# PRELIMINARY STUDY ON STRUCTURAL PROPERTIES OF ACTIVE TWIST BLADES

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## Abstract

The objective of this paper is a finite element (FE) parameter study on the effect of various geometric and material parameters on the twist performance of active twist blades with distributed piezoelectric actuation. Parameters that were investigated include geometry and design such as layer set up, degree of anisotropy and fiber angle of the passive material and the actuator as well as thickness ratio of passive to active material.

In this initial study the blade skin was considered to have the largest influence on the torsional rigidity of a blade. That is why the output parameter that was looked at is not only the twist, but the rigidity, also.

Investigations were based on a simple (almost) rectangular cross section with the thickness to chord ratio of a NACA 23012 airfoil.

The goal was a qualitative comparison of the different configurations.

## Nomenclature

| | |
|---|---|
| $a$ | Distance of electrodes in an actuator |
| $d_{ij}$ | Piezoelectric constants |
| $E$ | Electric field |
| $E_{x,y,z}$ | Youngs modulus with direction |
| $G_{xy}$ | Shear modulus with direction |
| $GI$ | Torsional rigidity |
| $h_a$ | Thickness of active ply |
| $h_p$ | Thickness of passive ply |
| $T$ | Temperature |
| $U$ | Voltage |
| $W$ | Working capability (twist * GI) |
| $\alpha$ | Fiber angle |
| $\alpha_T$ | Thermal expansion coefficient |
| $\beta$ | Actuation angle |
| $\varepsilon$ | Strain |
| $\vartheta$ | Twist angle of Box |
| $\nu$ | Minor Poisons ratio |
| $\rho$ | Density |
| $\varphi$ | Fiber volume ratio |

## Introduction and Motivation

Individual blade control for helicopter rotors promises to be a method to increase flight performance and to reduce vibration and noise.

One focus in developing such systems is the use of active materials. Quite a bit of research (especially by NASA and MIT [1] [2]) is going towards the feasibility and effectiveness of distributed patch actuators within the bladeskin for twist actuation. These actuators are embedded in the blade skin to induce anisotropic strain. Recent developments enabled the use of the longitudinal piezoelectric effect for the design of smart composites [6]. To benefit from the higher longitudinal effect ($d_{33}$) so called interdigititated electrodes (IDE-electrodes) are used. This design is realized with two interlaced comb like electrodes symmetrically arranged on each side. To obtain an anisotropic and structural conformable actuation, piezoelectric ribbons are used to manufacture low profile and flexible actuators for integration in composite structures. The manufacturing process uses commercially available PZT-wafers that are cut into ribbons. In this case the wafer is placed on a tacky film and cut using a wafer saw that is typically used for the production of computer chips. With this automated process the ribbons are aligned exactly in parallel. In the following manufacturing steps the gaps between the ribbons are filled with resin and polyimid films with IDE-electrodes are glued on the top and the bottom of the assembly. This design has been developed by NASA and is called "Macro Fiber Composite" [7]. It is now commercially available from Smart Materials Cooperation [8].

Within the DLR/ONERA common rotorcraft research a project called Active Twist Blade (ATB) was established in which two concepts of active twist are investigated. Because of the low stiffness and comparatively easy structure of the Bo 105 blade, both concepts are to be implemented into the geometry of a Bo 105 model-rotor-blade (scaled 1:2.5). The structural properties – like eigenfrequencies and stiffnesses – of the blade should be changed as little as possible. One of these concepts is actuation by distributed actuators within the blades skin. Differing from other concepts using distributed actuation the benefits of using anisotropic structural material to optimize the twist performance of the blade will be investigated. In

most former studies glass fabric has been used as structural material. The use of carbon fibers will be examined within this project as well.
The objective of the present paper is a preliminary FE-parameter study of different actuation schemes as proposed by Brockmann [3]. Those schemes include twist actuation with and without structural couplings as well as extension actuation with extension-twist coupling. To investigate these different actuation schemes a variation of geometric and material parameters on the twist performance of a thin walled beam was performed. Parameters that were considered include layer set up, degree of isotropy and fiber angle of the passive and active material as well as thickness ratio of passive to active material.

## FE-Model and Parameters

This study was based on a simple demonstrator structure called Active Twist Box (ATBx). The cross section of this Box is (almost) rectangular with the thickness to chord ratio of a NACA 230012 blade, the length of this probe is 2 m.

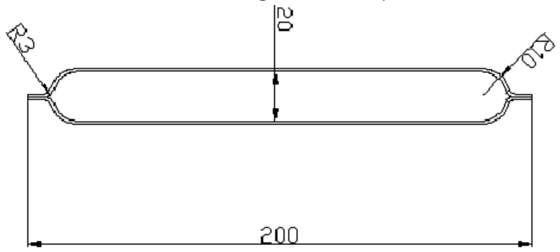


figure 1: Crossection of the ATBx (measurements in mm)

For modeling the finite element (FE) code ANSYS was used. In this code the piezoelectric effect is implemented in solid (volume) elements only. Therefore a layered shell element with thermal expansion capability was used: SHELL99. This thermal analogy to the piezoelectric effect is defined as follows:

$$\left.\begin{aligned} \varepsilon &= d \cdot E = d \cdot \frac{\Delta U}{a} \\ \varepsilon &= \alpha_T \cdot \Delta T \end{aligned}\right\} \Rightarrow d = \alpha_T \;\&\; \frac{\Delta U}{a} = \Delta T$$

The skin was modeled to consist of two types of layers: active and passive ones, where the material properties of the active layers contain a complete PZT fiber-actuator including electrodes, and insulation. The passive layer consists of the structural important fiber reinforced polymers. Six different configurations were chosen as layer set ups (figure 2).

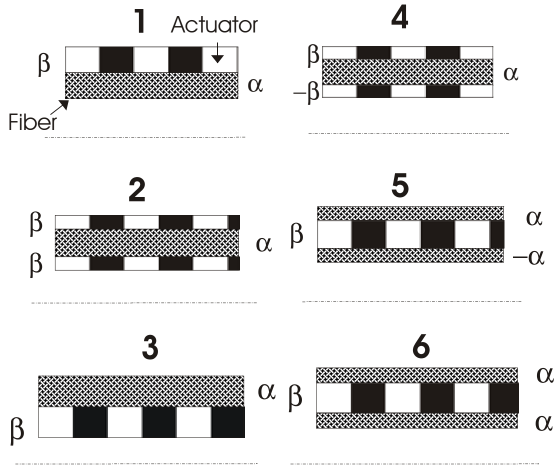


figure 2: Different tested Layer set-ups (α-fiberangle; β-actuationangle) location towards the center is indicated by symmetry line

In each case the total thickness of the active layers as well as the thermal load was kept constant, so the applied electrical field was the same in each case. The actuator type that was modeled is that of a anisotropic (piezoelectric fiber composite patch with interdigitated electrodes) actuator, so that active strain is introduced in one direction only to model the behavior of piezoelectric fiber composite patches. Static deflections were looked at, only. Four types of material were used for the passive material: GFRP and CFRP as unidirectional (UD) fibers and as fabric respectively (see Table 1 for properties). That way the extremes with respect to both: total stiffness and degree of anisotropy were covered: low and high stiffness (glass and carbon fiber), high stiffness in one direction (UD) and high stiffness in two directions (fabric).

Table 1: Material properties of different passive materials

| mat. no.: | 6 | 7 | 8 | 9 |
|---|---|---|---|---|
| description | ud-carbon (K13C2U) ep-resin LY556/HY917 ϕ=60% | ud-S-glass fiber ep-resin LY556/HY917 ϕ=60% | carbon fiber fabric (K13C2U) ep-resin LY556/HY917 ϕ=60% | S-glass fabric ep-resin LY556/HY917 ϕ=60% |
| $E_X$ [GPa] | 541,36 | 52,96 | 278,83 | 33,11 |
| $E_Y$ [GPa] | 14,97 | 12,85 | 278,83 | 33,11 |
| $E_Z$ [GPa] | 14,97 | 12,85 | 14,97 | 12,85 |
| $G_{XY}$ [GPa] | 8,664 | 6,785 | 10,397 | 8,142 |
| $G_{XZ}$ [GPa] | 8,664 | 6,785 | 8,664 | 6,785 |
| $G_{YZ}$ [GPa] | 5,717 | 4,851 | 8,664 | 6,785 |
| $\nu_{XY}$ | 0,31 | 0,262 | 0,016 | 0,102 |

| | | | | |
|---|---|---|---|---|
| $\nu_{YZ}$ | 0,325 | 0,325 | 0,31 | 0,262 |
| $\nu_{XZ}$ | 0,31 | 0,262 | 0,31 | 0,262 |
| ρ [kg/m³] | 1800 | 1974 | 1800 | 1974 |

The angle of the passive fiber as well as that of the active material was varied between 0° and 90°/180° (fabric/unidirectional material) in increments of 5°. That way the actuation schemes e.g. extension-torsion coupling as well as direct twist were investigated. Results were obtained for various thickness-ratios of passive to active material, keeping the latter constant. That way the amount of active material was the same in each case. The simulations showed the twist resulting from constantly applied electric field at the actuator.

The torsional rigidity was determined using the thin-walled, closed section, composite beam theory developed by Rehfield [4].

The layer set up as well as the passive and active fiber angles were to be optimized in order to maximize the twist with given amount of active material and torsional rigidity. Since twist increases with the decrease of torsional rigidity a skin set up had to be found that is a compromise of both. Therefore the product of twist and torsional rigidity was used as an indicator of a sections working capability for a given rigidity. The maximum of this working capability was found for each combination of skin set up and passive material respectively. Also the fiber and actuator angles associated with each of these maxima were examined.

## Results and Discussion

Results were obtained with the following varying parameters:

- 6 different layer set ups
- 2 different fiber types
- fabric versus unidirectional fibers
- 10 different thickness-ratios (hp/ha) between 0.7 and 2.5 (plus a few additional when needed)
- variation of fiber angle α between 0° and 90° in increments of 5°
- variation of actuator angle β between 0° and 90°/180° (fabric/unidirectional material) in increments of 5°

In order to compare the twist capabilities of different layer set ups, each combination of passive material, thickness-ratio and layer set up was modeled. For each of these models a variation of the angles of passive and active material was carried out. For all these cases the working capability was calculated as the product of torsional rigidity and twist angle. These working capabilities were then printed as a function of the two angles α and β. One resulting graph of such working capabilities is found in figure 3.

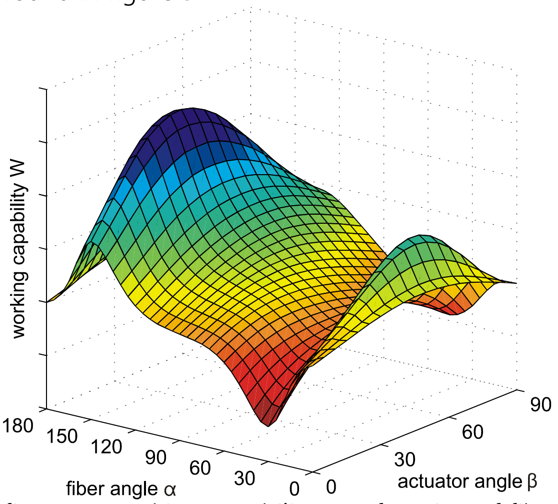


figure 3: working capability as a function of fiber and actuator angle; layer set-up no. 1; unidirectional CFRP (6); thickness ratio 1.1

For each of these figures the point of maximum working capability was found. Rigidity and twist of those points were listed together with the angle of the active and passive layer for a given layer set up. That way different layer set ups and materials could be compared.

Influence of fiber and actuator angle The influence of the fiber and actuator angle cannot be discussed in general. Each layer set up has its own behavior. In general high torsional rigidity is produced by reinforcement in α=±45° direction. At the same time induced strain in direction β=±45° is resulting in a maximum of twist – not considering coupling effects through unisotropy. In order to induce twist it is suitable to have as little stiffness as possible in this direction. These two demands have to be paired as good as possible.

According to that, there is an optimum configuration for unidirectional reinforcement at α=45° and β=-45° (based on layer set up no.1), which is in fact a comparatively good configuration. This actuation scheme represents twist actuation with twist torsion coupling. Due to a strong influence of the coupling there are some combinations of fiber- and actuator angle - which are close to that optimum described - with even better working capabilities. The maximum is found around α=-30° and β=40° (see figure 3). This matches former analytical studies by Yang [5] who found the optimum for this combination at α=-30° and β=42°.

Using fabric as passive material the angles that produce a maximum of working capability vary with the material used and the layer thickness ratio. For GFRP best values for small thickness ratios are found at α=+40° and β=-40° (see figure 4). A similar (α=+45° and β=-45°) angle combination has been used to build the active twist rotor (ATR) [1,2] and others. This configuration represents the actuation scheme twist actuation without structural coupling. Angle combination α=+35° and β=-40° show highest working capabilities for higher thickness ratios. Again these configurations are a compromise between best actuation and best rigidity. For CFRP these angles are α=+30° and β=-25°, showing the compromise again. The angle between reinforcement and actuation is bigger for this stiffer fabric.

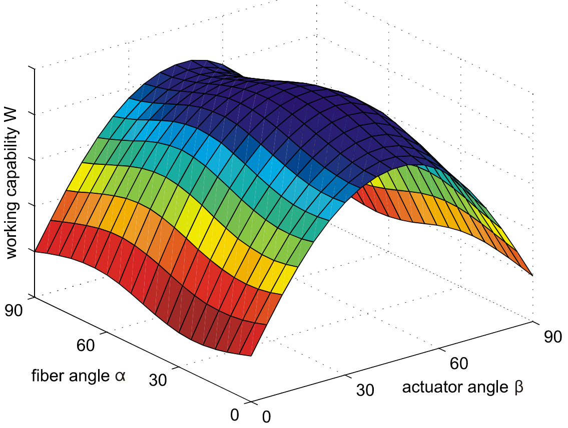


figure 4: working capability as a function of fiber and actuator angle; layer set-up no. 1; GFRP fabric (9); thickness ratio 1.1

Influence of the layer set up Concerning the performance of different layer set ups (as shown in figure 2) it was evident that there is a major influence of the layer set up on the active twist performance of the ATBx. This influence can be seen in figure 5.

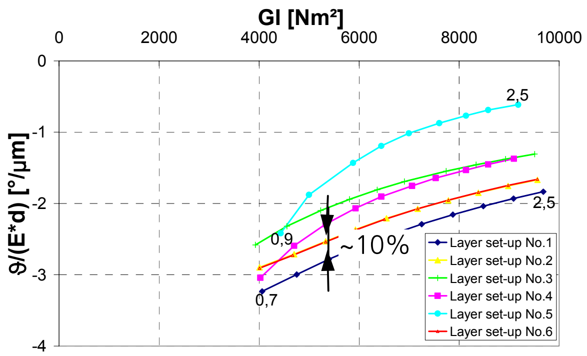


figure 5: Torsional rigidity and twist angle for material UD-CFRP (6); see appendix for figures with other materials

It was shown that putting the actuator to the outer side of the skin (layer set up No. 1) caused the largest effect for twist actuation, showing around 10% higher twist values than the second most effective configurations no. 2 and 6 (see figure 5). This was especially true for set ups with high torsional stiffness.

Compared to configuration no. 3 with the actuators on the inner side of the skin, the outer side is always to be preferred as actuator location. A significant difference between those two was found for all materials tested.

For all tested materials, angles and thickness-ratios, layer set up no. 2 and 6 produce almost identical results. The two set ups have in common that they are symmetrical, which is also true for the strain induction.

Layer set-up no. 4 building a sandwich of actuators, with angles of differing sign containing passive material inside, is an efficient lay-up for glass fabric and low thickness ratios.

Configuration 5 where two passive layers with different passive angles build a sandwich with an active layer inside, is counterproductive with high modulus unidirectional passive layers and increasing stiffness.

Even though these calculations show a preference for configuration 1 it has to be kept in mind, that the strain induced by one given actuator is limited. In this study all lay ups containing 1 actuator incorporate the same total mass of 'actuation material' as those with 2 actuators. This would not represent real application, where only one type of actuator will be used for all configurations. Giving different thickness to different configurations was done so the effectiveness of a set up could be compared. Now each set up contains the same total amount of active material.

Due to this there is a limit to those configurations which base on only one active ply (e.g. no. 1) compared to those containing two of such (e.g. no. 2 and 4).

Influence of different passive materials The influence of the passive material on the rigidity of the ATBx is obvious. The higher the stiffness – especially in fiber direction α=±45°, which is the main strain direction for twist deflection with isotropic material - the higher is the torsional rigidity of the box. Obviously using fabric also causes a higher torsional rigidity than using unidirectional fibers. It is not surprising that the highest torsional rigidity for a given thickness ratio is found with CFRP fabric (α=45°). That way the fiber direction matches the main strain direction for twist deflection. Unfortunately this configuration also hinders the effectiveness of the induced strain to produce twist. The twist stays at a minimum, so that the working capability is comparatively low for this material, too.

As it can be seen in figure 6 unidirectional passive materials show high rigidities at thickness ratios which are little higher than those of corresponding carbon fabric set ups. In addition to this good torsional rigidity it also shows a good twist capability when active and

passive fiber angle are with opposing sign (e.g. α=-30° and β=40°). The twist for those lay ups is similar for UD-glass fiber and UD-carbon fiber, but the torsional rigidity differs significantly (e.g. for fabric, thickness ratio = 0.7:
$GI_{glas}$=1400 Nm² ; $GI_{carbon=}$=4000 Nm²)
This trend gives a clear hint, that UD-carbon fiber as passive material is superior to any other configuration in respect to the working capability.

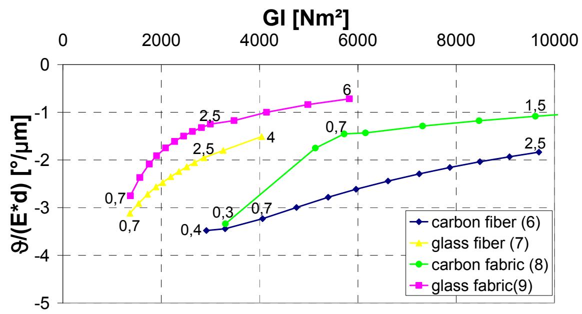


figure 6: Torsional rigidity and twist angle for layer set up no.1; different materials; thickness ratios are given at the points

<u>Influence of thickness ratio</u> The thickness ratio between passive and active material is obviously not a parameter that can be chosen freely. The thickness of the actuators are defined by the type of actuator used. Also the complete skin has to produce a certain rigidity. These two parameters have to be considered, when choosing a thickness ratio. Depending on the material stiffness the same thickness ratio leads to different torsional rigidities.

## Conclusions

The twist performance of a thin walled box with distributed actuation is influenced by many parameters. Concerning the layer set up it could be shown that it is most effective to place the actuator patch to the outside of the structure. The advantage of this placement compared to other set ups it in the range of 10% more twist actuation.
Choice of fiber and actuator angles depend on the material used. These two parameters always have to be looked at together.
The choice of passive material properties is most responsible for the torsional rigidity. It could be shown that using unidirectional CFRP in a +30° angle out of the span wise direction combined with a actuation angel of -40° produces the highest amount of twist at a given torsional rigidity. This combination of angles represents the actuation scheme twist actuation with twist torsion coupling. The absolute advantage that stiff unidirectional fibers (like carbon fibers) hold over glass fiber fabric depends on the torsional rigidity needed for the design. This results from a high stiffness through fibers in +30° direction and much lower stiffness perpendicular to that, which is used for the actuation.
Due to the increase in twist performance it can be suggested to use stiff UD fibers or fabric for reinforcement of future distributed twist actuation. Next steps in this project will include a discussion of the influence of torsion-bending coupling as a result of helical windings. Depending on this discussion UD-fabric lay ups will be considered or not.
It is planned to build a box with this most promising configurations to verify the numerical results. That way absolute values can be obtained.
Next steps will also include the transfer of the selected configuration to a real blade geometry.

## References

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Appendix

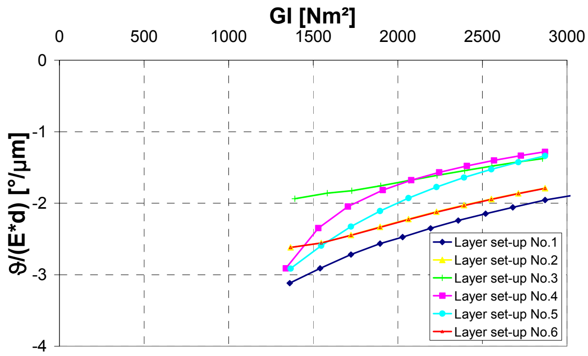


figure A1: Torsional rigidity and twist angle for Material UD-GFRP (7)

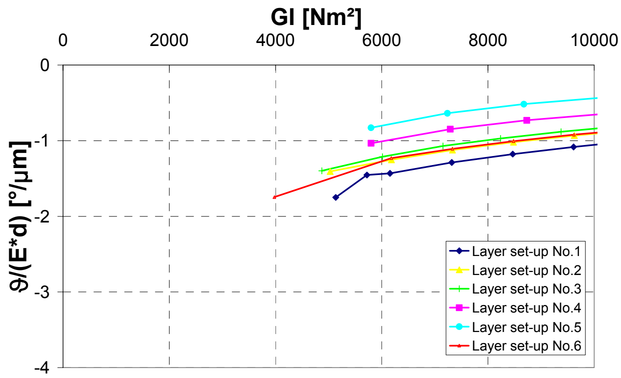


figure A2: Torsional rigidity and twist angle for Material CFRP-Fabric (8)

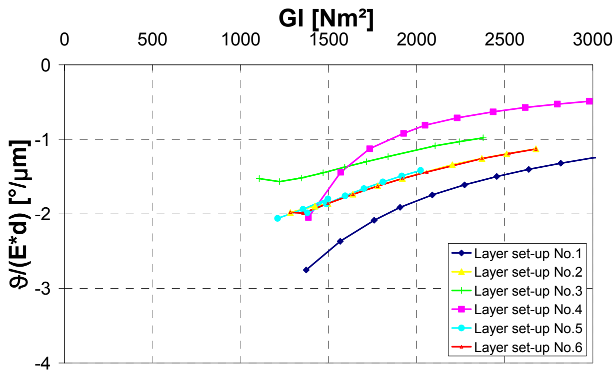


figure A3: Torsional rigidity and twist angle for Material GFRP-Fabric (9)