Piezoelectric d\textsubscript{15} shear response-based torsion actuation mechanism: an experimental benchmark and its 3D finite element simulation

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(Received 8 June 2010; final version received 19 July 2010)

An experimental benchmark is proposed for piezoelectric, direct-torsion actuation using mono-morph piezoceramic d\textsubscript{15} shear patches. This is reached by designing and assembling an adaptive plate having two identical composite faces sandwiching a core made of connected six oppositely polarized (OP) piezoceramic d\textsubscript{15} shear patches along the length. An electronic speckle pattern interferometry system was used to measure the static tip deflection of the adaptive sandwich composite plate that was mounted in a cantilever configuration and actuated in torsion by progressively applied voltages on the piezoceramic shear core electroded major surfaces. Then, the effective rate of twist was post-processed and proposed as an evaluation criterion for smart composites under piezoelectric torsion actuation. For verification of the experimental results, the proposed experimental benchmark was simulated using three-dimensional piezoelectric finite elements (FE) within ABAQUS\textsuperscript{®} commercial software. The comparison of the obtained experimental and simulation results showed reasonable agreement, but the slight nonlinear experimental response was not confirmed by the linear FE analysis. The experimentally proved torsion actuation mechanism, produced by OP piezoceramic d\textsubscript{15} shear patches, can be applied actively to prevent torsion in many applications, such as in wind turbines, helicopter blades, robot arms, flexible space structures, etc.

**Keywords:** torsion actuation; shear-mode piezoceramic; benchmark; experiment simulation

1. Introduction

Preventing or controlling twist (or torsion) deformation is a necessity for many applications, such as in wind turbines, helicopter blades, robot arms, flexible space structures, etc.; this can be reached indirectly via bending–twisting [1,2] or extension–twisting [3] stiffness couplings or directly through the electromechanical coupling between through-the-thickness applied electric field and twist strains via the coupling constant d\textsubscript{36} [4]. However, the latter is nil for mono-morph piezoelectric materials rendering the direct twist deformation sensing or actuation non-feasible; nevertheless, this coupling can be obtained indirectly using either skewed piezoelectric polymers [5–7], thanks to their orthotropic piezoelectric coupling properties, or piezoceramic fiber composite actuators or sensors that were made orthotropic thanks to a suitable fiber/epoxy blend [1].

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In order to overcome these difficulties, researches on the torsion actuation using the direct $d_{15}$ shear response of mono-morph piezoceramic materials have attracted noticeable interest since the mid-1990s [8]. This torsion actuation mechanism (TAM) was achieved experimentally using tubular actuators assembled from eight segments that were cut from circumferentially-polarized piezoceramic tubes [9–11], and theoretically using symmetrically surface-bonded width-polarized patches [12,13]. A simulation benchmark (theoretical) was also recently proposed consisting of a cantilever long and thin beam consisting of two piezoceramic layers oppositely-polarized (OP) along their length and superposed along their width [14]. This concept is proved experimentally here for a cantilever plate consisting of two identical glass fiber/epoxy composite faces sandwiching a core torsion actuator constructed by the connection of six OP piezoceramic $d_{15}$ shear patches along their length and superposed along their width.

In this study, the TAM concept was first considered theoretically; then, its characteristics were studied experimentally by an electronic speckle pattern interferometry (ESPI) system with out-of-plane displacement measurement sensitivity [15] for a designed and manufactured cantilever sandwich plate test setup, made of a piezoceramic $d_{15}$ shear-based torsion core actuator and two identical glass fiber/epoxy composite faces. The piezoelectric adaptive sandwich plate experiences static torsion due to the progressively applied electric potentials on the electroded major surfaces of the piezoceramic $d_{15}$ shear core. The latter’s torsion actuation capability was evaluated through the plate measured static maximum tip transverse (along thickness) deflection and post-treated maximum rate of twist and maximum effective rate of twist. The latter parameter is defined as the rate of twist per unit voltage. This new torsion actuation benchmark was also simulated within ABAQUS® commercial code using three-dimensional (3D) elastic and piezoelectric finite elements (FE) for the composite faces and piezoceramic core, respectively. The above TAM evaluation parameters were extracted and compared to those obtained from the experimental tests. This numerical analysis is expected to help for the evaluation of the cross-section warping (axial displacement) and its importance for developing representative theoretical models for this new TAM.

2. The concept of piezoelectric $d_{15}$ shear-induced torsion actuation mechanism

Consider a cantilever single-layer plate assembled from six piezoceramic patches OP along their length, as shown in Figure 1. The plate is subjected to only an electric voltage ($V$) applied on its electroded major surfaces so that the through-the-thickness applied electric field is perpendicular to the polarizations; in this case, it is well known [8] that only transverse shear actuation strains can be induced.

Since the polarization is conventionally along the material 3-axis, the induced actuation strains by the bottom ($b$) row of piezoceramic patches of Figure 1, that are polarized along the plate positive $x$-axis, are

$$
\begin{bmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{zz} \\
\gamma_{yz} \\
\gamma_{zx} \\
\gamma_{zy}
\end{bmatrix} =
\begin{bmatrix}
d_{33} & 0 & 0 \\
d_{31} & 0 & 0 \\
d_{31} & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & d_{15} \\
0 & d_{15} & 0
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
E_z \\
0 \\
d_{15}E_z \\
0
\end{bmatrix}.
$$ (1)
Figure 1. A cantilever plate assembled from piezoceramic shear $d_{15}$ patches OP along the $x$-axis.

Hence, as stated above, only a transverse shear actuation, $\gamma_{b}^{z} = d_{15}E_{z}$, is produced by the bottom row of piezoceramic patches. Due to the OP direction, the top ($t$) row of piezoceramic patches should produce $\gamma_{t}^{z} = -d_{15}E_{z}$; this expression is obtained by adding a negative sign to the piezoelectric constants of Equation (1). So, if the applied electric field is constant and positive, the bottom layer of piezoceramics should deform the plate positively along the $z$-direction, whereas the top layer should deform it negatively to this direction; the combination of these deformations should produce a global torsion of the cantilever plate because the patches are identical (have the same shear modulus) and the transverse shear stress $\sigma_{xz}$ should be continuous at the bottom/top layers interface. The latter is the location of the neutral and torsion axes due to the construction symmetry; hence, it should not move transversely.

3. Shear-induced torsion actuation experimental benchmark

To validate the above torsion actuation mechanism, the cantilever piezoceramic plate of Figure 1 was integrated in an adaptive plate construction as a core layer sandwiched between two identical composite faces, as shown in Figure 2. This benchmark was designed and assembled using PIC255 piezoceramic shear patches (from PI Germany), of dimensions $25 \times 25 \times 0.5$ mm$^3$, for the core, and Polyspeed G-EV 760R glass fiber/epoxy layers (from Hexcel Austria), of dimensions $75 \times 50 \times 0.49$ mm$^3$, for the composite faces; a methacrylate-based two-component adhesive (of 0.1 mm thickness) was used for bonding the faces to the core.

The bonding thickness has been controlled during the gluing process by using other glass fiber and piezoceramic patches adjacent to the glass fiber and piezoceramic patches being glued and they are raised to the thicknesses of the adhesive layers by other special glue bands of the same thicknesses of the adhesive layers. The piezoceramic shear patches are bonded to each other by using very thin adhesive layers. These special glue bands used during the process are 0.1 mm thick; this bond thickness has been selected because its value is controllable. The glass fiber epoxy has been particularly selected in this composite structure because of its non-conductive properties. The role of the composite faces was to make the assembled patches work together as a homogenous core, and their primary effect was to stiffen the whole actuator.
The thicknesses of the glass fiber/epoxy composite faces and adhesive layers play a crucial role in the torsion actuation performance of the composite structure since they affect the torsion stiffness and torsion moment created by the piezoceramic patches; indeed, these are functions of the thicknesses of all layers. Besides, if the structure is longer, more transverse deflection can be obtained for the same whole thickness; whereas if the composite layers were stiffer, less rate of twist would be obtained. The proposed design is then a compromise between all material and geometric parameters effects on the torsion actuation.

A series of experiments was then carried out on the experimental benchmark by applying increasing voltages (from 45.3 to 198 V) to the piezoceramic torsion core in order to measure the maximum rate of twist of the adaptive structure. For this purpose, the maximum static tip deflection of the cross-section at the free side of the composite plate was measured by an ESPI system (Dantec-Ettmeyer ESPI Q300). Figure 3 shows a photo of the experimental benchmark (right) and ESPI system (left).

The other pieces of equipment in the experimental setup were a high-voltage (HV) amplifier (Elba Tech type T-502), laboratory power supply (EA type EA-3016) and ISTRA data processing software for the control and evaluation of the ESPI system (Figure 4). The latter provides more sensitive and full-range measurement possibilities than strain gages and has the advantage of being able to measure deformations and deflections of engineering structures and materials without contact. It does not change, the response of the objects being studied, because of its non-contact nature. Therefore, results obtained by an ESPI
system represent reality and can be used to validate analytical or/and numerical solutions. The visualization occurs in the form of fringes on the image. From the speckle patterns, the out-of-plane and the in-plane deformations can be determined. Digital image equipment processes the information included in the speckle patterns and displays the consequent interferogram on a computer monitor. The ESPI system can be used not only for one-step measurement but also for a series of measurements. The main difference of the out-of-plane displacement measurement by the ESPI system with respect to an in-plane displacement measurement is that in out-of-plane displacement measurement, a single illuminating beam is used. The coordinate system of Figure 2 is in agreement with that of the ESPI system (Figures 3–4).

Figure 5 shows the transverse deflection fringes (Figure 5a) and its through-height (y-direction) variation at \( x = 1.14 \text{ mm} \) (Figure 5b) of the cantilever adaptive sandwich composite plate when torsion was actuated by a 198 V voltage. It can be seen that the tip transverse deflection is anti-symmetric with regard to the plate length (x-direction), as in Figure 5a, and that it is linear through the cross-section (in the y–z plane) height as can be seen from Figure 5b.

Due to this asymmetry, the measured and FE (with asymmetric response) transverse deflection was calculated as half of the difference between the maximum and minimum values (for example, as in Figure 5b for the measurement at \( x = 1.14 \text{ mm} \)); in addition, since the length and width ranges of the torsion actuator are not totally covered by the ESPI measurement system (see the x and y ranges in Figure 5a), the transverse deflection was measured twice near the free \((u_z^1 \text{ at } x_1 = 1.14 \text{ mm and } y_1 = 48.88 \text{ mm})\) and clamped \((u_z^2 \text{ at } x_2 = 72.30 \text{ mm and } y_2 = 46.98 \text{ mm})\) ends; then the maximum transverse deflection was approximated using

\[
u_z^{\text{max}} = \frac{u_z^1 - u_z^2}{L}. \tag{2}
\]

The maximum rate of twist of the shear-induced torsion actuated composite plate was then obtained by dividing the maximum measured transverse deflection in the z-direction by the length (75 mm) and half width (25 mm) of the composite plate (the adhesive thickness was here neglected). The effective rate of twist, which is proposed as the evaluation criterion for piezoelectric torsion actuated smart composites, is calculated by dividing the maximum
rate of angle of twist by the applied voltage. The experimental results are given later for the comparison with numerical results.

4. Finite element simulation of the experimental benchmark

The experimental benchmark described above was simulated using ABAQUS® commercial FE code. Static torsion actuation analyses of the cantilever adaptive plate were conducted.
using, respectively, piezoelectric (C3D20RE) and elastic (C3D20R) quadratic brick elements for the piezoceramic core and composite faces. The FE mesh has 30 elements along the plate length, 20 elements along its width and two elements per layer through their thickness for the piezoceramic and glass fiber/epoxy layers and one element per layer through-the-thickness for the adhesive layers, leading to a total of 4800 elements and 30,166 nodes (Figure 6). Electric potentials were applied to the piezoceramic core major surfaces that were forced to be equipotential (EP) electrodes. The EP constraints of the core electrodes were expressed by linear relationships so that the electric potentials for the major surfaces of the piezoceramic core are coupled to the electric potentials of the master nodes assigned to each surface using \^EQUATION option. The OP of the top row of piezoceramic shear patches is implemented by changing the sign of the piezoelectric coefficients as negative. For this purpose, two different material properties and sections were assigned to the two rows of piezoceramic shear patches. The materials properties are given in the Appendix.

The plate global and tip transverse deflections under static torsion actuation of 198 V are shown in Figures 7a and 7b, to be compared to Figures 5a and 5b, respectively, for the measurements under 198 V.

From Figures 5 and 7, it is clear that the simulated and experimental transverse displacements have qualitatively similar plate axial and cross-section height distributions. Quantitatively, by taking the effect of 0.1 mm thick adhesives into consideration, the FE simulations provided these maximum tip displacements for which only the transverse one has been measured ($\theta = 5.267 \mu m$):

$$
\begin{align*}
  u_x^{\text{max}} &= 0.05964 \mu m, \\
  u_y^{\text{max}} &= 0.223 \mu m, \\
  u_z^{\text{max}} &= 4.980 \mu m.
\end{align*}
$$

Values indicated in Equation (3) show that the transverse displacement component dominates the other ones; in particular, the axial displacement, which is governed by the section warping, is negligible compared to those in the cross-section; this can also be seen from the plate global and cross-section twist deformations shown in Figures 8a and 8b, respectively.

From results in Equation (3) and the deformations shown in Figure 8b, the displacement field can be written in a first approximation as

$$
\begin{align*}
  u_x &= 0, \\
  u_y &= -z \theta(x) = -z x \alpha, \\
  u_z &= y \theta(x) = y x \alpha; \\
  \alpha &= \theta_x,
\end{align*}
$$

where $\theta(x)$ and $\alpha$ are the twist angle and constant rate of twist (or twist angle per unit length).

![Figure 6. The 3D finite element model of the experimental benchmark.](image)
Figure 7. Transverse deflection (a) surface distribution and (b) tip cross-section variation for 198 V.

Hence, the Saint Venant torsion kinematics can be used, in a first approximation, to build an analytical model for the theoretical analysis of this new TAM.

From the relations of Equation (4), the effective rate of twist is defined as the maximum of the rate of twist per unit voltage; it is obtained, for the simulations and experiments, by calculating the maximum tip transverse deflections and dividing them by the applied voltage ($V = 198$ V) and, the length ($L = 75$ mm) and half of the width ($b = 50$ mm) of the composite plate (the adhesive thickness is neglected here); this leads to

$$\theta_{x}^{\text{max}} = \alpha_{x}^{\text{max}} = \frac{2\mu_{\text{max}}}{LbV}.$$ (5)

A comparison of the results obtained from experiments and FE simulations is presented in Table 1 for 198 V and in Figures 9 and 10. The results show that the adhesive layers between the active core and composite faces have an important effect on the torsion deformation produced by the piezoceramic shear actuators. It is also worth noticing that the experimental results show a slight nonlinearity, which is one of the characteristics
of piezoceramic $d_{15}$ shear actuators. The comparison between the experiment and the FE simulation shows a reasonable agreement when the adhesive layers are considered. It is thought that the observed deviations in this case can be attributed to the non-realistic (nil displacements) representation of the real (softer) clamp by the FE model. Uncertainties related to the materials data used for the simulations also partly explain these deviations; finally, the bonding assembly (assumed perfect in the FE model) can influence the static deflection simulation. Nevertheless, these are usual difficulties that are met when simulating experimental benchmarks; hence, these results validate the proposed TAM concept.

5. Conclusions and perspectives

An experimental benchmark and its three-dimensional (3D) finite element (FE) simulation were proposed for the new piezoelectric $d_{15}$ shear response-based direct torsion actuation mechanism (TAM). For this purpose, the maximum static tip transverse deflection of a composite plate progressively actuated in torsion by the connection of six oppositely polarized (OP) piezoceramic $d_{15}$ shear patches was measured by an electronic speckle pattern interferometer (ESPI) system. The effective rate of twist was post-processed from a simple
Table 1. Summary of the torsion actuation experimental and FE results (at 198 V).

| Description                                                                 | Value       |
|-----------------------------------------------------------------------------|-------------|
| Experimental transverse deflection in the $z$-direction ($\mu$m) at 198 V   | 5.267       |
| FE simulated transverse deflection in the $z$-direction ($\mu$m) at 198 V   | 4.980       |
| (with adhesive)                                                             |             |
| FE simulated transverse deflection in the $z$-direction ($\mu$m) at 198 V   | 6.906       |
| (without adhesive)                                                          |             |
| Experimental rate of twist (mm/m)                                           | 2.809       |
| FE simulated rate of twist (mm/m) (with adhesive)                           | 2.656       |
| FE simulated rate of twist (mm/m) (without adhesive)                        | 3.683       |
| Experimental effective rate of twist (mm/m/V)                               | 0.0142      |
| FE effective rate of twist (mm/m/V) (with adhesive)                         | 0.0134      |
| FE effective rate of twist (mm/m/V) (without adhesive)                      | 0.0186      |

Figure 9. Transverse deflection comparisons between the experiment and FE simulations.

Saint-Venant torsion displacement field model deduced from the experimental and numerical observations of the proposed benchmark results. This parameter is proposed as the main static evaluation criterion for piezoelectric torsion actuated smart composites; it is defined as the maximum rate of twist under an applied unit voltage. The nonlinearity of the piezoelectric shear $d_{15}$ actuators was also observed during the experiments. The experimental benchmark was simulated using 3D FE within ABAQUS® commercial code by taking into consideration the adhesive layers between the composite faces and the active core. The experimental effective rate of twist value was compared to its 3D FE simulation and the obtained results showed reasonable agreement.

This experimentally and numerically validated TAM concept, produced by OP piezoceramic $d_{15}$ shear patches, can be applied in preventing or controlling twist (or torsion) deformation for many applications, such as in wind turbines, helicopter blades, robot arms, flexible space structures, etc.

As an immediate continuation of the present work, experimental modal analyses of this benchmark are being conducted for the evaluation of its effective electromechanical
coupling coefficient. The latter is post-processed from the measured short-circuit and open-circuit frequencies in the aim to assess the energy conversion efficiency of this new TAM.

**Acknowledgments**

The authors would like to thank Professor Helmut Rapp, Head of the Institute for Lightweight Structures of the Universität der Bundeswehr München (Germany), for his help during the experiments, and Professor Rudolf Wörndle, Head of the Institute for Designing Plastics and Composite Materials of the University of Leoben (Austria) for his support to the first author. The latter also acknowledges the support of the Polymer Competence Center Leoben (Austria) for the support of the present work.

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### Appendix. Material properties

#### Table 2. Material properties.

| Material | Constant | Notation | Value |
|----------|----------|----------|-------|
| PIC 255 (data for standard thickness poling) | Piezoelectric stress constant (C/m²) | $e_{15} = e_{24}$ | 11.9 |
| | | $e_{31} = e_{32}$ | −7.25 |
| | | $e_{33}$ | 14.41 |
| | Permittivity constants at constant strain (nF m⁻¹) | $\varepsilon_{11}^s = \varepsilon_{22}^s$ | 8.245 |
| | | $\varepsilon_{33}^s$ | 7.122 |
| | Young’s moduli | $E_1 = E_2$ | 62.89 |
| | | $E_3$ | 47.69 |
| | Shear moduli (GN/m²) | $G_{13} = G_{23}$ | 22.26 |
| | | $G_{12}$ | 23.15 |
| | Poisson’s ratios | $\nu_{13} = \nu_{12}$ | 0.36 |
| | | $\nu_{23}$ | 0.41 |
| G-EV 760R glass fiber/epoxy | Young’s moduli (GN/m²) | $E_1$ | 33.11 |
| | | $E_2 = E_3$ | 13.1 |
| | Shear moduli (GN/m²) | $G_{13} = G_{12}$ | 3 |
| | | $G_{23}$ | 2.3 |
| | Poisson’s ratios | $\nu_{13} = \nu_{12}$ | 0.27 |
| | | $\nu_{23}$ | 0.40 |
| Adhesive | Young’s modulus (GN/m²) | $E$ | 1.03 |
| | Poisson’s ratio | $\nu$ | 0.37 |