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Non-linear electromechanical behaviour of piezoelectric bimorph actuators: Influence on performance and lifetime

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Abstract Piezoelectric bimorph bender actuators find application number of areas, ranging from automotive to health care. High voltage operation in harsh environments poses ever more stringent demands on functionality and lifetime. In these high performance benders, the trade-off between functionality and lifetime becomes of increasing importance, and a model-based understanding is imperative for further tailoring actuator performance. An important issue in this is the non-linear electromechanical coupling and mechanical poling/depoling processes. PZT materials are known to exhibit non-linear stiffness when strained. This effect is attributed to domain re-orientation and can result in mechanical depoling. In bimorph benders where only one of the PZT members is actuated, the non-linear stiffness effect results in higher deflections than are predicted by linear elastic models. This effect is larger for soft PZT materials than for hard PZT materials. In this work, the non-linear behaviour of piezoelectric bimorphs was characterized by dynamic mechanical thermal analysis (DMTA). Unimorph benders were characterized in different configurations. Two different PZT materials (one soft, one hard) were used. The non-linear stiffness behaviour is included in a model for piezoelectric multimorphs. The multimorph model predictions are compared to measured deflection and blocking force of bimorph benders made from soft PZT material. The model incorporating non-linear stiffness predicts deflection and blocking force values more accurately than the linear model for the situation studied. Attention is paid to the stresses induced during poling of the bimorphs and their effect on performance and lifetime.

Keywords Bimorph actuator · Non-linear piezoelectric behaviour

1 Introduction

Bimorph benders are used as actuators in a variety of applications, ranging from Braille pads [1] to components in mobile phones [2] or tools for minimal invasive surgery [3]. In every application, but especially in high performance applications, both performance (i.e. deflection and blocking force) and reliability are important and of contradicting requirements. When designing a bimorph actuator, one must be able to predict its performance adequately in order to obtain an optimal lifetime. The unipolar drive bimorph actuators studied in this research consist of two PZT plates and an (optional) interlayer as is shown in Fig. 1.

In unipolar driven bimorphs, one PZT layer is active upon actuation. This layer contracts and the strain difference will result in bending of the sample. The passive part of the actuator, consisting of the passive (often non-piezoelectric) inner layer and the PZT layer which is not subjected to the actuation voltage, are dragged along with the active PZT layer, i.e. they are mechanically deformed by it. The non-piezoelectric inner layer usually behaves linear elastic fashion, but the passive PZT layer does not,

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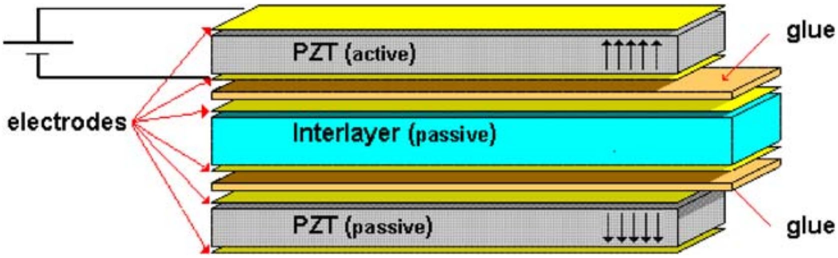


Fig. 1 Schematic representation of a typical bimorph bender composition

due to mechanical depolarisation mechanisms. In this work, a model has been developed which incorporates the non-linear mechanical behaviour of the PZT. The model is compared to experimental bimorph data.

This non-linearity has been incorporated into a model in the following manner:

1. Experimental data on unimorph benders was used to calculate the stiffness of the passive PZT layer as a function of strain in the layer.
2. This stiffness function was used as input for the model.
3. The model subsequently iteratively calculates the deflection of the bimorph bender.

The theory of the non-linear model is explained in Section 2, including the effects of the non-linear stiffness of the PZT material.

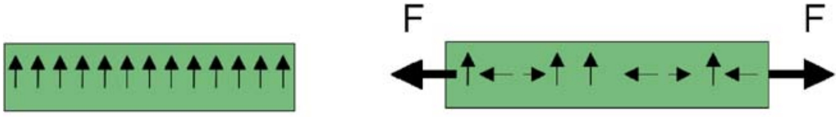
2 Theory

In unipolar drive bimorph benders, the deflection is limited by the stiffness of the passive PZT layer, which has to be forced into deforming. A reduction in the stiffness of this layer with progressive bending naturally leads to a higher deflection than expected based on purely linear elastic and piezoelectric behaviour, since the extension of the passive PZT layer due to depolarization enhances the bending of the bimorph actuator. In both bending tensional experiments reported in literature the non linear stiffness behaviour of PZT is studied [4–7]. In these publications, a decrease of effective stiffness was shown, similar to the effect shown here for piezoelectric benders. The behaviour is explained by a process of tensile stress-induced depolarization/domain switching in the passive piezo layer (see Fig. 2).

Due to the in-plane extension accompanying (partial) reorientation of ferroelectric domains, this depolarization amounts to what can be described as a yielding effect. This leads to a reduction in effective stiffness with progressive tensile strain, and also to a different stiffness in compression and tension. It is known from literature [7], it is expected that this effect is largest for passive PZT layers (i.e. not subjected to an electric field), that PZT material which is subjected to an electric field behaves fairly linearly in compression (this is the situation in the active part of the bender). When PZT material is not subjected to an electric field however, and loaded in tension, the material stiffness decreases with progressing strain [4–8]. Therefore, the passive PZT layer was assumed to be the largest contributor to the non-linear deflection behaviour of the bimorph. If the stiffness of the PZT layer in a bimorph bender is measured as a function of strain, this can be used as an input for the non-linear model, to calculate deflection and blocking force, as described in the following sections.

2.1 Calculation of PZT stiffness

The strains in a (passive) PZT layer of a unimorph bender (i.e. a bender with only one PZT layer and a passive layer), can be calculated by standard equations for a composite beam from the apparent stiffness of the bender (E_{app}) by using Eqs. 1, 2 and 3. This apparent stiffness is calculated from the force-displacement curves of a bender in a three-



Situation 1:
unstrained PZT, ferroelectric domains are poled

Situation 2:
PZT in tension, mechanical depoling, or 'yielding', occurs

Fig. 2 Schematic representation of the electromechanical yielding effect in PZT point bending test. The configuration of a bender is depicted schematically in Fig. 3:

$$z_{\mathrm{nn}} = \frac{1}{2}\frac{\sum_{r=1}^{n} E_r t_r \left\{2\left\{\sum_{i=1}^{r} t_{i-1}\right\} + t_r\right\}}{\sum_{j=1}^{n} E_j t_j}, \text{put } t_0=0, \tag{1}$$

$$I = \frac{w}{3}\left[z_{\mathrm{nn}}^3 + \frac{1}{E_1}\sum_{r=2}^{n}\left[(E_{r-1} - E_r)\left\{\sum_{i=1}^{r=1} t_i - z_{\mathrm{nn}}\right\}^3\right]\right], \tag{2}$$

$$E_{\mathrm{app}} I_{\mathrm{app}} = E_1 I, \text{with } I_{\mathrm{app}} = \frac{wh^3}{12}, \tag{3}$$

where:

z_{nn}	neutral axis of the beam
E_{i}	stiffness of layer i
t_i	thickness of layer i
I	normalised moment of inertia of the beam (wrt layer 1)
I_{app}	effective moment of inertia of the beam
E_{app}	effective stiffness of the composite beam
w	width of the sample
h	thickness of the entire sample

The set of Eqs. 1, 2 and 3 can be solved numerically to obtain E_2 as a function of E_{app} for a given bender configuration. The average strain in the PZT layer can be calculated as follows:

$$\varepsilon_2 = \frac{M(z - z_{\mathrm{nn}})}{I_{\mathrm{app}} E_{\mathrm{app}}}, \tag{4}$$

where M is the moment acting on the beam and $z - z_{\mathrm{nn}}$ is the distance from the middle of the PZT layer to the neutral line of the unimorph. When solving Eqs. 1, 2, 3 and 4 for a given unimorph configuration, a relation can be established to calculate the stiffness of the PZT layer, as a function of the average strain (ε_2) in this layer. In this model, the strain in the PZT layer is defined to be zero when the applied voltage is zero.

$$E_2 = f(\varepsilon_2). \tag{5}$$

The calculated E_2 as a function of strain in the PZT layer (ε_2) can be used as input data for the bimorph model.

2.2 Deflection and blocking force calculations

Models for deflection and blocking force of unimorph and bimorph actuators have frequently been published [9–11]. However, for the unipolar driven bimorph benders used in this research, these models did fit the experimental data for both deflection and blocking force. In this work, a multimorph model derived by M. S. Weinberg [12] is modified for non-linear stiffness of passive PZT.

The model in [12] was modified in the following steps:

1. Starting with the linear elastic model, the deflection of the actuator is calculated.
2. The resulting strain in the passive PZT layer is calculated.
3. This is used as input for the calculation of the PZT stiffness.
4. Using the stiffness calculated in step 3 the deflection is calculated.
5. Steps 2–4 are repeated until the deflection converges.

The curvature (C) of an n-layered multimorph actuator as described in [12] (for instance a bimorph such as shown in Fig. 3), which is not subjected to external loads, can be described with the Eqs. 6, 7 and 8:

$$C = \frac{1}{R} = \frac{\left(\sum_{i=1}^{n} z_i E_i d_{31,i}\frac{V_i}{t_i}\right)\sum_{i=1}^{n} E_i A_i + \left(\sum_{i=1}^{n} E_i A_i d_{31,i}\frac{V_i}{t_i}\right)\sum_{i=1}^{n} z_i E_i A_i}{\sum_{i=1}^{n} z_i E_i A_i \sum_{i=1}^{n} E_i (I_i + z_i A_i) - \left(\sum_{i=1}^{n} z_i E_i A_i\right)^2}, \tag{6}$$

where:

R	radius of curvature of the bimorph
z_i	distance of the centre of layer i to the neutral axis of the bimorph (z_{nn})

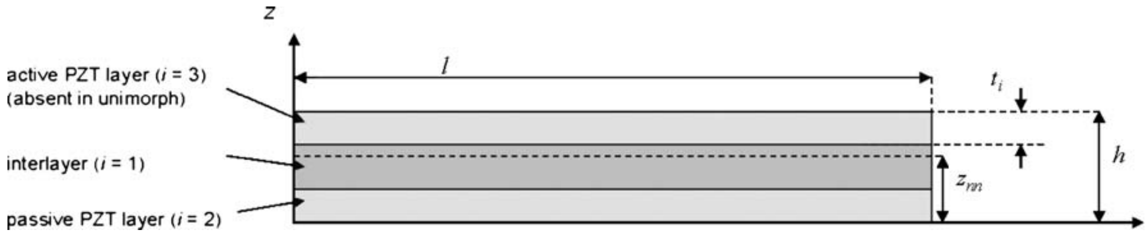


Fig. 3 Schematic representation of a unimorph or bimorph sample. In unimorph samples, the active PZT layer (i=3) is absent

$d_{31,i}$ transverse piezoelectric constant of layer i
V_i voltage applied to layer i
A_i cross sectional area of layer i
I_i Moment of inertia of layer i

In the current situation, it is assumed that there is only negligible bending in the transverse direction (along the width of the bender), thus deformations in this direction are constrained. This is the case when a stiff interlayer constrains the lateral contraction. This leads to an effective increase in both the stiffness and the piezoelectric constant d_{31} in the longitudinal direction:

$$\begin{array}{l} E_i \to E_i / \left(1 - \nu_i^2\right) \\ d_{31} \to d_{31,i}(1 + \nu_i) \end{array}, \tag{7}$$

where ν_i is Poisson's ratio of layer i. Equation 7 can be substituted into Eqs. 1, 2 and 6, in order to obtain the correct stiffness values for the bimorph model. After substitution, the deflection (δ) is then calculated by:

$$\delta(l, V) = \frac{Cl^2}{2}. \tag{8}$$

l=The free length of the bimorph bender.

The strain in the PZT layer can be calculated with equation 9.

$$\varepsilon_2 = \frac{z_{\mathrm{nn}} - z}{R}, \tag{9}$$

where, ε_2 again is the average strain in the passive PZT layer. The average strain is defined here as the strain in the middle fibre of the PZT material (i.e. at half height of the layer).

Using the result from Eq. 9, the stiffness of the passive PZT layer can be calculated using the specific relation described in Eq. 5, and a second iteration of Eqs. 6, 7, 8 and 9 can be performed. This iterative process must be repeated until the solution converges.

The blocking force can be calculated from the deflection using the simple beam equation (Eq. 10).

$$F_{bl} = \frac{3\delta \sum_{i=1}^{n} E_i(I_i + z_i A_i)}{l^3} \tag{10}$$

The stiffness of the passive PZT layer (E_2) is taken to be the stiffness value at full deflection of the actuator. This value for E can be treated as constant for the purpose of calculating the blocking force, because of the way the blocking force is defined in this research (see also Section 3), as the blocking force is dependent on the deflection of the actuator. The initial stiffness of the passive PZT layer is of much smaller influence in this case, as is explained in Section 4.

The predictions by this model can now be compared to experimental values of deflection and blocking force obtained from a series of bimorph benders. The results of this research are listed in Section 4.

3 Experimental

3.1 Unimorph and bimorph samples

Several bender samples with different PZT types were used to determine the effect of the non-linear stiffness of PZT material. A soft PZT type and a hard PZT were selected. In soft PZT the non-linearity of the stiffness is expected to be higher than in hard PZT. The type of soft PZT, typically used in bimorph benders is PZT507 (material courtesy of Morgan Electro Ceramics). The hard PZT type used was PZT805 (also supplied by Morgan Electro Ceramics). The width of the benders (w) is 6.0 mm. For the benders tested, the thickness of the PZT layers was 0.2, 0.25 or 0.3 mm and the thickness of the carbon fibre reinforced epoxy inner layer was 0.18 or 0.28 mm depending on the type of bender that was tested.

3.2 Three-point bending measurements

The three-point bending measurements were performed on a dynamic mechanical thermal analyser (DMTA, TA instruments 2980). In the DMTA test, the distance between the two lower supports of the three-point bending configuration is fixed at 20 mm. Seven benders of each unimorph type were tested. The unimorph was placed with the PZT layer facing upwards to load the PZT in compression, and with the PZT layer facing downwards to load the PZT in tension.

3.3 Bender displacement and blocking force measurements

Bimorph displacement was measured using a laser displacement sensor. The displacement sensor was set to zero at zero applied voltage. A voltage was applied to the bender and the displacement was measured after 5 s. For measurement of blocking force, the following measurements were conducted. The force sensor was positioned onto the actuated bender. The load sensor was used to push-back the bender after it was fully deflected, until it was returned to its original position and the maximum blocking force measured during this time was registered. The free length of the bimorph samples was 36 mm. The measurement set-up is shown in Fig. 4.

4 Results and discussion

The results from the three-point bending tests show that the force–displacement curves of the unimorph benders are indeed non-linear (Fig. 5). The non-linear effect is much stronger in soft PZT (PZT507) than in hard PZT (PZT805). The non-linear behaviour of passive PZT is also of great

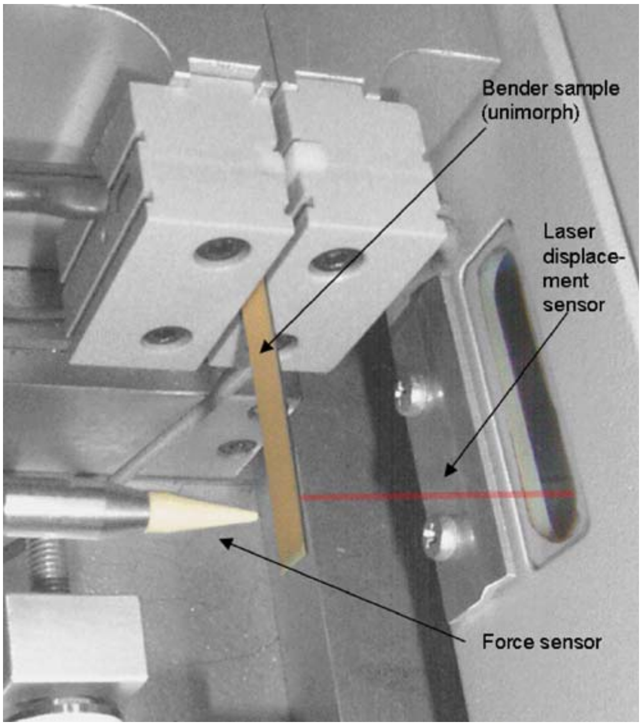


Fig. 4 Photograph of the PZT bender test equipment. Including the force sensor (*left*) and laser displacement sensor (*right*)

influence on the mechanical behaviour of the unimorph structure.

In the DMTA tests on unimorph structures the hysteresis of the PZT material is partially counteracted by the linear elastic behaviour of the interlayer (in this case carbon fibre reinforced epoxy). The stiffer interlayer will deform elastically upon the application of a load on the unimorph. When this load is removed, the interlayer will unload and release the elastic stress in this layer. This will tend to party relieve the hysteresis in the adhered PZT layer. In bimorphs, a similar situation occurs, partly undoing the hysteresis in the passive PZT layer after actuation. However, when loaded the decrease in apparent stiffness of the unimorph structure (i.e. the elastic layer and one PZT layer) is clear. The effective stiffness of the passive PZT layers can be calculated by solving Eqs. 1, 2, 3 and 4. In Fig. 6, typical results for a unimorph with a 180 µm thick carbon fibre layer and a 200 µm thick layer of PZT507 are depicted.

In this figure, the stiffness shows the greatest changes for strains up to 0.01%, measured from the zero deflection situation, for which zero strain was defined. The results shown in Fig. 6 show that the stiffness of soft PZT behaves differently in tension and compression and for poled and unpoled PZT, as can be expected from literature results on bulk PZT material [4–8].

This figure shows differences in calculated PZT stiffness, depending on the stress state and poling condition. The stiffness behaviour of the PZT in the benders matches the results in the referred literature. In unpoled state, the stiffness of the PZT decreases with increasing strain in the material for both tension and compression tests. Further-

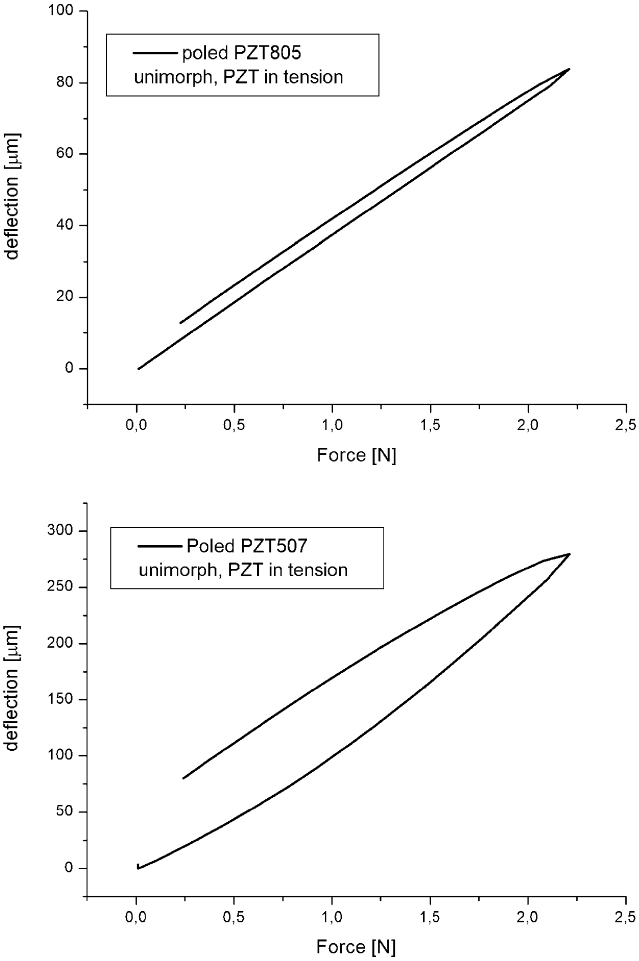


Fig. 5 Typical force deflection curves of PZT507 and PZT805 unimorph benders during three-point bending tests. The hysteresis in the PZT507 material is larger than in the PZT805 material

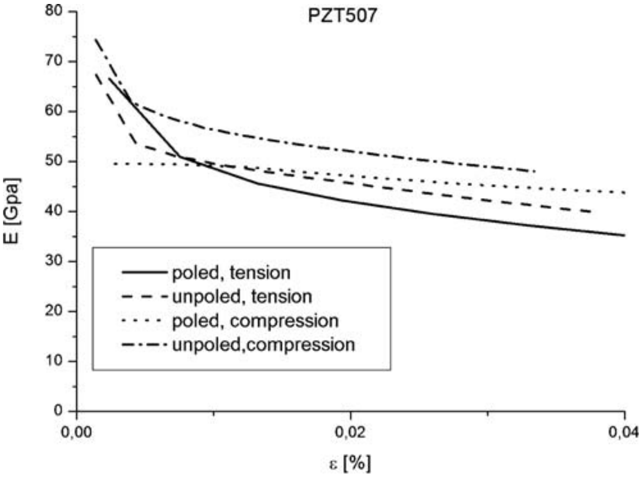


Fig. 6 Effective stiffness of passive PZT507 layers during three-point as a function of the average strain in the PZT layer

more, unpoled PZT loaded in compression is stiffer than unpoled PZT under tension. This corresponds to earlier reports in literature [4–8] for PZT. In the unpoled state, the PZT is largely stress free at zero deflection. However after glueing the PZT layers to the interlayer they are poled, which leads to poling strain in the PZT. This behaviour is constrained by the interlayer, thus causing remnant stresses in the PZT. Therefore, the behaviour of the PZT layers in poled state is different. The stiffness of poled PZT in tensile is lower than the unpoled PZT, as this material is already under stress at zero deflection of the unimorph. This is due to the residual (tensile) stress which is present in the PZT after poling, lowering the stiffness. Also, in the poled state, the release of this poling tensile stress present in the material initially causes no change in stiffness, after which a slight decrease is observed. In bulk PZT, poled material subjected to compressive stress exhibits a stiffness which is much less dependent on strain than PZT in unpoled state or subjected to tensile stress. In bimorphs, the level of residual tensile stress in the PZT is even expected to be somewhat larger than in unimorphs, as the unimorphs can deform (bend) during poling while bimorphs are symmetrical and will stay straight when poling both PZT layers, but the PZT material will show the same behaviour when strained. These stiffness strain relations can therefore be used to model the non-linear behaviour of the PZT in bimorph benders. In Fig. 7, the non-linear model prediction for PZT507 benders is compared to linear elastic model predictions and experimental data. For this soft PZT material the effect is most visible, as it shown the largest non-linear bending behaviour. The PZT805 benders show similar but much smaller non linear behaviour (data not shown in Fig. 7).

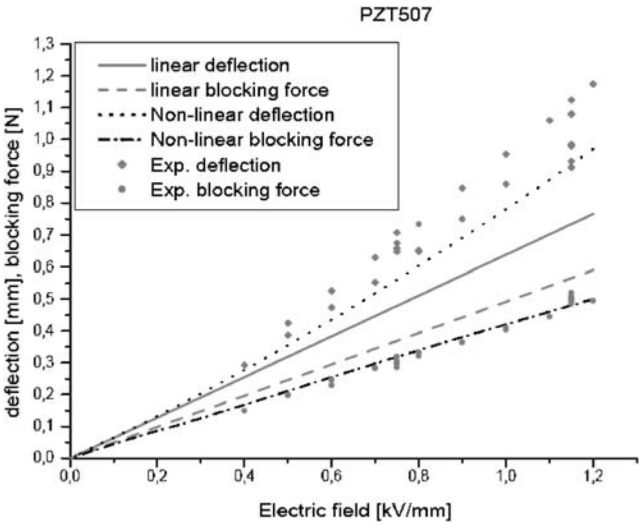


Fig. 7 Predictions of a linear elastic model (*grey lines*) and the non-linear model (*black lines*) compared to experimental data (*grey dots*) of PZT507 bimorphs

Figure 7 shows that the predictions of the linear model (grey lines) do not match the outcome of the experiments (grey marks). The blocking force is overestimated while the deflection predicted by the linear model is lower than the experimentally measured deflection of the bimorphs. In fact, the experimental data shown in Fig. 7 clearly show that the measured deflections cannot be modelled by a linear model, passing through zero. When the non-linear stiffness behaviour of the passive PZT layer is added to the model, these predictions correlate more adequately to the measured deflection and blocking force.

The experimentally measured deflection shows a higher than linear increase with actuation electric field. This behaviour is also present in the non-linear model, resulting in predicted deflections which are closer to measured values than when using a purely linear model.

The blocking force is greatly influenced by the strain dependent stiffness of PZT and the model yields closer predictions when this behaviour is incorporated. As was explained in section 3, the blocking force was measured by pushing back the bimorph from full deflection to zero deflection.

For practical use of the model in predicting bimorph properties, the following condition must be met: In an application, bimorph benders must be actuated to both sides alternatively (as for instance in switches). As stated earlier, the passive PZT element (layer 3 in Fig. 3) will partially depole mechanically during the 1st actuation. Upon the second actuation, this will be the active element. The applied voltage on this partially depoled element will re-pole it to a great extent, especially if the actuation voltage is greater than the coercive field of the PZT. Otherwise the effects of the non-linear stiffness are much lower as was found in [5]. It is also possible to model this situation using the non-linear model described in this paper. However the strain dependence of PZT after it has already been partially depoled must be experimentally obtained. These measurements have not been performed within this research.

The effect of lifetime can be explained by analysing the effect of non-linear bending behaviour. The deflection of a unipolar driven bimorph is generally higher than linear elastic models predict. Thus, these bimorphs designed according to linear models may achieve higher deflections than needed for the application. By optimising the geometry of the bimorph using a non-linear model, the actuation strains may be reduced, leading to increased lifetime of the actuator. Also, lifetime is naturally lower if a higher tensile stress as a result of the poling procedure is present. In addition, benders with higher initial tensile stress are expected to realize a higher displacement, due to the lower stiffness of the PZT, the more the material is strained, which in turn increases stresses in the passive PZT layer. If the effect of poling stress on PZT stiffness is not incorporated in bender design, this may lead to actual displacements that are higher than required for the application. This will lead to a bimorph having a higher displacement but with a shorter lifetime.

5 Conclusions

Measured experimental deflection of a bimorph bender with one passive PZT layer is higher than a linear elastic model predicts. This is partly attributed to the non-linear stiffness of the passive PZT layer. The non linear model predicts the bender deflections and blocking force more accurately than a linear elastic model, but differences remain. This remaining difference is attributed to either the role of the active PZT layer (higher stiffness) or the time dependence of the hysteretic effects. The effect the non-linear behaviour on lifetime of the actuator is the following: when this behaviour is not taken into account, the bender design may not be optimal for the required displacement or blocking force and stresses arising in the bender during actuation may be higher than optimal. Therefore, lifetime may be compromised and the non-linear effects must be accounted for when modelling bimorph benders when they are to be optimally tailored to their application.

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