Piezoelectric PVDF sensor as a reliable device for strain/load monitoring of engineering structures

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Abstract. This study investigates the potential of PVDF (polyvinylidiene fluoride) piezoelectric polymer material as a strain/load sensor for engineering structures. The PVDF sensor can be made in any shape/size and are flexible. In addition, the PVDF sensor is passive and offers the advantage of requiring no power to function. PVDF sensors were bonded to an aluminum specimen representative of an engineering structure and the voltage output of the PVDF sensors was found to vary linearly with the applied tensile load. This paper evaluates the possibility to make develop cheap, reliable and efficient sensors for structural health monitoring of engineering structures.

1. Introduction

Engineering structures, such as aircraft, wind turbines, marine vessels, buildings and offshore platforms, are experiencing a range of uncertain dynamic loadings during their life time, due to changes in operational and environmental conditions [1, 2].

These structures are usually over-engineered in order to prevent failure. This general situation is because there is not an appropriate and cost efficient devices to monitor the subjected loads, and therefore not possible to predict the fatigue life of these structures.

In order to have an accurate prediction about fatigue life of engineering structures, a Structural health monitoring (SHM) technology should be developed to understand the loads intensity and numbers.

A device, designed by NASA [3], showed the applicability in counting the strain-level for aircraft structures. This device was using a resistance strain gage that was used as the sensor with solid-state circuits and electro-mechanical counters. The device performance was compared against mechanical scratch guard. Unfortunately, the sensor was large (20.8 x 12.2 x 4.3 cm³ - without the counters) and had a high power consumption, requiring the provision of energy by the aircraft’s auxiliary power supply.

Later, a patent was filed by Man Technologie in 1998 [4] that designed a portable device that can count and sort load levels. Again, a mechanical strain gauge was used, however, the results were not
consistent over the rain-flow plots. The significantly-sized device was attached to the structure by screws and had its own power-supply.

PVDF film can be used for energy harvesting purpose as well as being developed as primary sensor due to its vast dynamic range, wide frequency coverage, high conversion efficiency, high elastic compliance, cost effectiveness etc. [5-7]. PVDF also shows excellent potential for embedding into structures because of its low Young’s modulus when compared with modern materials [8]. This means that embedding such a sensor has little effect on the mechanical properties [9].

As a result, using PVDF as a sensor for the load-counting purpose can result in a compact, low-power consumption and wireless device that can be easily implemented in engineering structures. As a result, in another study [10], PVDF film was used to replace the strain gauge to monitor the load history of engineering structures. These results showed that PVDF can potentially be used to replace the strain gauge, however, no investigation was done about the reliability of the produced results measured by the PVDF sensor compared with the strain gauges.

This research is investigating the feasibility of replacing strain-gauges with Piezoelectric PVDF film, as a dynamic load gauge. The overall aim is to develop a monitoring-based method for fatigue life assessment with use of long-term monitoring data by PVDF.

2. Methodology and procedure

As shown in Figure 1, the experiment was coordinated by attaching the PVDF sensor attached to a piece of mild steel and subjecting it to cyclic tensile tests with different load levels. The examined sample was created by mounting the PVDF sensor 20mm from the midpoint of the steal which was cut to length of 300mm. This was followed by another sensor mounted on the other side of the mild steel to compare the results (see Figure 3).

The PVDF sensors were manufactured by TE Connectivity (part number 1-1002910-0) and the employed data acquisition system was Vishay Model 6100 scanner. Table 1 summarises some parameters and dimensions of the PVDF sensors. Table 2 shows characteristics of the steel substrate. The PVDF sensors was loaded in D33 direction where it has the highest piezoelectric co-efficient and therefore highest sensitivity.

The sample was cut from a longer piece with a length of 300mm, width of 25mm and a depth of 6mm. The sample was subjected to both tension and compression in order to evaluate the PVDF performance in both conditions. Different loads were applied in a sinusoidal wave pattern by varying the amplitude in order for the specimen to be strained, as the amplitude was varied the data acquisition device collected information for both the strain acquired and the voltages in respect to the amplitudes. The sinusoidal pattern was necessary as piezoelectrics do not perform adequately when subjected to static loads or a constant loading condition but rather require a dynamic loading approach for voltage generation.

The machine was calibrated to 0 mean amplitude with no preload applied, and the specimen was subjected to tension under 2kn, 4kn, 6kn, 8kn and 10kn on different times. Readings were derived by the data acquisition device from the voltage signals obtained by the piezoelectric sensors and the strain signals acquired by the strain scanner.
Figure 1. Experimental setup a) The tensile test and b) The data acquisition system.

Table 1. Dimensions and parameters of the PVDF sensors.

| Parameter                      | Value          | Units          |
|--------------------------------|----------------|----------------|
| Thickness                      | 28             | µm             |
| Piezoelectric Coefficient D31  | $23 \times 10^{-12}$ | (C/m$^2$)/(N/m$^2$) |
| Piezoelectric Coefficient D33  | $-33 \times 10^{-12}$ | (C/m$^2$)/(N/m$^2$) |
| Piezoelectric Coefficient G31  | $216 \times 10^{-3}$ | (m/m)/(C/m$^2$) |
| Piezoelectric Coefficient G33  | $-330 \times 10^{-3}$ | (m/m)/(C/m$^2$) |
| Capacitance                    | 1.38           | NF             |
| Young’s Modulus                | $2 – 4 \times 10^9$ | N/m$^2$        |
| Electrodes Material            | SILVER INK     |                |
| Electrode’s Thickness          | 0.484          | µm             |

Table 2. Characteristics of the beam.

| Parameter             | Value  | Units |
|-----------------------|--------|-------|
| Mass Density          | 7850   | Kg/m$^3$ |
| Young’s Modulus       | 210    | GPa   |
| Poisson Ratio         | 0.303  |       |

Figure 2. Schematic of the steel specimen with the attached PVDF sensors and strain gauges.
3. Results

Figure 3 shows the amplitude dependence of both the PVDF sensor according to the magnitude of the cyclic force, from 2kN to 10kN. As can be seen from Figure 3, there is a higher voltage by increasing the load level. This is because in the high load level, a higher displacement level is experienced by the piezo-electric material, compared with the low load level.

The ability for the PVDF sensors to detect cyclic load is examined by comparing the outputs of strain gauges to those of the PVDF as illustrated in Figure 4. As can be seen, the voltage results resemble a good correlation with strain gauge readings indicating PVDFs capability to monitor the load variation.

Results also show that PVDF was more sensitive to sense deformation than strain gauges giving it an advantage over strain gauge technology. As illustrated in Figure 5, the output voltage varied linearly with a peak amplitude of 0.11 volts being achieved for 2 kN of force and 0.39 volts for 10 kN.

![Figure 3](image-url)  
*Figure 3.* Voltage versus time results for the cyclic loads with different amplitudes.
5. Discussion
The PVDF sensors appear well matched to the task of load monitoring on structures. Even though a direct comparison of the strain gauge values and PVDF output cannot be made, however the trends in results between the two are undoubtedly visible.

This is especially obvious from Figure 5 which show the linear relationship between the load level and the voltage/strain. The sensitivity of the PVDF sensors appears to be adequate for the dynamic load monitoring purpose.

5. Conclusion
- Monitoring the load level of steel sample with PVDF sensors, the output of the sensors was found to vary linearly with applied load. A similar pattern was observed for the strain gauge measurements.
- It was concluded that the PVDF piezoelectric sensor is a good alternative to conventional strain gauges in order to measure dynamic loadings for structural health monitoring purposes.
- The PVDF sensors offer the advantage of needing no power to function and the sensors can be made to suit any size and geometry, therefore reducing the size and cost of the load monitoring device.
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References

[1] de Camargo F V, Guilherme C E M, Fragassa C and Pavlovic A 2016 Cyclic stress analysis of Polyester, Aramid, Polyethylene and Liquid Crystal Polymer yarns, Acta Polytechnica 56(5) 402-408

[2] de Camargo F V 2019 Survey on Experimental and Numerical Approaches to Model Underwater Explosion, Journal of Marine Science and Engineering 7(1) 15

[3] Pitts F L and Spencer J L 1973 Electronic Stain-Level, Counter, United States Patent: 3733424

[4] Friedho R and Kubsch G 1998 Portable Device for Counting and Sorting Load Cycles in supporting, Structures with Various Loads, United States Patent: 5,763,788

[5] Vodicka R and Galea S C 1998 Use of PVDF Strain Sensors for Health Monitoring of Bonded Composite Patches, Airframes and Engines Division Aeronautical and Maritime Research Laboratory, DSTO-TR-0684

[6] Chiu Y Y, Lin W Y, Wang H Y, Huang S B and Wu M H 2013 Development of a piezoelectric polyvinylidene fluoride (PVDF) polymer-based sensor patch for simultaneous heartbeat and respiration monitoring, Sensors and Actuators A: Physical 189, 328-334

[7] Xin Y, Sun H, Tian H, Guo C, Li X, Wang C and Wang S 2016 The use of polyvinylidene fluoride (PVDF) films as sensors for vibration measurement: A brief review, Ferroelectrics 502(1) 28-42

[8] Fotouhi M, Saghaﬁ H, Brugo MT et al. 2017 Effect of PVDF nanofibers on the fracture behavior of composite laminates for high-speed woodworking machines. Proc. Inst. Mech. Eng., Part C: Journal of Mechanical Engineering Science 231(1) 31-43

[9] Fotouhi M, Xiao B, Pozegic T et al. 2017 High Performance Piezo Electric Nanocomposite Sensors, ICCM-21, Xi’an, China

[10] De M, Pozegic T, Hamerton I and Fotouhi M 2018 Development and evaluation of a novel piezoelectric PVDF sensor as a load spectrum counter, ECCM 18