Piezoelectric d_{15} Shear-Mode Sensor in Parallel and Series Configurations

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The sensor response experiments of piezoceramic shear same poled d_{15} patches which are integrated in a composite sandwich beam-like structure and connected in parallel and series configurations are presented in this letter. The core of the smart structure is formed from four piezoceramic shear d_{15} patches arranged in the same polarization (SP) direction and sandwiched between two identical glass fiber/epoxy layers. The dynamic response of the composite structure was monitored using these four piezoceramic shear d_{15} patches acting as sensors in parallel and series configurations and the data were evaluated by a pulse-multianalyzer system. A charge amplifier was used as a signal conditioning circuit between the piezoceramic shear d_{15} patches and the pulse-multianalyzer system. The outputs of the piezoceramic shear sensor were in a short-circuit state with the use of the charge amplifier. The results are promising as the proof of using piezoceramic shear same-poled d_{15} patches to sense the response of beam-like composite structures.

Introduction

Piezoelectric materials can be used for sensing a structure's response, when they are embedded into a laminated composite. This is achieved thanks to the electromechanical interaction that occurs in a piezoelectric material by the application of a force which produces electric charges (direct piezoelectric effect). Therefore, the dynamic response of a composite structure with incorporated piezoelectric shear d_{15} patches can be monitored through the measure of the induced electric charges which accumulate on the electrode surfaces of the piezoceramic patches. Piezoelectric shear d_{15} transducers which are nested in structures experience less damage and smaller stresses compared to surface mounted extension ones. Piezoelectric d_{15} shear strain coefficient is higher than the transversal and longitudinal piezoelectric coefficients (d_{31} and d_{33}), and piezoelectric shear d_{15} transducers can be used to produce shear and torsional deformation [**1-10**].

Most of the preceding piezoelectric sensing and actuation techniques were based on the surface mounted piezoelectric d_{33} and d_{31} transducers in which the electric field and poling vectors were always parallel, the inherent shear effects were neglected and piezoelectric d_{15} effect was not applied [**11-16**]. A piezoelectric sensor can measure a longitudinal strain by using the longitudinal piezoelectric strain coupling constant d_{33} [**17**], in-plane strains by using the transverse piezoelectric strain coupling constant d_{31} [**18**] and shear strains by using the shear piezoelectric coupling constant d_{15} [**6**].

Berik *et al*. [**19**] assessed the piezoelectric transverse d_{15} shear sensing mechanism experimentally for a cantilever smart sandwich plate made of a piezoceramic axially opposite poled (OP) patched core and glass fiber reinforced polymer composite faces in open-circuit electric condition by means of sensed voltages. Altammar *et al*. [**20**] proposed and analyzed a bondline-integrity health monitoring approach utilizing shear-mode (d_{15}) piezoelectric transducers. It was found that d_{15} PZT sensors exhibited larger changes in voltage amplitude when compared to the signals produced by the surface-mounted d_{31} PZT sensor. Ma *et al*. [**21**] investigated a cement-based 1−3 piezoelectric composite sensor for the characterization of shear stress in civil engineering structures by embedding two sensors into a concrete beam, and characterized its performance with a three-point bending test technique. Reported results showed very good accuracy, linearity, and frequency bandwidth for both sensors.

Compared to the author's previous work [**19**] on the sandwich plate-like experimental benchmark, the present one contributes originally with the new sandwich beam-like experimental benchmark formed by same poled piezoceramic d_{15} shear patches; previously only sensing of a sandwich plate composed of opposite poled piezoceramic d_{15} shear patches was conducted.

The objective of this paper is to present a new adaptive sandwich beam structure with embedded piezoceramic same poled d_{15} shear patches capable of sensing a structure's response. In particular, the present study focuses on the experimental investigation of the piezoceramic same-poled shear d_{15} patch sensors for monitoring the produced voltage under applied dynamic forces.

Benchmark and Experiments

In the present experiments, different electrical connection configurations of same poled (SP) piezoceramic d_{15} shear patches were evaluated for their sensing performances in terms of produced electric charges involving short-circuit condition. The composite structure was exposed to dynamic forces applied by a shaker. A charge amplifier should be used in order to measure the quantity of the charges generated by a piezoelectric sensor. Because a charge amplifier can convert the piezoelectric sensor's charge into a usable signal [**22**]. A charge amplifier is used as link between the piezoelectric sensor's output and a readout device. The piezoelectric sensor was connected to the charge amplifier and different harmonic forces were applied to the sensor. The output signals of the piezoelectric shear sensor were going through the charge amplifier for conversion and amplification.

The sensing functionality of a piezoceramic material is governed by its direct piezoelectric effect. More detailed information about the piezoelectric d_{15} shear sensing mechanism can be found in the author's previous work [**19**]. For the case of transverse shear stress loading of a piezoelectric longitudinally poled d_{15} material, the constitutive equations can be written in terms of shear stress T_5 and strain S_5 and through-thickness electric field E_3 and displacement D_3 as follows [19, 23]:

$$\begin{Bmatrix} D_3 \\ S_5 \end{Bmatrix} = \begin{bmatrix} \varepsilon_{11}^T & d_{15} \\ d_{15} & s_{55}^E \end{bmatrix} \begin{Bmatrix} E_3 \\ T_5 \end{Bmatrix} \quad (1)$$

where ε_{11}^T is the dielectric coefficient at constant stress, d_{15} is the thickness-shear piezoelectric coefficient, and s_{55}^E is the transverse shear compliance at constant electric field. Supposing displacement to be constant through-thickness, then

$$D_3 = \frac{Q_3}{A} \quad (2)$$

where Q_3 is the charge collected on the electrode area A.

The beam benchmark was designed and assembled using four pieces of PIC255 shear patches (from PI Germany) of dimensions 25x10x0.5 mm^3 and Polyspeed G-EW 760R glass fiber/epoxy layers (from Hexcel Austria) of dimensions 100x10x0.5 mm^3 (**Fig. 1**) The piezoceramic patches were glued in same poling (SP) configuration with a non-conductive adhesive (Henkel Loctite 9466).

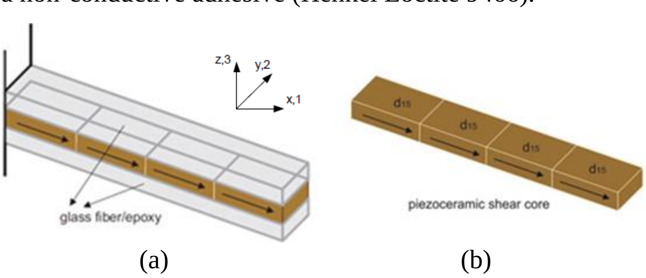


Fig. 1. The sketch of the experimental benchmark (a) and its piezoceramic d_{15} shear core (b).

The dynamic sensing experiments were carried out on the experimental benchmark by applying different harmonic forces ranging from 0.025 N to 0.260 N at 20 Hz to the in order to sense the maximum produced electric charge of the structure. The harmonic forces are exerted on the middle of free edge of the structure using a shaker. The test equipment used in the experiments were a pulse-multianalyzer system (Brüel & Kjaer with input/output module type 3109 and LAN interface module type 7533), force sensor (PCP ICP type 208B02), a Bruel-Kjaer power amplifier (type 2718) and a Bruel-Kjaer charge amplifier (type 2635). In the force transducer, 1 N corresponds to 22.256 mV. The experimental flow-chart is presented in **Fig. 2**.

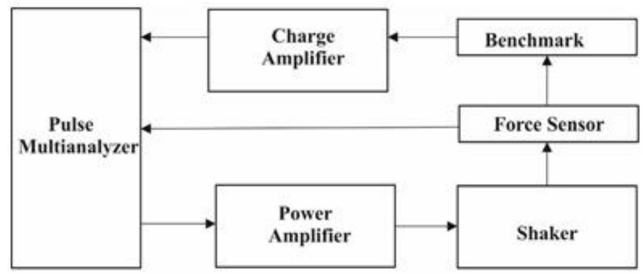


Fig. 2. The experimental set-up flow chart.

The associated sensor connections of the experiments are presented in **Fig. 3**. In the parallel connection type (**Fig. 3a**), the top electrodes of the patches are connected together, the bottom electrodes are also connected separately and a charge amplifier is attached to the system between *a* and *b*. In the series connection type (**Fig. 3b**), the charge amplifier is attached between *a* and *e*. The piezoelectric sensor is in the short-circuit state each time when it is linked with a charge amplifier. It should be noticed that, the series electrical connection which was implemented in these performed experiments involves both short-circuit and open-circuit electrical conditions depending on the existence of a link of the patches' electrodes to the charge amplifier, whereas the parallel configuration acquires only the short-circuit condition. But for both of the series and parallel connections, the outputs of the piezoceramic sensor are in short-circuit condition.

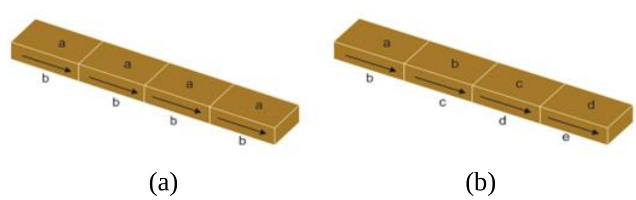
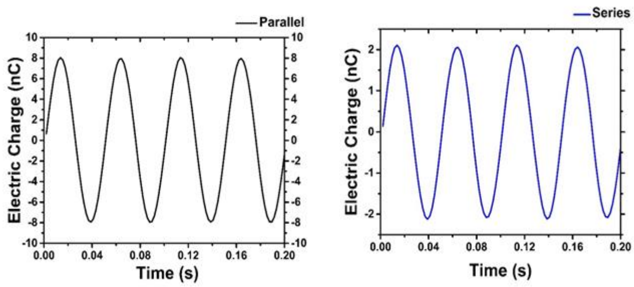


Fig. 3. Parallel connection: *a-b* electrodes are short-circuited with the charge amplifier (a) Series connection: *a-e* electrodes are short-circuited with the charge amplifier (b).

Results and discussion

Harmonic forces of different amplitudes at 20 Hz ranging from 0.025 N to 0.260 N were exerted on the composite sandwich structure. **Figs. 4, 5** and **6**, and **Table 1** and **Table 2** show the produced electric charge values under applied dynamic forces for two associated parallel and series sensor connections. **Fig. 5** presents the superposed comparison of these two sensor connections under per unit dynamic force. As we can notice, the parallel connection produced higher electric charge amplitude then the series sensor connection. This would be the inverse case for the produced voltage values.



(a) (b)

Fig. 4. Measured electric charge amplitudes (nC) for the parallel connection (a), and series connection (b) at 0.250 N.

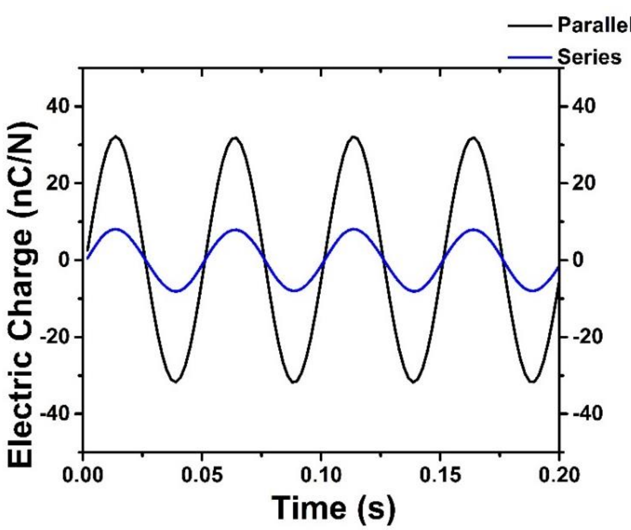


Fig. 5. Comparison of measured normalized electric charge amplitudes (nC/N) for the parallel and series connections.

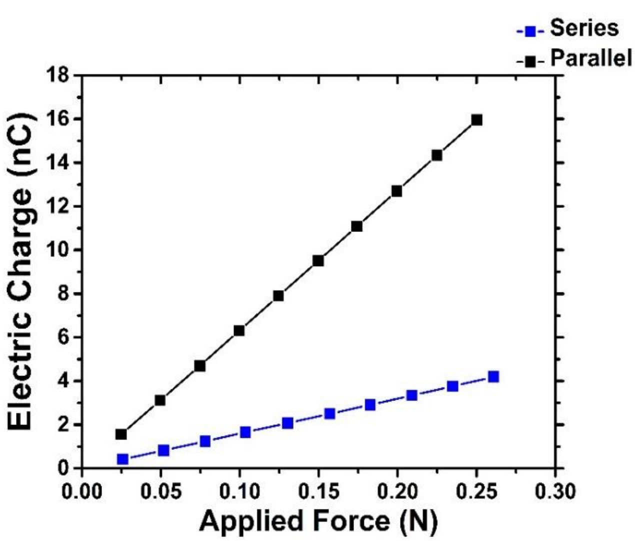


Fig. 6. Experimental sensed electric charge (nC) versus applied force values for the parallel and series connection cases.

Table 1. Sensed peak to peak electric charge values (nC_{p-p}) versus applied dynamic loads (N).
for the *parallel connection*

Applied load (N)	Electric charge (nC)
0.049	3.111
0.125	7.891
0.250	15.952
Normalized	63.808

Table 2. Sensed peak to peak electric charge values (nC_{p-p}) under different applied dynamic loads (N)
for the *series connection*

Applied load (N)	Electric charge (nC)
0.052	0.823
0.130	2.076
0.260	4.186
Normalized	16.100

The induced voltage outputs were post-processed from the electric charge measurements and capacitances using the equation $V=Q/C$. Open-circuit refers to the situation in which at least one of the outputs of the piezoelectric sensor has non-zero potential condition or nor connected to a charge amplifier. **Table 3** shows the measured capacitances of the parallel and series design connections. The capacitances were determined through discharging curves for each connection types by applying 1 V and then removing it. **Table 4** and **Fig. 7** illustrate the voltage outputs for the corresponding parallel and series sensing cases. As it can be noticed, the series connection produces more voltage than the parallel connection case. **Fig. 7** is obtained by dividing the maximum produced voltage values with their corresponding maximum exerted forces. Compared to the piezoceramic opposite poled d_{15} shear sensor reported in [**19**], this piezoceramic same poled d_{15} shear sensor produced higher normalized voltage output values. In [**19**], the normalized voltage value as the collective sensor was 0.49 V/N.

Table 3. Measured capacitances (nF)

Connection	Capacitance (nF)
Parallel	29.6
Series	1.97

Table 4. Maximum normalized peak to peak voltage outputs (V_{p-p})

Connection	Normalized Voltage (V_{p-p})
Parallel	2.156
Series	8.173

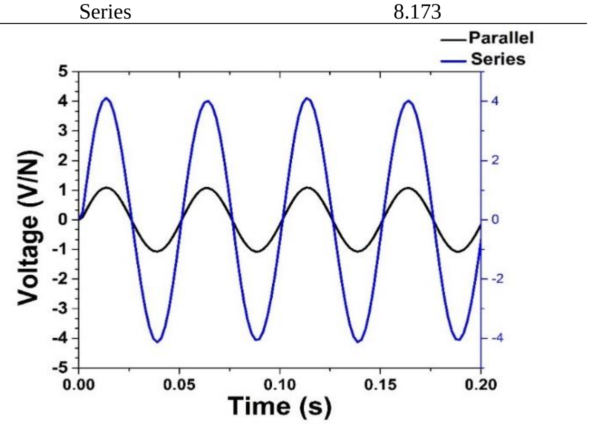


Fig. 7. Comparison of normalized voltage amplitudes (V/N) for the parallel and series connection cases.

Conclusions

In this study, it is shown that piezoceramic same poled shear d_{15} patches can be effectively used as sensors in parallel and series connections in order to monitor the response of a composite structure which is exposed to applied forces or vibration. The electric charge outputs were measured using a charge amplifier in parallel and series design configurations. The induced voltage outputs were post-processed from the measured electric charge values. It was found that the parallel connection is more advantageous than the series type in terms of produced electric charges whereas the series type is able to produce more voltage outputs. Findings also revealed that this piezoceramic d_{15} shear sensor made from patches with the same polarization direction exhibited higher performance than the previously reported piezoceramic opposite poled d_{15} shear sensor. The present work provides a foundation for future device configurations using piezoceramic same poled d_{15} shear patches to sense the response of composite beam-like structures. Since embedded piezoelectric shear d_{15} sensors are exposed to less damage compared to surface mounted extension actuators, monitoring of composite structures using piezoceramic same poled d_{15} shear sensors would be more beneficial. The corresponding experimental data can also serve for evaluating future extensions of analytical formulations of composite beam-like structures with a piezoceramic core formed by same poled d_{15} shear patches.

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Keywords

piezoceramic, sensor, shear, d15, electric charge

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