezo composites are a combination of piezoceramic materials with ductile polymers to form a robust and easy to use actuator and/or sensor. Especially their susceptibility to damage is significantly reduced by this measure. By the arrangement of the piezoceramic material the properties of the composite (e.g. stiffness or damping) can be specifically adjusted. Components like electrodes, electrical contacts or insulators can also be embedded into the composite. Generally the embedding is done at the curing temperature of the polymer (typical 120-180°C). Because of the different coefficients of thermal expansion (CTE) of the polymer in comparison to the piezoceramic material and due to the shrinking of the polymer during curing, the piezo material is provided with a beneficial mechanical pre-compression. This pre-compression allows applying (limited) tensile loads to the actuator during operation.

In adaptive structures only the longitudinal (d_{33}-effect) and the transversal (d_{31}-effect) effect are used for technical relevant piezo composites. The arrangement of the electrodes determines which effect will be used. The simplest configuration can be realized by using the d_{31}-effect. In this case the in plane contraction of the piezoceramic material is used when a positive electrical field is applied in perpendicular direction through the thickness of the piezoceramic plate. Thus the piezoceramic plate is provided with very thin layers of conductive material (a few µm) to build uniform surface electrodes. The electrical field is generated homogenously between these electrodes (Figure 1a). The thickness of the piezoceramic plate defines the distance between the upper and lower electrode and therefore the voltage that is needed to generate a certain electrical field. With a usual plate thickness of 0.2mm a voltage of 200V is necessary to generate an electrical field of 1kV/mm.

Up to three times higher deformations can be achieved with the d_{33}-effect. In this case the electrical field and the effective deformation have the same direction. Applying a positive field will result in an expansion of the piezoceramic device in the direction of the field and in a contraction perpendicular to this direction. The challenge is the generation of an in plane electrical field. A feasible technical solution is the use of interdigitated electrodes. In this configuration the electrodes are made of two comb-like electrodes with opposite polarity, which are applied on the surface of the piezoceramic material. The electrical field is generated between the fingers of the electrode and penetrates the piezoceramic material as well. Due to this special design the electrical fields are not very homogenous (Figure 1b). This has a direct impact on the minimal electrode distance and hence on the operation voltage. If the distance between the electrode fingers is too small in comparison to the thickness of the piezoceramic material, the electrical field cannot sufficiently penetrate the piezoceramic material and the efficiency of the actuator is reduced. In addition to that, the areas below the electrode fingers do not contribute to the actuation strain. If the electrode distance is reduced, the number of electrode fingers increases and also the "dead" areas below the electrodes. This can only partly be compensated by very thin electrode fingers. Besides technical limitations in producing very thin electrode fingers, such a configuration will also cause very high electrical field gradients in the vicinity of the electrodes. These high gradients are leading to high mechanical loads in the piezoceramic material, having an impact on lifetime and durability. A suitable electrode distance for a piezoceramic device with a thickness of 0.2mm is between 0.5 – 1mm. In this case, without considering the field inhomogeneity, a voltage of 500 – 1000V is necessary to generate an electrical field of 1kV/mm.

For piezo composites with interdigitated electrodes, fibre like architectures that are referred to as Active Fibre Composites (AFC) turned out to be advantageous in comparison to monolithic designs[14]. Cracks caused by the inhomogeneity of the electrical field will propagate through monolithic plates whereas these cracks are stopped at each interface between the polymer and the piezoceramic fibre. Besides this, fibre based actuators allow a directed actuation what is of advantage especially for active twist blades. A negative aspect of fibres with a circular cross section is that there is only a very small contact area between the electrode fingers and the piezoceramic fibre. Thus the penetration of the electrical field is aggravated resulting in even higher operation voltages or less performance. An improvement is the usage of fibres with rectangular cross sections to reduce the dielectric loss[17].

An essential drawback of fibre based composites is the very labour intensive manufacturing process. Up to know it is primarily handwork to place many single fibres close to another. This causes quality problems resulting in deviations of the actuator characteristics. Also the production and the following sintering process of PZT fibres are very cost intensive. An alternative manufacturing process uses commercially available PZT-wafers that are cut into ribbons[16]. In this case the wafer is placed on a tacky film and cut with a wafer saw that is common within the production of silicon based integrated circuits. With this automated process the rectangular fibres or ribbons are aligned exactly in parallel. This type of piezocomposite is called Macro Fibre Composite (MFC) and is commercialized by Smart Materials Cooperation[16].

In many applications it is required to significantly reduce the operation voltage of piezoelectric actuators without reducing the active strain. The use of high voltages in technical systems is associated with some severe drawbacks. Besides harder official safety regulations there are insulation issues and high voltage electronic components are usually more expensive. Also the acceptance of the user is may be lacking. The desire to reduce the operation voltage of piezoelectric actuators led to the development of multilayer stack actuators. Conventional stack actuators are made of piezoceramic plates, which are glued together in a stacking sequence. To contact the electrodes, sheets of copper are also incorporated within the glue layer. The drawback of this design is the decreasing stiffness of the actuator with increasing length (or increasing number of glue layers). Also the operation voltage cannot be reduced significantly because this would mean a reduction of the piezoceramic plate thickness; hence an increased number of plates with even more glue layers. Also the manufacturing and handling of individual thin plates is difficult.

In the manufacturing process of multilayer stacks the electrodes are incorporated during the sintering process as very thin layers (few µm). The stack itself is a monolithic block with integrated electrode layers. Therefore the influence of the electrodes on stiffness and performance is very low. This allows a reduction of the distance between the electrodes, what leads to a significantly reduced operation voltage. Standard multilayer stack actuators are operated with a maximum voltage between 120 - 160 V, achieving active strains up to 1800µm/m. Recent developments in automotive industry lead to the usage of multilayer stacks in fuel injection systems. Due to the mass production a reduction in price and an improvement in quality and reliability of multilayer stacks can be observed. Encouraged by this progress a concept has been developed to utilize multilayer stack actuators for a new type of low profile piezo composites[19][20][21].

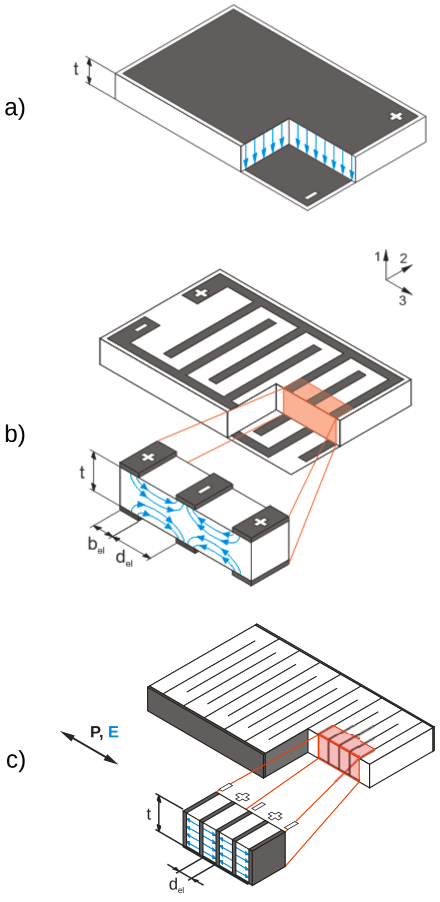

Figure 1: Field distribution in different electrode configurations; a) d_{31}-actuator; b) d_{33}-actuator with interdigitated surface electrodes; c) d_{33}-actuator based on multilayer stacks

To exploit the multilayer technology for low-profile piezo composites a technology has been developed that allows to cut multilayer stacks into thin (0.2-0.5mm) plates and to embed the fragile multilayer plates into a composite to form a robust and easy to use transducer. As depicted in Figure 1c this design results in a homogenous field distribution over large areas of the piezoceramic material.

The starting point to produce a high strain low voltage piezo composite is a commercial available multilayer stack (Figure 2a). In a first step the multilayer stack is provided with a thin conductive collector electrode (Figure 2b). External loads, or loads that a generated during operation of the stack actuator can lead to cracks in the collector electrode. This would result in a partially or complete failure of the actuator. To compensate for this problem an additional elastic collector electrode is applied (Figure 2c). Several stacks are aligned in one row to increase the productivity of the process. Using a dicing saw, thin plates with a thickness of 0.3mm are cut from the block (Figure 2d, e). The next step in the manufacturing process is the embedding of the brittle and sensitive multilayer plate in a polymer to form the actual composite (Figure 2f). Because the dimensions of the multilayer plates are limited, an array of plates can be arranged in one composite to enlarge the active area. To increase the productivity of the process several composites are manufactured at once and separated afterwards.

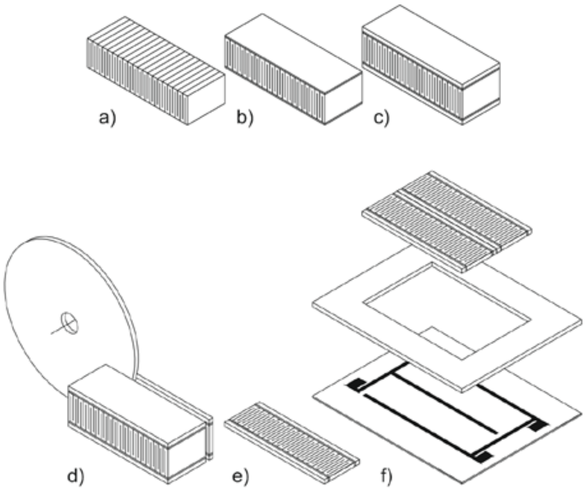

Figure 2: Principle manufacturing steps to produce a low voltage high strain piezocomposite actuator; a) multilayer stack; b) collector electrode; c) flexible collector electrode; d) dicing; e) multilayer plate; f) packaging

A typical strain-voltage curve of a multilayer piezo composite is plotted in Figure 3. With an electrode distance of 53µm and a maximum voltage of 120V, a maximum electrical field of 2.26kV/mm was applied. All measurements were made applying a quasi static excitation of 0.1Hz with a triangle wave form. The average active free strain that was measured with an operation voltage of 120V was 1285µm/m. In comparison to state of the art d_{33}-piezocomposites with interdigitated surface electrodes, which need voltages of up to 1500V or even 2000V to achieve same active strain levels, this actuator has demonstrated that it is possible to drastically reduce the operation voltage of d_{33}-piezocomposites without a loss in strain performance.

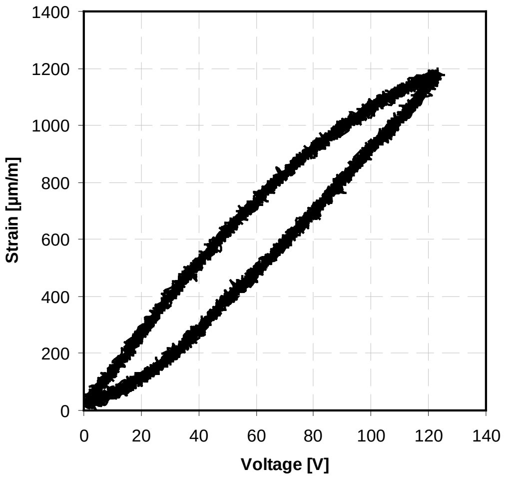

Figure 3: Exemplary strain-voltage curve of a multilayer piezocomposite

4 BLADE DESIGN AND MANUFACTURING

The main characteristics of the blade were taken from the well-known BO 105 model rotor blade. The BO-105 blade features a C-Spar made of unidirectional glass fiber, a glass fiber skin and a foam core (Figure 2). The chord length of 121mm and the radius of 2m are in agreement with the original model rotor blade, whereas the profile was changed into a symmetrical NACA 0012, which does not really change the blade from a structural point of view. Because at this point no aerodynamic investigations were planned, it was not necessary to realize an aerodynamic effective blade and the manufacturing effort was reduced by building only one mold. For the same reason the blade was not pre-twisted. The actuator orientation was chosen to be +45°, whereas the skin was made of unidirectional glass fiber laminates with an orientation of -45° (inner skin). The area surrounding the actuators was provided with additional unidirectional glass fiber layers in a +45° direction in order to carry the loads of the actuators and to decrease the change in stiffness in the transition region between skin and actuators. The anisotropy of the skin allows the actuators to work in a relatively soft direction (approximately perpendicular to the fibers in the inner skin), whereas the complete blade still keeps its torsional stiffness by the shear stiffness perpendicular to the actuators.

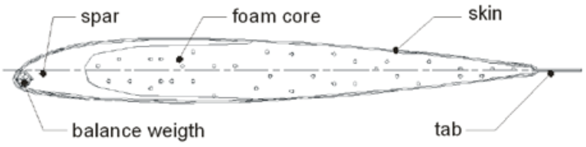

Figure 4: Cross section of the model rotor blade

The manufacturing process of the upper and lower blade skin started with the placement of the actuators into the mold followed by the glass fiber prepreg. Accordingly the strain gauge instrumentation and the complete wiring were positioned onto the uncured prepreg. In the next step the lay-up was put in a vacuum bag and cured in an autoclave at a temperature of 120°C and a pressure of 6 bars. Because actuation and instrumentation are entirely integrated into the rotor blade skins, it was possible to keep the internal design similar to that of conventional passive blades. The spar and the foam core were machined to the desired shape using pre-cured unidirectional glass fiber laminates and foam blocks, respectively. Balancing weights made of tungsten 40mm long rods were added into the nose of the spar using a cold setting epoxy. Finally the upper and lower skin, the spar and the foam core were bonded together with an adhesive film and cured at 120°C.

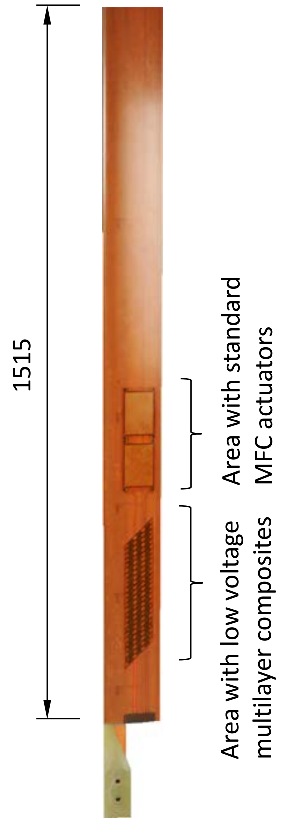

Figure 5: Top view of the active twist blade

To keep the costs of the experiment to a minimum only a small section of the blade was equipped with 25 multilayer actuators on each side. To compare the new actuators with conventional ones also two standard 45° Macro Fiber Composite (MFC) actuators were placed on each side of the blade (Figure 5). The designs of the two actuators are depicted in Figure 6. In this configuration the low voltage multilayer actuators covered an active surface of 0,0104m² and the MFC actuators covered an active surface of 0,0194m².

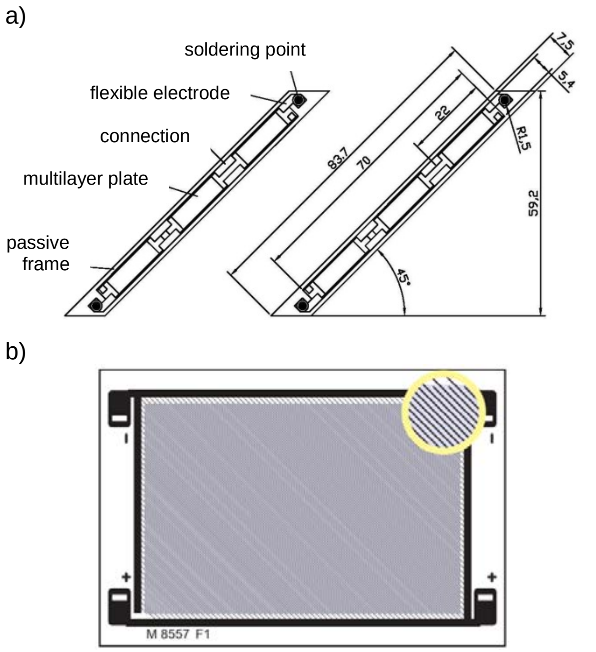

Figure 6: a) Low voltage multilayer actuators operating at -20…+100V; b) High voltage MFC actuators operating at -500V…1000V[18]

A detailed view of the multilayer actuators integrated into the blade skin is shown in Figure 7.

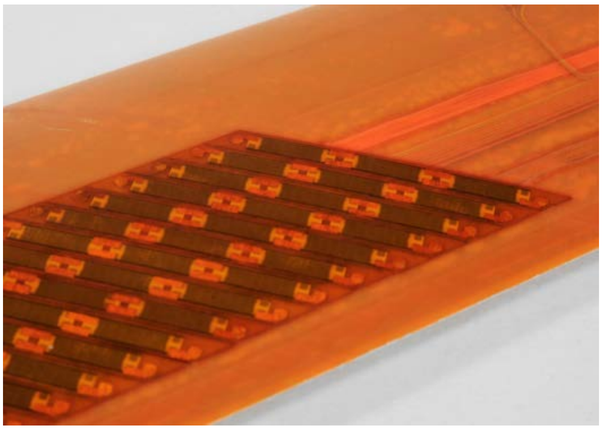

Figure 7: Detailed view of the multilayer actuators integrated into the blade skin

5 EXPERIMENTAL TEST SETUP

The objective of the test was to demonstrate the performance of the actuation system and the structural concept under centrifugal loads by showing that the expected twist deformation can be achieved at the nominal rotation speed and different actuation frequencies. For this purpose a test rig was installed at the DLR rotor tower in Braunschweig (Figure 8). The test rig is driven by a 30kW DC shunt-wound motor. A balancing weight is mounted on the opposite side to balance the blade. The direction of rotation is clockwise. To reduce the mechanical complexity the pitch links have been removed. Data transfer is realized by 24 slip rings and an additional telemetry system with 12 channels for strain gauge measurements (full bridge or half bridge) and 4 ICP channels for acceleration sensors. Four special designed high voltage slip rings transfer the required electrical power to the actuators in the blade. The actuators were driven with power amplifiers with a peak to peak voltage of +/-2000V and a maximum current of 400mA. A camera, installed in the rotor tower, allows a permanent monitoring of the experiment from the control room.

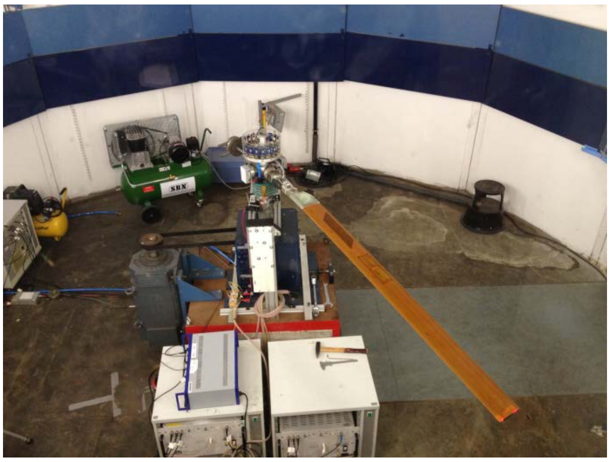

Figure 8: Blade mounted in the test rig

To measure the active twist angle an optical measurement system was installed. The system consists of two LED’s attached at the leading- and trailing edge of the rotor blade tip and a stationary high speed camera system. By properly triggering the camera the twist movement of the blade can be visualized by the two light dots of the LED’s. In comparison to a system that needs a powerful stroboscope light, capable of sufficiently illuminate the blade tip, this solution is much cheaper and also facilitates the analysis of the blade tip motion. Because the LED’s appear as clearly distinguishable points, standard image processing tools can be used to automatically determine the twist angle.

6 TEST RESULTS

For the centrifugal tests a comprehensive test matrix was derived beginning with the measurement of the static peak to peak twist displacement with increasing rotation speed starting from 280 RPM up to the nominal rotation speed of 1043 RPM (109 rad/s; 17,35 Hz). All measurements were made using the optical measurement system. The actuators were driven within a voltage range of -500V to +1000V for the MFC actuators and -20V to +100V for the multilayer composites with a quasi static excitation of 0.15 Hz.

As shown in Figure 9 for all rotation speeds the tip twist is nearly the same at a quasi-static excitation of 0.01Hz. This measurement confirms, that the actuation system is capable of generating sufficient twist under centrifugal loads and that there is no performance decrease in comparison to the no rotating case.

The next test comprised a measurement of the tip twist at different excitation frequencies from 1/rev (17,4 Hz) to 6/rev (104,3 Hz). The actuators were driven in the same voltage range. At a frequency of 1/rev and 2/rev the tip twist is equal to the quasi static twist. Because of resonance effects in the vicinity of the first torsional eigenfrequency the amplitude at 3/rev and 4/rev is even higher. Above the first torsional eigenfrequency the tip twist is reduced at 5/rev and 6/rev.

A comparison of the new actuation system with the conventional MFC actuators is given in Figure 10. Here only the values at the nominal rotation speed of 1043 rpm are shown. The measured tip twist is normalized with respect to the active area of each actuator configuration (0.0194m² for MFC, 0.0104m² for Multilayer composites).

It is obvious that for all actuation frequencies the new actuation system generates more active twist. At 3/rev and 4/rev a significant higher twist is measured with the new actuation system. This is mainly due to the position of the actuators near to the blade root, which is a better position to excite the 1st torsional eigenform.

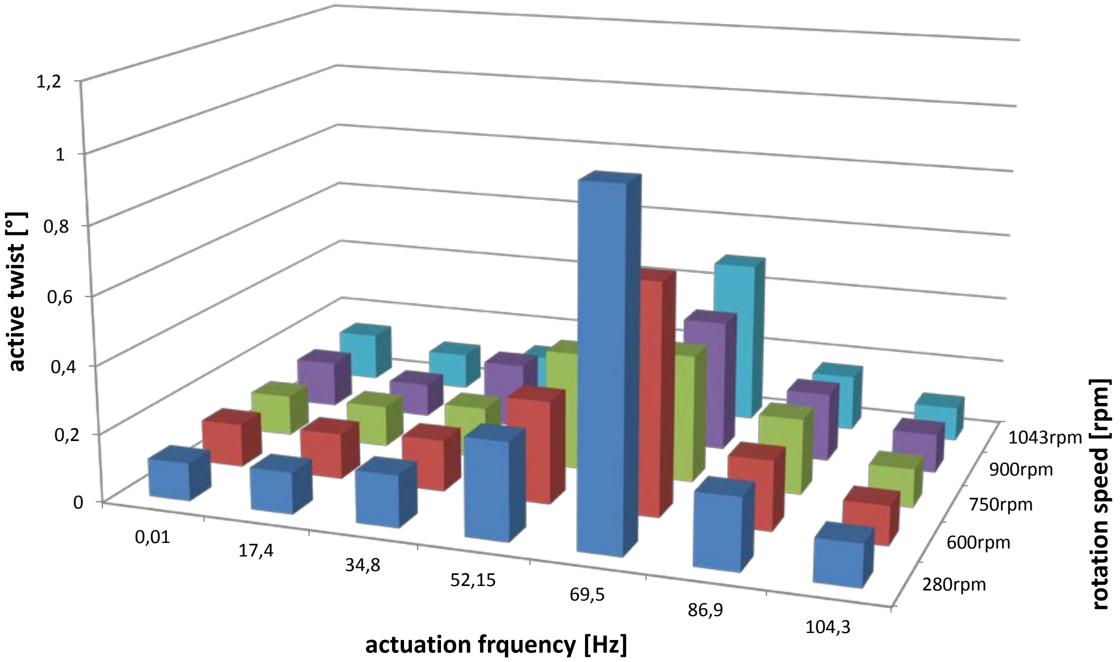

Figure 9: Active twist performance at different rpm and actuation frequencies for the new actuation system

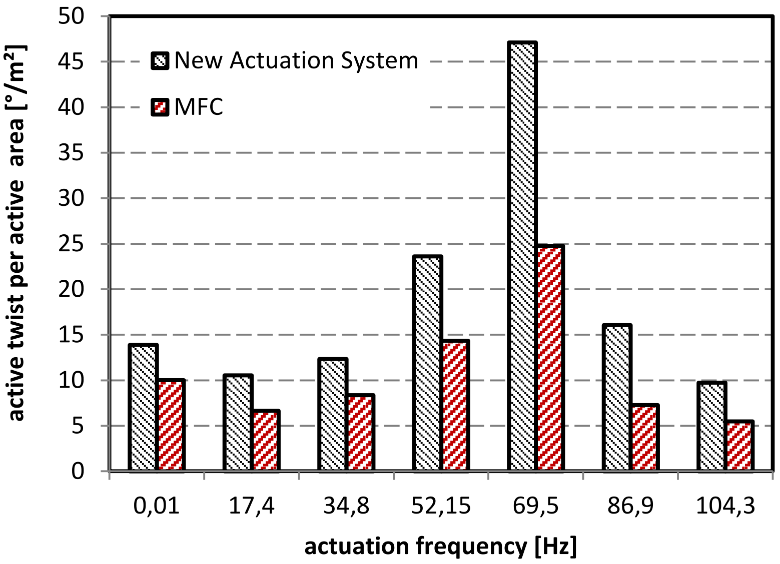

Figure 10: MFC vs. multilayer composite actuation system with respect to active area at a nominal rotation speed of 1043 rpm

7 SUMMARY AND CONCLUSION

The test has shown that it is possible to integrate the new actuation system into the composite structure of a model rotor blade. All actuators survived the manufacturing process, which is related with a temperature of 120°C and a pressure of 6 bar. It was demonstrated that the new actuation system is capable to operate under high centrifugal loads. In comparison to MFC actuators (operation voltage -500…1000V) the new actuation system (operation voltage -20..120V) exhibits higher active twist performance per active area.

The next step is to build a 2m full scale blade segment equipped with this new actuation technology. This blade segment will be tested in a special test rig, which allows applying tension, torsion, bending and lateral forces in parallel to simulate realistic blade loads. The purpose of this test is to proof the maturity of the concept for full scale rotor blades.

ACKNOWLEDGEMENT

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