Upwind Work Package 1B3, deliverable 3:

“Inventory of actuators and first order evaluation of 2 actuators and structural concepts”

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2. Introduction

This is the deliverable for the work package 1B3 “Smart Rotor Blade and Rotor Control” that addresses the research into the structural implementation of the aerodynamic control concepts discussed under deliverable 2 “Inventory of aerodynamic concepts and first order modeling of 4 concepts”.

The outline of this section will be as followed. First it will be argued why there is a emphasis on the use and integration of so called adaptive or smart materials. Secondly, it will discussed which adaptive materials are suitable and finally an introduction into the structural integration of these materials will be given. In the next chapters these issues will be elaborated on.

2.1 Why adaptive materials?

The aim of the project is to add aerodynamic control capability to HAWT blades. The wish for this capability originates from the realization that blades of increasing size encounter increasing fluctuating loads and that with upscaling aeroelastic stability boundaries will be encountered. However, this control capability must be attained without increasing the price of blades to much and without adding additional maintenance issues. Therefore we are aiming for a solution where so called adaptive materials – defined here as materials that strain under a (usual electrical or magnetic) stimulus – will be employed. The advantage is that this way the adding of the control capability can be integrated in the production process, possibly adding no or little additional production steps. Moreover, many possible adaptive materials are insensitive to corrosion and the eliminate the need for moving parts, thus leading to a more durable solution.

2.2 Possible adaptive materials

A literature study into the possible adaptive materials has been performed and the following were considered:

- Piezo electric materials (both ceramics and polymers). With piezo electrics a strain of the latice or crystal structure is attained by applying an electric field.
- Ionic polymers (often called ``artificial muscles''). Ionic polymers can bend because ions, which bind water, are transported though the thickness of a gel by means of an electric field. The water transport makes one side swell and the other shrink, resulting in a bending motion.
- Electrostrictive materials. Similar to piezo electrics, but with a quadratic relation between field and strain and high temperature dependency.
- Magnetostrictive materials. They have a similar physical functionality as electrostrictives, but magnetostrictives are driven by a magnetic instead of a electric field.
- Shape memory alloys. Large strains can be recovered with SMAs due to a change in lattice structure.
- Shape memory polymers. In some polymers that exist of two phases with different glass and melt temperatures, when one phase goes in to the molten state, ``frozen in'' stresses in the other are released and the material recovers.

- Magneto-rheological fluids. The viscosity of of magneto-rheological fluids can be altered fast en dramatically by the presence of a magnetic field.

The most serious candidates are piezo electrics and shape memory alloys, which are discussed first. Others can be quickly discarded as a serious candidate for shape control. This is because of being unable to reach the required bandwidth (SMPs and ionic polymers), sensitivity (electrostrictives), the need for heavy coils (magnetostrictives) and a change in viscosity instead of dimensions (magneto-rheological fluids). The physical principle of piezo electrics and the first order evaluation that has been performed on them, will be elaborated on in chapter 3.

2.3 The importance of structural integration

Unlike has been suggested in section 1.1, adaptive materials cannot be incorporated in a blade without making some modifications to the design. in order to make structural integration feasible, some design and material issues will have to be tackled. An example of this is the fact that most current blade designs use a sandwich construction outside the spar(cap/box) area to ensure the stability of the aerodynamic shape and to increase the critical buckling load. However, in the case of trailing edge flaps, the most promising aerodynamic solution, it is very hard to deform the sandwich because it has a very high resistance against bending. This is just an example that will be tackled in chapter 4.

3. First order evaluation of piezo-electrics and shape memory alloys as adaptive materials for actuators

In this chapter, the state of the art of both adaptive materials will be presented. Subsequently, the work that has been performed within UpWind WP 1B3 will be elaborated on.

3.1 Shape Memory Alloys

3.1.1 Physical principle

Unique behavior shape memory alloys (SMA) in thermomechanical loads has been studied since early 70ties and many successful engineering applications are already in use. SMA elements are able to recover large inelastic strain upon mechanical loading at constant temperature (superelasticity), upon heating (shape memory effect), do reliably mechanical work upon heating (work as thermally driven actuators) due to the intrinsic coupling between the stress and temperature. Figure 1 summarizes basic functional behaviors of SMAs.

However, the SMA responses in thermomechanical loads, even if reversible and reproducible, are nonlinear, hysteretic and path dependent:

$$\varepsilon = f(\sigma, T, history)$$

The same value of macroscopic tensile strain may be realized at a relatively broad range of the applied stress and temperature conditions in a cyclic thermomechanical loads depending on the history (stress-temperature path). This nonlinearity and hysteresis originates from the energy dissipation accompanying thermoelastic martensitic transformation (MT) by which the SMA wire responds to stress and/or temperature variations and causes most of the problems for modelling to be dealt with below.

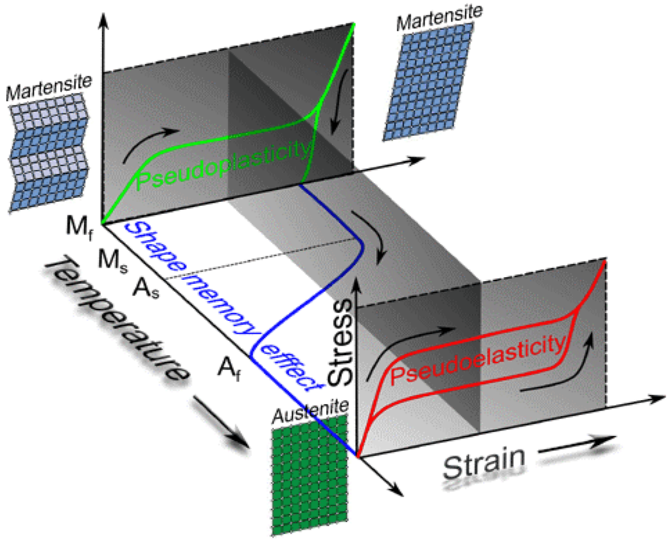

Figure 1: Basic functional thermomechanical behavior of SMA wire in uniaxial tension.

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The general aim of the SMA modelling is to develop constitutive law that would reliably capture any thermomechanical response of SMA element to thermomechanical activation (figure 1). 3D tensorial SMA models capturing SMA responses under general multiaxial stress conditions are necessary to predict thermomechanical behaviors of more complex SMA elements. On the other hand, 1D uniaxial models are sufficient to deal with the problems accounted while developing linear actuators using SMA wires. Both approaches are followed in the SMA literature for at least 40 years, nevertheless, in spite of that, no fully accepted and reliable models exist yet. In our opinion, the reason for that is multiplicity of deformation transformation processes derived from martensitic transformation taking place in activated SMA element.

A brief overview on the SMA behavior and modelling approaches

The use of SMA alloys with shape memory and superelastic properties has promoted extensive research on developing constitutive models. A micromechanics model based on the analysis of phase transformation in single crystals of copper based SMA alloys has been presented by Patoor [1] in 1994. Another micromechanical model for SMA alloys capturing different effects of SMA behaviour such as superelasticity, shape memory and rubber like effects has been presented by Sun and Hwang [2] in 1995. Phenomenological constitutive models have been presented by Tanaka, Liang and Rogers, Brinson, Boyd and Lagoudas [3-7], among others. The phenomenological model RLOOP developed by Sittner at al [8] is a promising tool for modelling of SMA actuators. A model representative of the rate-dependant models for SMA alloys has been presented by Abeyaratne and Knowles [9-10]. Recently, Fisher [11] has proposed a general framework for SMA constitutive modelling involving evolution of transformation as well as plastic strain.

Most of the mechanical testing on polycrystalline nickel-titanium alloys found in literature has been performed for uniaxial loading. As a result most phenomenological constitutive models are based on uniaxial data. Only a limited amount of experimental data concerning multiaxial loading/unloading of SMA alloys are available e.g. Lagoudas, Shu [12], and Leclercq with Lexcellent, [13].

Further potential functional properties and behaviour of SMA’s for design of actuators

Although many commercial NiTi wires commonly exhibit sequential austenite B2↔R-phase ↔ martensite B19’ transformations, their unique stress-strain-temperature behaviors are readily comprehended and modeled as being solely due to the cubic to monoclinic (B2↔B19’) martensitic transformation (Figure 1). Omitting the R-phase is commonly advocated by the fact that the B2↔R transformation strains are much smaller. The R-phase transformation strains are indeed small (<1%), since R-phase structure is created by a relatively small rhombohedral distortion [14,15], of the parent cubic austenite lattice preceding the martensitic transformation upon cooling or loading. However, the small strain might be a beneficial feature for e.g. passive structural damping applications [16] aimed at vibrations with small strain amplitudes, smart SMA polymer composites in which the NiTi wire is embedded in hard polymers and can not undergo large strains anyway [17], or for actuator applications requiring very large number of cycles, small actuation temperature range and stable functional properties. However, beyond the small transformation strains, there are additional very interesting features of the R-phase – e.g. the rhombohedral angle varies continuously with the temperature [14,15] or the elastic modulus of NiTi is lowest in R-phase near the Rf temperature and increases upon further loading or cooling in the R-phase state [18].

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3.1.2 Application

Designing of adaptive SMA-composites

The studies of SMA based functional composites have revealed the lack of basic knowledge in understanding the SMA material behaviour. Especially the issues concerning the generation of recovery stresses of embedded SMA wires are very important. Designing and manufacturing of complicated structures requires knowledge about the thermo-mechanical behaviour of the adaptive composites. Despite of that only a few studies have been presented.

When the stress in the SMA exceeds the plateau stress, it also shifts the phase transformation temperatures upwards, which means that the wires need to be heated to higher temperature to get full transformation. In many experiments reported in literature this shift of transformation temperatures has not been taken into account and thus the heating has been inadequate. The explanation to the observation that the pre-strain of the wires does not have a straight effect on the generation of recovery stresses is that in the embedded SMA only small part of the potential transformation takes place. Increasing the heating gives more transformation, but at a slow rate.

If the wires were placed in sleeves before embedding and thus bonded only at their ends, the situation is somewhat different, especially if the laminate can bend. In this case the restriction caused by the matrix on the strain of the SMA wires is not as severe as in complete bonding. The stress in the SMA wires does not increase as much as in the case of perfectly bonded wires and thus more transformation and thus more strain recovery is achieved and also at a higher rate. If the laminate can bend, this will leave some room for the wires to shorten more than the laminate, but when the curvature of the laminate grows the wires will start pushing towards the walls of the sleeves. This internal transverse loading may break the laminate in cyclic loading.

The sleeve method is preferred for shape control if relatively small bending is needed. If the bending needed is large, either the wires should be bonded at intervals throughout the laminate or the laminate around the sleeve should be reinforced for internal transverse loads.

An important thing which should be taken into account in the design of adaptive structures based on embedded SMA wires is the small cooling rate due to the thermally insulating polymer matrix. Cooling may be enhanced by placing the wires close to the surface of the laminate and using a cooling flow (usually air or water). In a wind turbine blade there is always flow around the blade, which eases the cooling. Flow inlets that would let the air flow inside and out of the blade would further enhance the cooling of the SMA wires at the inner surface of the upper skin.

Modeling

SMA laminates and the adaptive airfoil were modelled at VTT by using the ABAQUS FE program both as 3D and shell models using with the rebar and rebar shell options of ABAQUS for the SMA wires. The shortening of the SMA wires was modelled by thermal expansion analogy with negative thermal expansion coefficient. Thus the models cannot give absolute displacements nor the correct displacement history but only the relative shape of the deformed structure. The shape obtained with the model corresponded well with the experimentally obtained shape.

Adding a SMA material model into the FE models will remove the above mentioned restraints and also give more reliable stress values, as the effects of partial bonding and flexibility of the matrix close to the wires can be modelled. The phenomenological SMA material model of Petr Sittner is being implemented to ABAQUS as UMAT (User programmed MATerial model) at VTT. The model can reproduce the 1D tensile SMA behaviour with rather good accuracy, while still being physically relatively reliable. Recovery stress generation in embedded SMAs and the consecutive effects on the transformations are included in the model. The original model is intrinsically stress-temperature controlled. Because ABAQUS is a strain controlled program, the model was transformed to strain-temperature controlled form at VTT.

Manufacturing

The manufacturing process of adaptive SMA composites has only a few differences to traditional manufacturing of FRP composites. The most challenging procedure is the embedding of the SMA wires into the structure. Integration of the SMA wires is always some kind of a compromise between maximum force generation and structural integrity. By using large diameter wires it is possible to generate high force volume ratio, but this may increase local stress concentrations and lead to cracking and delamination of the structure. Typical manufacturing process of SMA composites includes an assembly jig where SMA wires are stretched and reinforcement layers are laminated around the SMA wires. On the industrial manufacturing point of view the procedure is quite impractical.

Basically two different approaches are used in manufacturing of SMA composites: in the first one the SMA wires are placed inside mechanical sleeves and in the second, more sophisticated, method an adhesive joint is created between the SMA wire and the matrix. The adhesive joint is very critical on the stress levels and temperatures experienced by the SMA wires. In this study a more advanced method to manufacture SMA composites was developed. The method is a combination of mechanical sleeves and adhesive joining. The new method enables use of larger diameter wires because the forces generated by the wires are evenly distributed and pullout of wires is prevented.

The manufacturing of an adaptive airfoil comprises of two steps: 1) manufacturing of the insert laminate which includes the SMA wires and the desired sensors. 2) manufacturing of the airfoil including the insert laminate. Insert laminates were manufactured in a jig which was designed and manufactured for this purpose. Because high actuation forces are needed to deform the airfoil SMA wires with 0.5 mm diameter were selected as principal actuators. The new manufacturing method allows the use of larger diameter wires, which means that the required forces are more easily achievable.

In the first stage of the research adaptive airfoils with 100 mm span width were manufactured. The active structure studied is a glass fibre reinforced plastic airfoil (wind turbine blade section) shown in Figure 2. It is 700 mm long (chord), 100 mm wide and the laminate mean thickness is 3 mm. The SMA actuators are embedded inside the laminates. There are separate actuator wires for the upper and lower skins. The basic dimensioning of airfoil structure was made by modelling but the final structure was determined experimentally so that structural properties were modified after each test piece.

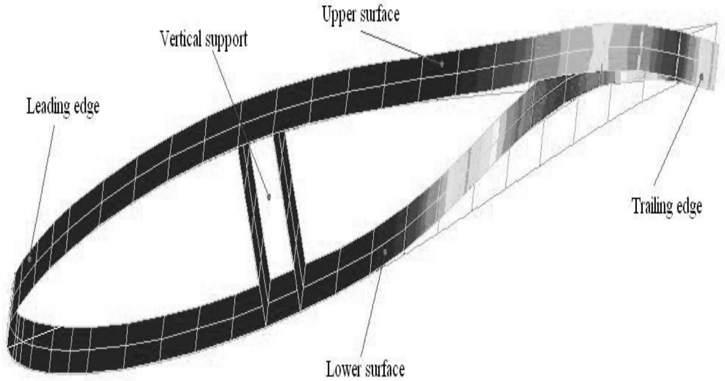

Figure 2: The adaptive airfoil

When the desired properties of the airfoil were reached with small scale airfoil the structure was up-scaled to the appropriate size for the wind tunnel tests. An adaptive airfoil section with 1000m span width was designed, manufactured and instrumented with strain gages, fibre optic sensors and thermocouples. Unfortunately fibre optic sensors were damaged during the installation process.

Figure 3: Adaptive airfoil in preliminary testing before installation to the wind tunnel.

Wind tunnel tests

A one meter span width section of a wind turbine blade was installed and tested in a wind tunnel to find the lift and drag properties of the shape controlled airfoil. The wind tunnel tests were conducted at week 39 and analyzing of the results is on-going. The preliminary results of the wind tunnel tests are shown in Figure 4. It can be easily seen that activation of SMA wires causes a remarkable change in lift force with both wind speeds (30 m/s and 44 m/s) and all of the attack angles. Especially from the right figure it can be seen that some plastic deformation occurs in the blade section during the activation. This is quite typical behaviour in SMA composites during the first's activation cycles. After some tens of cycles the behaviour of SMA composite is typically stabilized same type behaviour is detected in wind tunnel tests.

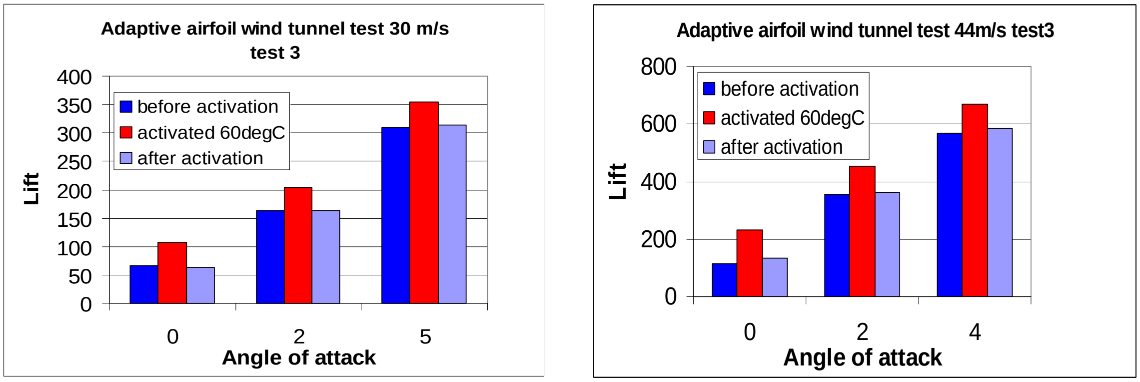

Figure 4: in lift force with different attack angles during the activation airfoil.

Analysing of the test results is on-going and detailed reports about the results will be made in near future.

Conclusions

An adaptive wing profile was designed, manufactured and tested. New tools for designing and manufacturing of SMA actuated FRP composite structures were developed and demonstrated. The performance of the system was measured in laboratory conditions and also in wind tunnel. The developed control system works accurately enough for the shape control purpose of the airfoil in laboratory conditions. The changes in lift obtained are very large. The changes in drag were not very large, so changes in the lift/drag ratio were favourable. The power consumption was not too big for wind turbine application. These results show the applicability of the system for wind turbine application provided that the long term strength and durability of the system can be ensured.. These issues will need further research and development.

The development of an adaptive structure is an iterative process that requires knowledge from many fields of engineering. An important part of the research work is the development of tools and manufacturing methods that can take the process closer to industrial scale. Especially the modelling tools and the manufacturing processes need further development to make this kind of adaptive structures to be commercially accepted.

Future plans

One remedy to many of the problems encountered with embedded SMAs could be utilizing the R-phase transformation of NiTi. The R-phase transition was already explained in section 3.1.1. With the R-phase transformation, the Clausius-Clapeyron constant determining the effect of stress on the phase transformation temperatures is much larger [17 MPa/K] for R-phase transformation than for martensitic transformation [5-6 MPa/K] and thus stress in the SMA wires does not move the transformation temperatures as much as in martensitic transformation. The width of the phase transformation zone of R-phase transformation is also much smaller [2-10 K] than for the martensite transformation [25-30 K]. This means faster heating and cooling and smaller power consumption. The R-phase wires with suitable R-phase transformation temperatures are produced from ordinary NiTi wires by a special heat treatment. The R-phase transformation has been studied much less than the martensite transformation and data on many engineering issues, for examples stability and long term durability, is scarce.

Thermomechanical properties of NiTi wires and composites with R-phase transformation will be studied in co-operation of VTT and ASCR.

A new SMA model created at the ASCR, numerically more feasible than the old model of P. Sittner, will be implemented to ABAQUS at VTT. The implemented SMA material model will be added into the ABAQUS models of SMA-FRP beams and the active airfoil to give quantitative results for deformations and stresses. The results will be compared with experimental results. The R-phase transformations will be added into the Sittner's phenomenological SMA model and the developed model will be implemented to Matlab and ABAQUS. The active airfoil with embedded R-phase wires will be modelled in ABAQUS and this model will be used to optimise the active structure.

3.2 Piezo electrics

3.2.1 Physical principle

The actuation principle of piezo electric materials is that the material will strain under the application of an electric field. The principle also works in reverse: when a strain is applied, an electric field will be generated in the material. The piezo electric effect was actually observed first in this reverse manner. The word `piezo electrics' has also been derived from this: `piezein' means `squeeze' or `press' in Greek. So a piezo electric material is a material which exhibits a coupling between elastic and electric behavior. Here, the physical principle of two of the most common piezo electrics, PZT [1] and PVDF [2] will be discussed.

Lead zirconium titanate (PZT)

The physical principle is as follows: For a material to show the piezo electric effect, the material must have a unsymmetrical lattice. This way, the material is electrically neutral, but will exhibit a electric dipole because the centre of all positive charged particle does not coincide with that of the negative ones.

When viewing the material on a larger scale, it can be observed that adjacent lattices form area's in which the direction of the out-of-centre position of the centre atom is the same. These area's are called Weiss domains. However, when even stepping back one level further, it can be seen that all Wiess domains are orientated in arbitrary directions. This means that the material from a macroscopic point of view has no nett dipole. This can be altered by applying a very high voltage. This operation is called `poling'. It will cause domains that are in the direction of the applied voltage to grow at the expense of other, adjacent domains. When the voltage is removed, a nett dipole remains. After poling, when a positive electric field is applied in the poling direction, the material will elongate in that direction and contract perpendicular to that.

Polyvinyl-difluoride (PVDF)

There are also piezo electric polymers which exhibit a dipole in there molecular build-up. The most well known is PVDF. The actuation and sensor principle is the same as with PZT: The crystal structure has a dipole, so by applying a voltage the crystal will elongate in the dipole direction. Again, as with PZT the `trick' is to give the material a *nett* dipole, because in the unmodified material all the dipoles are randomly orientated. Here the big difference with PZT becomes apparent, because the material is completely different in nature: PZT is a ceramic and PVDF a polymer.

Making PVDF piezo electric requires two steps: obtaining the crystal structure that exhibits the dipole and secondly, obtaining the nett dipole. The second step is similar to PZT. It also involves applying a voltage at elevated temperature. However, in contrast with PZT, this operations does not involve the growth and shrinkage of Weiss domains, but the rotation of the PVDF-chain's building blocks around their C-C bonds. The crystals themselves remain unmodified. The first step, obtaining the right crystal structure, requires some more explanation.

With PVDF there are different crystal structures depending on the production steps and treatments that are performed. The structure that is formed from normal casting or extrusion with low orientation is the alpha-form. This form, can obtain some piezo electric capabilities after poling, but only very little. The form that exhibits the highest coupling coefficient is the beta-form. To obtain this structure, straining at elevated temperature is needed. After this, the material is poled. Either by a corona arc or by applying the electrodes first and using those for poling. Sessler [2] proposes the following method: stretch the base-PVDF material to 300\% strain (four times its original length) at 65°C. Anneal the material for 24 hours at 120°C. Finally pole the material with a field of 4MV/cm for 60 seconds and then apply the electrodes, or apply the electrodes first and pole the material at 105°C for 40 minutes with a field of 600kV/cm.

Functionality

Usually, piezo electric materials are produced in thin sheets with even thinner electrodes on both sides. This way, a relative small voltage applied over the thickness generates a high, evenly distributed electric field through the thickness. The constitutive behavior of a piezo electric material is usually described in the following way:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{12} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{13} & S_{23} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} + \begin{bmatrix} 0 & 0 & d_{13} \\ 0 & 0 & d_{13} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} E_1 \\ E_2 \\ E_3 \end{Bmatrix} + \begin{Bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ 0 \\ 0 \\ 0 \end{Bmatrix} T$$

A few remarks can be made with this:

- The coefficients d_{33} and d_{31} are very, very small. The strain that a piezo material can achieve under a voltage is usually in the order of 10^{-4} or ~0.1%.
- The coefficient d_{33} is usually bigger than d_{31}. This means that the strain caused by given voltage is higher in the thickness direction than in-plane. However, since we are talking about sheet material, the dimension in the thickness direction is much smaller. Thus, the displacement through the thickness is almost negligible. In the next section some means of employing the d_{33} effect are described.
- It can be seen that the piezo electric effect is very similar to thermal expansion. This is very helpful in understanding and modeling the effect. However, the piezoelectric effect is much larger (*[d]{E}>>{α}ΔT*).
- When embedding, attaching or assembling piezo material in any form in a construction, it can be seen that the amount of strain that can be attained, is very much dependent on the stiffness of the structures. This determines how much the structure ``pushes back". The strain-force behavior of a piezo electric is characterized by two quantities: the free strain (Lambda) and the blocking force. The first tells you how far the material will strain under a given voltage and the second one which force is required to keep the material from deforming. This also shows why PVDF is not very suited for actuation of rigid structures: because its intrinsic stiffness is very low, it is also not capable of exerting force on its environment. For this reason, and because it's light, PVDF is usually used for sensing applications.
- The in-plane coupling constants d_{31} are not equal with PVDF: there is also in-plane anisotropy because of the stretching in one direction and the orientation of the material to that direction.

3.2.2 Application

The most widely used piezo electric is PZT. It is a very brittle ceramic which can strain ~0.1\%. This goes for most piezo electric materials. The material is mostly available in patches on which on both sides an electrode is damped. The electrodes cause a homogeneous electric field in the material when a voltage is applied. Which can be attached to, or embedded in structures. A very sensible way of using the patches is by producing benders. A patch is adhered to one or both sides of a substrate. By applying a voltage, the patch will either stretch or contract, thus bending both itself and the substrate. When two patches are applied, the so called bimorph configuration, they must be set to work in opposite direction. In addition, non-linear configurations are available, which, by effectively buckling the bender, can attain higher deflections because their intrinsic stiffness is reduced [3,4]. These include PBPs [5], Thunders and LiPCAs [6,7]. Often, they are also more resilient because the piezo material is under compression. Modeling of benders is based on the classical laminate theory. When the non-linearities are introduced, the Rayley-Ritz method is used to predict the bender's behavior.
\indent In tackling the brittleness issue, NASA has developed so called MFC's [8] (Macro Fiber Composites). MFC's are produced by sawing very fine strips from a patch and embedding those in epoxy between Kapton film. They are very flexible and show considerable deformations. The can be applied as sensors, using the inverse effect, as well as actuators.

Other piezo electrics than PZT include Langatite, Langasite and Langanite, ruby-like crystals, and a variety of polymers of which PVDF shows the strongest piezo electric effect.

Research until now has been performed into benders which might drive aerodynamic devices, such as tabs. An evaluation of different piezo electric benders has been made. The evaluation included so called Thunder actuators and bi-morphs. In addition, so called LiPCA actuators have been produced. Bi-morphs (see Figure 5) are bending actuators, based on piezo-electric, or other adaptive materials with which one side expands and the second contracts. This in contrast to unimorphs, where only one active side drives the actuator. Thunders and LiPCA's are actuators that can bend further than normal unimorphs because, due to thermal residual stresses induced during production, they are "snapped through" and their intrinsic stiffness is reduced. It has been shown that normal bimorphs can deform almost as far as "thermal mismatch"-actuators such as LiPCAs or Thunders, but that they are much more fragile.

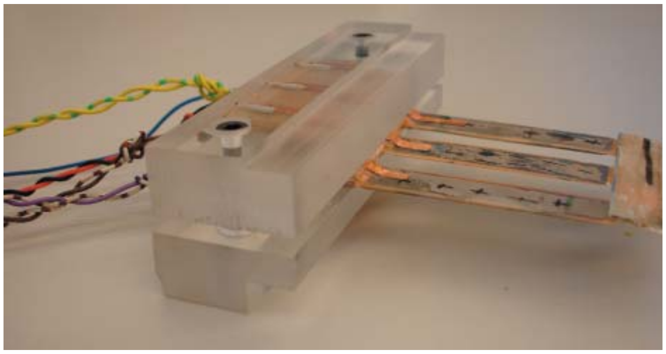

Figure 5: Three parallel bimorph actuators

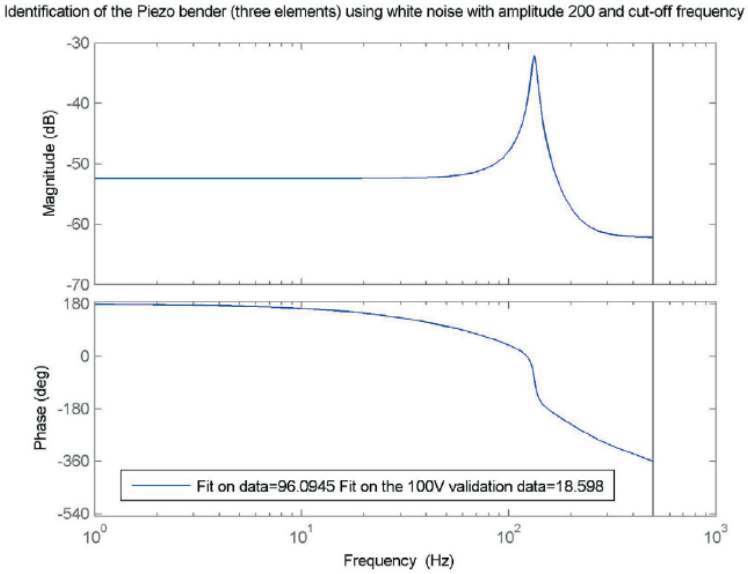

Figure 6: System identification of the bimorph actuators

In addition thermoplastic LiPCA's were produced. Thermoplastic have as advantages over thermosets that they are tougher and they can be welded to other thermoplastic construction elements. Thermoplastic adhesives are also used in the commercial Thunder actuators. Their behavior and properties are under investigation.

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4. Structural concepts

4.1 The application of adaptive materials

For the actuator material two possibilities exist, as been explained in chapters 0 and 3. Both can be implemented to obtain deformable surfaces, although SMAs show the most potential, because they are more suitable for embedding in laminates. Piezo-electrics, notably PZT, are brittle and are harder to incorporate in a laminate with a curved shape.

It is therefore suggested that PZT benders are considered as actuators to drive tabs or other devices. For morphing surfaces, embedded SMA wires are to researched further, as well as piezo electrics that are formable and producable in curved surfaces, such as PVDF and the earlier mentioned MFCs. Piezo electrics could also have a sensor function as pressure or strain sensors.

4.2 Structural lay-out

As mentioned in section 2.3 the application of adaptive materials in the blades skin, will most certainly be accompanied with the introduction of monolithic laminates there. The reduction in aeroelastic stability there is what is aimed for. However, the introduction of flaps near the trailing edge at certain positions along the blade’s span also has to other structural implications: the buckling strength is reduced there and stress concentrations are introduced around the edges of the “slots” where the trailing edge flaps are positioned. It is advisable to create load paths around these slots, so the aerodynamic devices will not be loaded by the stresses in the blade. A very nice way to use to transition from sandwich to monolithic laminates and the need for load paths, is to implement a so called rib-spar design. As mentioned, in traditional blade design the main loads are carried by the spar and the shell’s laminate is a sandwich to increase the buckling strength and aeroelastic stability of the blade’s shell. In a rib-spar design the blades bending stiffness is also attained by the main spar (or spars) but the buckling resistance and shape stability is attained by the implementation of ribs. Summarizing, this leads to the following advantages for “smart” blades:

- The use of monolithic laminates (which are deformable by adaptive materials) becomes feasible
- Load paths around “weak”, active parts are created

And beside that:

- A possibly lighter design is attainable by the omission of the sandwich’s core material
- In combination with a thermoplastic material system, gains in production speed and accuracy are attainable.

5. Conclusions

As explained in section 2.1, the search for actuators is limited to integrated adaptive materials to keep the concept low in maintenance and simple. The literature study of the different adaptive materials showed that piezo electrics and shape memory alloys are the only two suitable candidates because of weight, speed, force and strain properties.

A first order analysis of both adaptive materials has shown that both materials are suitable for driving the actuators that are under investigation from a aerodynamic point of view, namely (continuously deformable) flaps, tabs, and synthetic jets. Flaps require the skin laminate of the blade to be deformable and tabs require a actuator to drive them. SMAs show strong potential for the first application and piezo electrics for the second. However, piezo electric polymers and PZT dissolved in polymers are still being researched.

However, with both exist controllability and speed issues (SMAs) and problems concerning large scale integration in laminates (PZT). In addition a rib-spar lay-out is suggested for smart rotor blades because this is more feasible to allow for load paths around “active” parts of the blade, suspension for sensors and actuators and it may lead to a lighter blade.