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Preliminary investigation of self-sensing in piezoelectric bistable laminates

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ABSTRACT

Bistable laminated composites can enable morphing structures that can hold deformed stable shapes without external energy and require actuation only to switch between shapes. Piezoelectric macrofiber composites (MFC) embedded in bistable laminates have been demonstrated for actuation and energy harvesting. However, their relatively high stiffness, relatively complex architecture, and arbitrary fiber orientation limit their ability to sense shape change in bistable laminates. There has been little work on the integration of sensing methods to monitor an adaptive structure's shape; shape sensing has been investigated mainly for the detection of snap-through events. This paper provides initial results on the layering of piezoelectric PVDF films within bistable laminates for detecting both smooth and abrupt snap-through transitions. Measurement of smooth changes in the laminate's curvature is enabled by an automated drift compensation charge amplifier with an extremely low cutoff frequency of 0.01 mHz. The sensing function is demonstrated on bistable laminates created using mechanical prestress. Two sensor layers are configured in the composite such that one measures change in curvature and the other measures snap-through response. The shapes measured by the sensor in terms of voltage correlate well with the shapes measured with a 3D motion capture system. An analytical model is developed to relate curvature change to voltage output and is found to be in good agreement with the measured curvature-voltage sensitivities. The weakly coupled shapes of the laminate and the low cross sensitivity of PVDF enable real-time measurement of the principal curvatures.

Keywords: Bistable, morphing, analytical model, strain sensing, piezoelectric, PVDF.

1. INTRODUCTION

Devices that change shape enable mechanical activity in robotic manipulation[1] and morphing panels in automotive[2] and aerospace applications.[3] Bistable laminated composites are desirable for morphing structures as they are capable of maintaining stable deformed shapes without any external energy and only require actuation for transition. Active actuation of these structures involve integration of smart materials to provide realtime feedback in order to enable shape control. The solution that addresses these requirements should be sufficiently generic and applicable to systems of various structural stiffnesses. To this end, the sensor should also have negligible effect on the actuation performance of the device.

Piezoelectric materials such as PZT (lead zirconate titanate) are brittle and limited to composites that undergo small curvature changes. Macro-fiber composites (MFCs), on the other hand, are flexible and possess excellent sensing and actuation properties. They have been extensively utilized in bistable composites for shape sensing,[4] actuation,[5] and energy harvesting applications.[6] However, the stiffness of MFCs are not negligible and significantly influence the actuation performance of the device. Piezoelectric PVDF films are thirty times more compliant than MFCs and can be integrated into laminates via painting,[7] screen printing,[8] or 3D printing.[9] However, PVDF sensors are inherently suited for dynamic measurements and are limited to only measurement of dynamic snap-through response of bistable composites.[10] Further, existing configurations of piezoelectric embedded sensors in shape sensing applications involve either quasistatic measurement of continuous shape

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change[11] or measuring transient snap-through response.[10] In order to exercise sufficient shape control, we require measurement of both events simultaneously in the structure.

In this work, we utilize the flexibility, lower cross-sensitivity, and the near-static sensing capability of the PVDF strain sensing system toward development of a self-sensing rectangular mechanically-prestressed bistable composite that can sense changes in its curvature as well as dynamic snap-through (Figure 1). The composite consists of two rectangular PVDF films attached to an initially stress-free core layer and are orthogonally aligned to each other. The weak coupling between the stable shapes and lower lateral coefficient of PVDF (d_{32}) enable direct correlation between measured voltages and changes in the laminate's principal curvatures. The direct electromechanical conversion of the change in shape to voltage by the piezoelectric sensors also allows energy harvesting from the dynamic events in the structure. An analytical modeling approach to relate the change in curvatures to the output voltage from the PVDF sensors is presented in section 2. Fabrication of the composite and characterization experiments aimed at evaluating its sensing performance and validating the analytical model is presented in section 3. Conclusions and recommendations for future work are given in section 4.

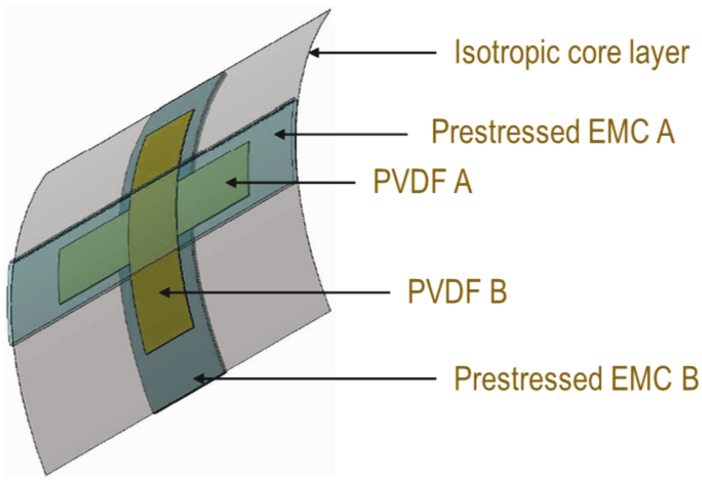

Figure 1: Conceptual representation of an asymmetric mechanically-prestressed bistable laminate with embedded PVDF sensors.[12]

2. ANALYTICAL MODEL

A sectional view of the active bistable laminate is shown in Figure 2. The analytical model is constructed as shown in Figure 3. The modeling process consists of two steps. The first step calculates the curvatures ($\kappa_a, \kappa_{ab}, \kappa_b$) and the in-plane strains (ϵ_a, ϵ_b) of the composite based on classical laminate theory and von Karman's hypothesis. The complete details of the analytical modeling of the curvature and the in-plane strains for mechanically prestressed bistable laminates are provided in Chillara and Dapino.[13]

The second step calculates the sensor voltage due to a change in the average in-plane stress in the composite. Assuming uniform strain in the PVDF film through its thickness, strains in the PVDF sensors are given by $\epsilon_x = \epsilon_x^0 + 0.5 t_{core}\kappa_a$ and $\epsilon_y = \epsilon_y^0 + 0.5 t_{core}\kappa_b$. The charge generated by a PVDF sensor due to a change in average in-plane strain is calculated as:[14]

$$Q = \frac{A_s}{1-\nu_{s12}\nu_{s21}}\left[(d_{31}+\nu_{s21}d_{32})E_{1s}\Delta\epsilon_{x,avg} + (d_{32}+\nu_{s12}d_{31})E_{2s}\Delta\epsilon_{y,avg}\right], \tag{1}$$

where $E_{1s}, E_{2s}, \nu_{s12}$, and ν_{s21} are the in-plane elastic moduli and Poisson's ratios, respectively. The piezoelectric charge coefficients are d_{31} and d_{32}. The area of the sensor is A_s. The subscript s is used to represent sensor parameters.

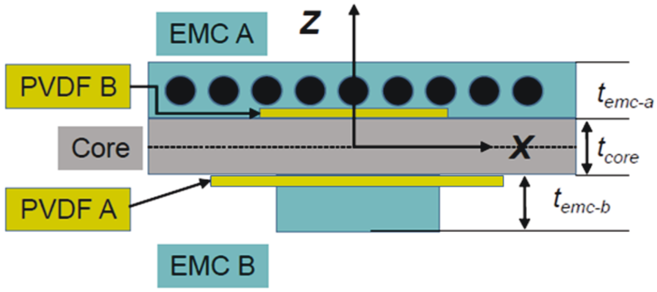

Figure 2: Sectional view of the active bistable laminate showing the orthogonal fiber-reinforced elastomeric matrix composites (EMC A and EMC B), the core section, and the PVDF sensor layers (PVDF A and PVDF B).

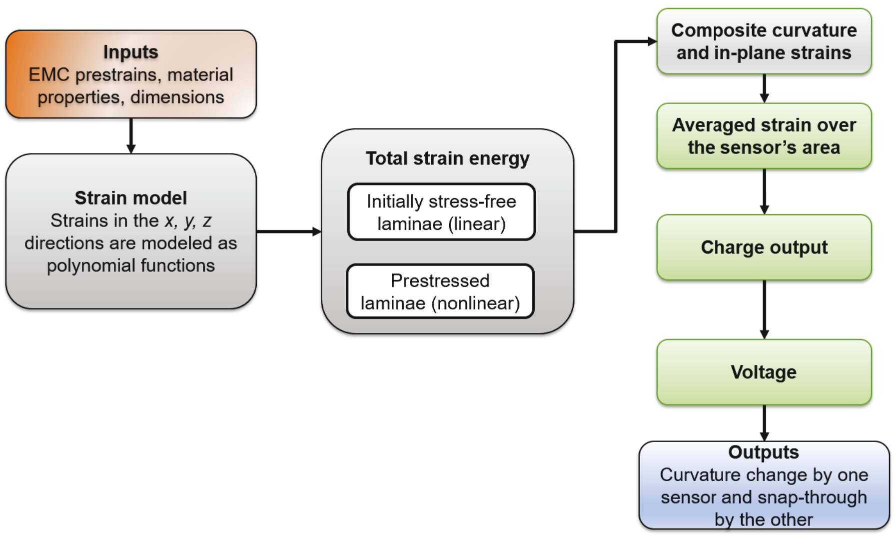

Figure 3: Analytical modeling approach to compute sensor voltages corresponding to changes in curvature.

Charge amplifiers are signal conditioners employed to convert the charge generated by a piezoelectric sensor into a readable voltage. The time constant of a basic charge amplifier is primarily dictated by its feedback resistance R_F and becomes infinite as $R_F \to \infty$. However, increasing the time constant of the charge amplifier leads to a drifting output voltage due to the input bias currents I_{B-} and I_{B+}. This hampers direct readout of change in strains and also eventually saturates the charge amplifier. Utilizing the insulation resistance of the feedback capacitor C_F itself as the feedback resistor R_F and by adding another impedance equal to the feedback impedance $R_F C_F$ between the non-inverting op-amp input and the ground as shown in Figure 4, the time constant of the charge amplifier can be greatly increased with minimal drift error in the output voltage. For $R_F \to \infty$ and assuming constant capacitance and bias currents, the voltage readout in the time domain is:

$$V(t) = \frac{Q(t)}{C_F} + \underbrace{\frac{t}{C_F}(I_{B-} - I_{B+})}_{e_d} \tag{2}$$

where $S_Q = 1/C_F$ is the gain or calibration factor of the charge amplifier and e_d is the residual drift error. Further details on the analytical modeling of the self-sensing bistable laminate are provided in Chillara et al.[12]

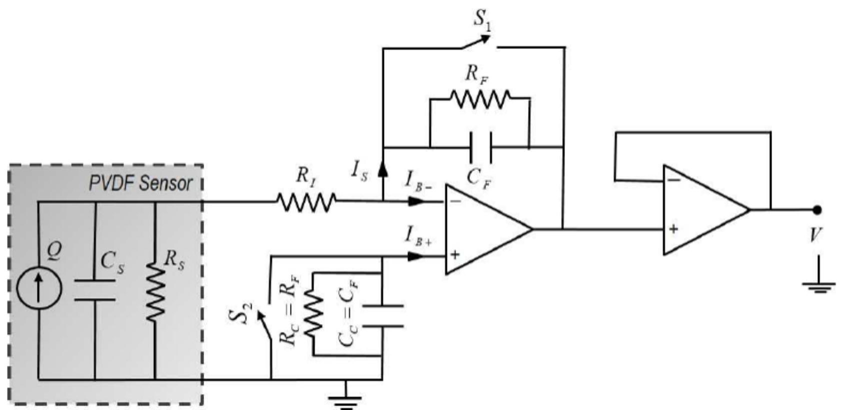

Figure 4: Compensated charge amplifier configuration utilized in this work.

3. COMPOSITE FABRICATION AND EXPERIMENTAL SETUP

3.1 Fabrication process

The self-sensing composite is fabricated following the steps presented by Chillara and Dapino[13] for fabrication of the mechanically-prestressed bistable composite in conjunction with the addition of PVDF sensing layers within the laminations. The composite shown in Figure 5 utilizes PVDF films with a thickness of 28 μm sourced from Measurement Specialities Inc. are laminated on either face of a 76 μm thick spring steel core using flexible silicone adhesive. A thin coat of primer is applied to the steel core layer to create electrical insulation between the core and the sensor. Rectangular EMC strips are then stretched to a prestrain of 40% ($\epsilon_a \triangleq \epsilon_b = 0.4$) and bonded simultaneously on either face of the core such that they are orthogonal to the rectangular sensors. The dimensions of the steel core, PVDF, and EMC are 76.2 mm x 76.2 mm x 0.076 mm, 30 mm x 12.2 mm x 0.028 mm, and 76.2 mm x 12.7 mm x 1.4 mm, respectively. The piezoelectric coupling coefficients (d_{31} and d_{32}) of PVDF are 23 pC/N and 5 pC/N, respectively.

Each PVDF lamina is interfaced with the proposed signal conditioner shown in Figure 4. The feedback and compensating capacitances of each amplifier are chosen as 100 nF such that their gains are 0.01 mV/pC. The insulating resistances of the capacitors are on the order of 1 TΩ yielding a time constant of 10^5 seconds. Ultra-low offset current CMOS operational amplifiers LMC6082 (Texas Instruments) are chosen and operated with a supply voltage of 4.5 V. Normally open switches are placed in parallel to the feedback and compensating capacitors. They are actuated simultaneously to reset the circuit to remove any residual charge prior to the start of the measurement.

3.2 Measurement of sensor voltages

Characterization experiments were conducted for measuring changes in the composite's shape with the embedded PVDF sensors. Controlled deformations were applied using a tensile test frame (Figure 5). The composite was hinged at the mid-points of its straight edges in one stable shape and flattened at a rate of 0.1 mm/s until it snapped into the next stable shape. A 3D motion capture system was used to track in real time the curvatures of the composite. Using a constant-curvature assumption, the composite shape was reconstructed using the marker coordinates. The voltages measured by the PVDF sensors were recorded using a data acquisition system (National Instruments) and LabView.

3.3 Model validation and discussion

The experimental results discussed in this section correspond to a transition in curvature from κ_a to κ_b. The case of snap-back would be similar since the curvatures in the chosen composite are equal. Prior to snap-through, the curved composite has sensor A on the outer face and sensor B on the inner face. In the absence of a charge amplifier, both sensors detect only the snap-through event in the form of a sharp transient response. Including

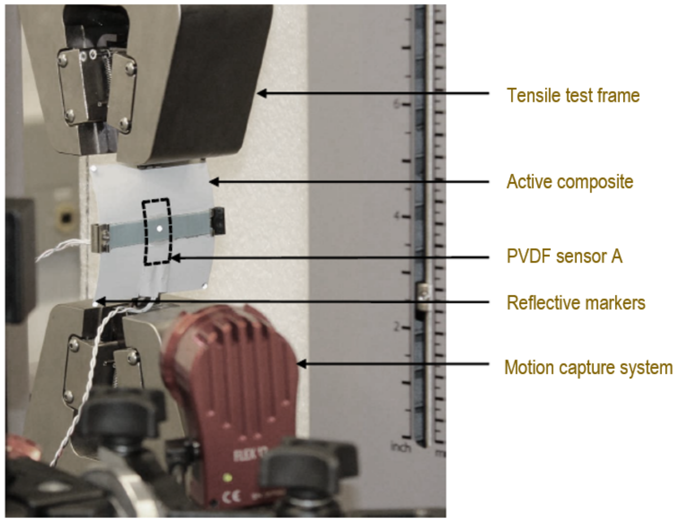

Figure 5: Setup to characterize the bistable laminate with PVDF sensors and a 3D motion capture system.

the large time constant compensated charge amplifier leads to a linear voltage rise in sensor A up to snap-through. Post snap-through the voltage remains steady. On the other hand, Sensor B only detects the snap-through event by a phase from zero to a finite voltage. Figures 6(a) and 6(b) show a strong correlation between voltages recorded by each sensor over a given timescale and the curvatures tracked by the motion capture system. Within the morphing structure, voltage V_a from PVDF A primarily tracks κ_a and voltage V_b from PVDF B primarily tracks κ_b. PVDF A experiences compression in its longitudinal direction as the composite undergoes shape transition, while PVDF B experiences tension at snap-through. Both sensors remain flat post snap-through as represented by the stable output of both curvature and voltage data. Without a large time constant charge amplifier, the steady-state signal would decay to zero. The deviation from linearity in V_a towards a higher slope, observed just prior to snap-through, can be explained by a downward shift in the post snap-through voltage due to compressive strain in the 2-direction. The shift or offset in the 2-direction is evident in the pre snap-through response of PVDF B (Figure 6(b)).

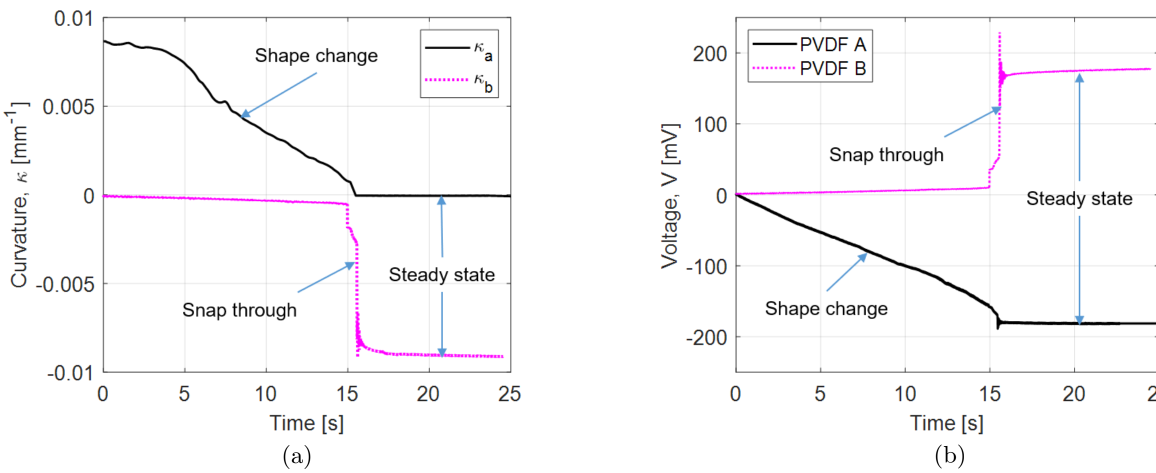

Figure 6: (a) Curvatures measured by the 3D motion capture system and (b) voltages measured by the PVDF sensors A and B representing the shape change and snap-through, respectively.

The generated voltage and the change in curvature is defined in terms of the sensitivities ($\lambda_{ij}, i = \{a, b\}$) of

PVDF A and PVDF B as:

$$\begin{Bmatrix} V_a \\ V_b \end{Bmatrix} = \underbrace{\begin{bmatrix} \lambda_{aa} & \lambda_{ab} \\ \lambda_{ba} & \lambda_{bb} \end{bmatrix}}_{\Lambda} \begin{Bmatrix} \Delta\kappa_a \\ \Delta\kappa_b \end{Bmatrix}, \tag{3}$$

where $\{\lambda_{aa}, \lambda_{bb}\}$ and $\{\lambda_{ab}, \lambda_{ba}\}$ are the laminate's direct and cross sensitivities, respectively. The voltage-curvature response of the sensing laminae obtained from measurements and analytical modeling is plotted in Figure 7. The variability in sensitivities are calculated using the analytical model for Young's moduli ranging from 2 to 4 GPa (range prescribed by the manufacturer).[15]

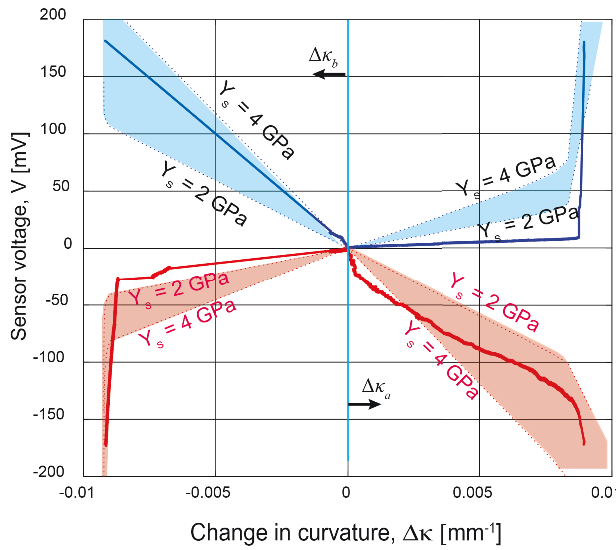

Figure 7: Voltages from PVDF A (red) and PVDF B (blue) vs. curvature obtained from experiments (solid lines) and modeling (dotted lines).

The direct sensitivities are captured within the range of the model-calculated values. The deviation of the calculated cross sensitivities from the measured values can be attributed to the assumption of constant curvature in the analytical model. Mechanically-prestressed bistable laminates with cylindrical shapes have flat regions across the width of the EMCs which limits their curvature.[13] Since the PVDF laminae have similar width as the EMCs, curvature in the PVDF in the 2-direction is lower than the model-calculated value, thereby resulting in lower cross-sensitivity. For both sensors, the ratio of the model-calculated direct sensitivity to cross sensitivity is calculated to be 2.65 for an average Y_s of 3 GPa. The measured voltages and sensitivities correspond uniquely to the principal curvatures. Therefore, the shape of the composite can be described in real time from the instantaneous values of V_a, V_b, and the curvature sensitivity matrix $\mathbf{\Lambda}$.

4. CONCLUDING REMARKS

This paper presents an active asymmetric bistable laminate that features piezoelectric PVDF films for sensing near-static changes in curvature as well as dynamic snap-through and snap-back responses. A method for fabrication of the active bistable laminate is described. A large time constant compensated charge amplifier is interfaced with the PVDF sensors to enable a direct readout of shape changes. An analytical model that relates the change in shape to voltage output by the sensors is presented. A strong correlation between the voltages measured by each sensor and the curvatures tracked by the motion capture system is observed. A direct measurement of the change in shape is enabled by the weakly coupled curvatures and the lower lateral sensitivity of PVDF. The theoretical model successfully describes the measured values of the direct curvature sensitivities. Due to the linearity between the change in curvature and voltages, the shape of the composite can be tracked in real time from the measured parameters. Further, the inherent ability of the piezoelectric sensors to generate electrical energy to power wireless sensor networks in response to change in elastic energy can be employed in autonomous structural health monitoring applications.

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