DEVELOPMENT AND EVALUATION OF A NOVEL PIEZOELECTRIC PVDF SENSOR AS A LOAD SPECTRUM COUNTER

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Engineering structures, such as aircraft, marine vessels, buildings and offshore platforms, are subjected to a range of uncertain dynamic loadings, due to changes in operational and environmental conditions, *etc.* Unfortunately, the load spectrum of these structures is usually an unknown with no appropriate device to assess it, leading to over-engineered structures. This project introduces a novel piezoelectric based sensor as a load spectrum counter that can measure the complex loading conditions over the structure's lifetime. The sensor has been designed using piezoelectric poly(vinylidene fluoride) (PVDF) combined with a custom electronic circuit, which counts the number of times the load in a structure surpasses pre-selected amount. Any force applied to the piezoelectric PVDF sensor generates an electrostatic output voltage due to the separation of charges in the atomic structure of the piezoelectric. The output from the piezoelectric PVDF (PE-PVDF) is a pulse wave with an amplitude proportional to the load input and an amplifier connected to the level detector used to enhance the pulse. When the amplitude of the data pulse exceeds a certain level, a signal emitted by the level detector activates the counter and stores the data. To prevent counting of noise an adjustable dead zone is added at each level detector. Therefore, after the load surpasses a specified level and a count is registered, no action occurs (*i.e.* the output is zero) and the load must drop under the dead zone and then rise again before another count is registered. The concept is validated experimentally both on an aluminium and epoxy/SE70 glass composites yielding load-spectra. The sensor is calibrated for different materials and geometrical conditions need to be investigated. The vision of the project is to make wireless and embedded fatigue counter sensors designed for real industrial applications.

Keywords: Load spectrum, PVDF, Structural health monitoring, Passive sensors, Fatigue counter

1. Introduction

Structural Health Monitoring (SHM) allows us to have knowledge of a structure on continuous real-time basis. SHM has undergone significant development and is an essential part of engineering structures to allow optimal use of it; engineering structures such as aircraft, marine vessels, buildings, offshore platforms, and wind turbine blades are known to be subjected to uncertain dynamic loadings. To have a durable structure, it would be useful to develop a SHM system that can monitor these loading conditions and to predict any inaccuracies when the structure is in real-life operation. Unfortunately, the load spectrum of these structures is usually an unknown when the structure is working with no appropriate SHM device to assess it, leading to an over-engineered structure.

This paper introduces a robust and novel device that can measure complex loading conditions over the structure's lifetime, leading to the analysis of the fatigue life of the structure and to determine plans for maintenance.

Previously, a device was designed by NASA that can count the strain-level for aircraft structures [1]. This was possible by using a resistance strain gage is used as 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 cm^3 - without the counters) and so to was the power consumption, requiring the provision of energy by the aircraft's auxiliary power supply. Later, a patent was filed by Man Technologie in 1998 [2] 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.

To the authors' knowledge, there are no appropriate SHM devices to monitor the load history of engineering structures. This paper aims to develop a novel device that can monitor structures complex loading conditions over the structure lifetime. The vision of the project is use new technologies to have a compact, low-power consumption and wireless device that can be easily implemented in engineering structures.

2. RESEARCH METHODOLOGY

A piezoelectric device, which counts the number of times the load in a structure surpasses specified preselected levels, was designed and fabricated (see Fig. 1). The PE-PVDF sensor generates an electrostatic output voltage due to a separation of charges in the atomic structure of the piezoelectric as it undergoes physical changes through the application of force (load). PVDF sensors produce a voltage, due to the piezoelectric effect, when stretched or compressed, and therefore require no power to operate [3]. The output from the PVDF is a pulse wave with an amplitude proportional to the load input. An amplifier connected to the level detectors is used to intensify the pulse. When the amplitude of the data pulse exceeds a certain level, a signal caused by the level detector registers as a count on the electromechanical counter. To prevent excessive counting of small load variations due to oscillations, an adjustable “dead zone” is added at each level detector. Therefore, after the load surpasses a given level and a count is registered, no action occurs (*i.e.* the output is zero) and the load must drop under the dead zone and then rise again before another count is registered.

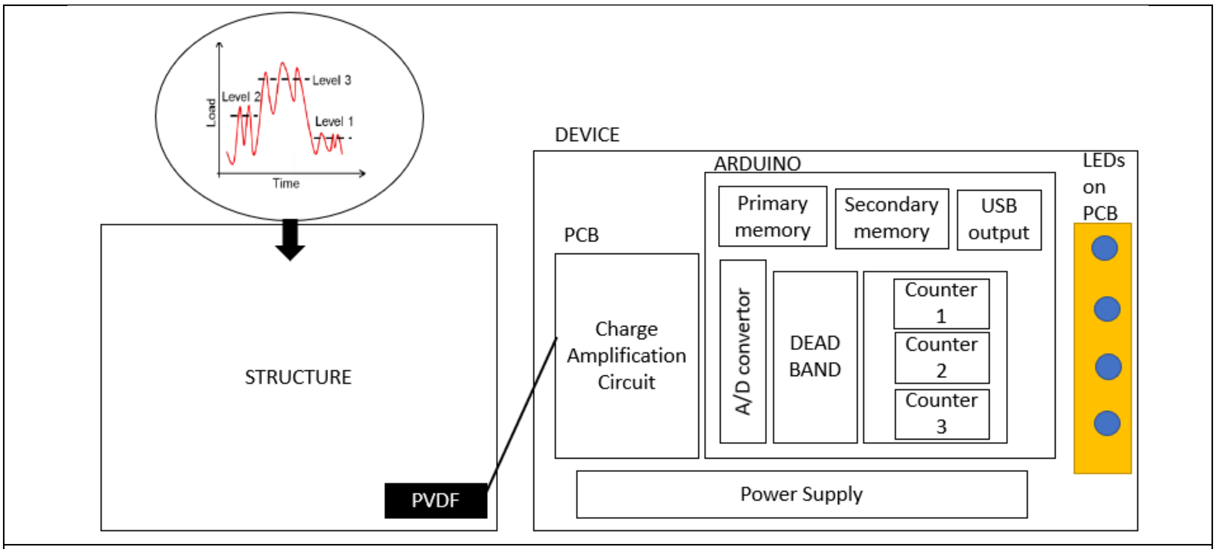


Figure 1. Block diagram, displaying the design of the device

The different stages of the research project are summarised below:

2.1 Comparing voltage output of the PE-PVDF sensor with a strain gauge

The suitability and effectiveness of PVDF piezoelectric films as substitutes for strain gauges (strain measured through changes in electrical resistance), for in-flight health monitoring of composite repairs and doublers were investigated previously by Vodicka *et al.* [4]. These PE-PVDF sensors offer the advantage of requiring no power to function and the sensors may be manufactured to suit any size and geometry. Furthermore, an excellent correlation was found between the conventional electrical resistance strain gauges and the PE-PVDF sensors, indicating the applicability of the latter for patch (localized) health monitoring. The output of the PE-PVDF sensors was found to vary linearly with applied load but a dependence on loading frequency was observed, along with a demonstration of good stability towards changes in environmental conditions, although care needed to be taken whilst handling the fragile sensors. These PE-PVDF sensors exhibited high durability, low acoustic impedance and possess a flat response over a wide frequency range as well as a broad dynamic response. Owing to their low mechanical impedance, several piezoelectric films can be distributed along the structure without drastically affecting its mechanical properties.

In this project, a feasibility test was conducted with an aluminium panel to verify whether the output obtained from a foil strain gauge (deemed credible sensor [1-2]) is comparable with a PE-PVDF sensor. For this reason, an aluminium panel was set up as a cantilever beam in a dynamic bending beam test configuration. The PE-PVDF sensor and strain gauge were bonded using a room temperature curing epoxy adhesive on opposite sides of the beam, to ensure that they are exposed to same strain field. The setup is illustrated in Figure 2 along with the location of sensors. The readings are passed through a conventional conditional circuit (Micro Measurements 2311) for strain gauges, with the strain being calculated by the standard calibration formulae. A sine-signal of 5-500Hz is applied to the panel and the results obtained are in form of transfer functions. The signal is amplified through a charge amplification circuit. It should be noted that the calibration was conducted assuming the correction factor from the bond layer.

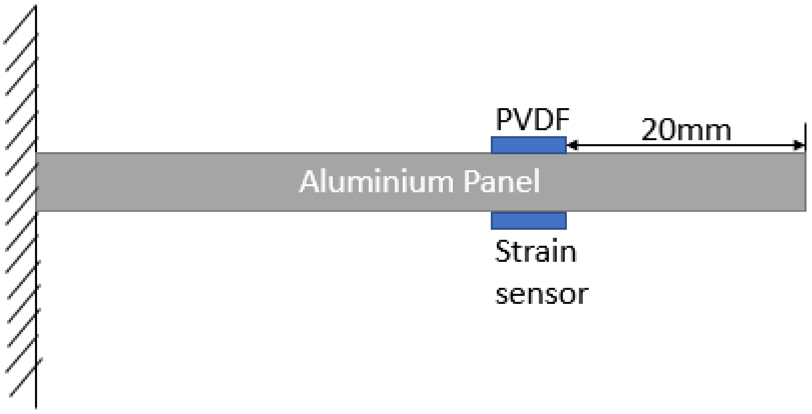


Figure 2. Experimental setup for the feasibility test, the bar's dimentions are 190 x 30 x 2 mm^3, length, width and thickness, respectively.

2.2 Circuit design

The circuit is initially designed on a bread-board and redesigned to minimise the size and improve efficiency. The block diagram in Figure 1 shows the flow of data between different sections of the device. The vibration signals are sensed by the PVDF and the information is passed *via* wires to the system to the charge amplifier circuit. The charge is converted into voltage signals followed by amplification. The data is further filtered and transferred to a processor. The processor works as the counter circuit and the comparator is responsible for comparing it with the pre-set levels.

The fabricated circuit is illustrated in Figure 3. An Arduino microcontroller was used as an open source electronics platform with C language programming for signal processing and counter circuit control. An A/D convertor is pre-built into the microcontroller. A high sampling rate of 150 KSPS was chosen and features of data-logging were added on to the circuit board. A shielded SD card reader was added to the circuit that served as a secondary memory that store the data. The counter circuit was programmed with the help of microcontroller. Initially a dead band was defined; each vibration corresponding to a different load applied on structure. Each load level was assigned with a defined voltage level and each voltage was compared against the corresponding levels defined in the program. Three different levels have been defined in the program with different ranges. Output points from the Arduino as shown in Figure 3 are connected by jumper wires to a bread board by 5 Ohm resistors. Each of the wires relate to their LED bulbs responsible for different levels. The LED gives an output only when the circuit has repeatedly counted certain level five times. The 4th LED is responsible to inform the user when all the first three LEDs have indicated that levels have been crossed. In other words, the 4th LED works as a final indicator and informs the user that all the 3 pre-selected levels have crossed the desired level and the structure might be in danger.

2.3 Production of the printed circuit board:

All the separate components must be integrated together to build one device. Before integration, debugging needs to be done with the Arduino. The Arduino board is connected with the final PCB board which contains the charge amplification circuit with filtering, then the output signals (LEDs) are connected from the Arduino board back to the PCB board. The PE-PVDF sensor is connected with wires to the PCB board. Two holes are made on the box from which wires are passed through to be connected with peizoelectric PVDF sensor. The electronic components are surface mounted in front of the board. The whole device is powered by battery and is placed inside the circuit box PCB and Arduino microcontroller required 9 V power supplies. The components are placed together inside a box made of iron, with the batteries placed on the side of the wall. The integration of all the components with power supply, along with PVDF is the result and can be defined as the complete device. The circuit box is of size 138.3 x 68 x 65 mm^3. The final designed product is smaller than previous [1] devices, has low power requirements and is capable of counting load levels, comparing it against pre-set levels. The advantage of having a microcontroller is that it can be reprogrammed and the pre-set levels can be changed.

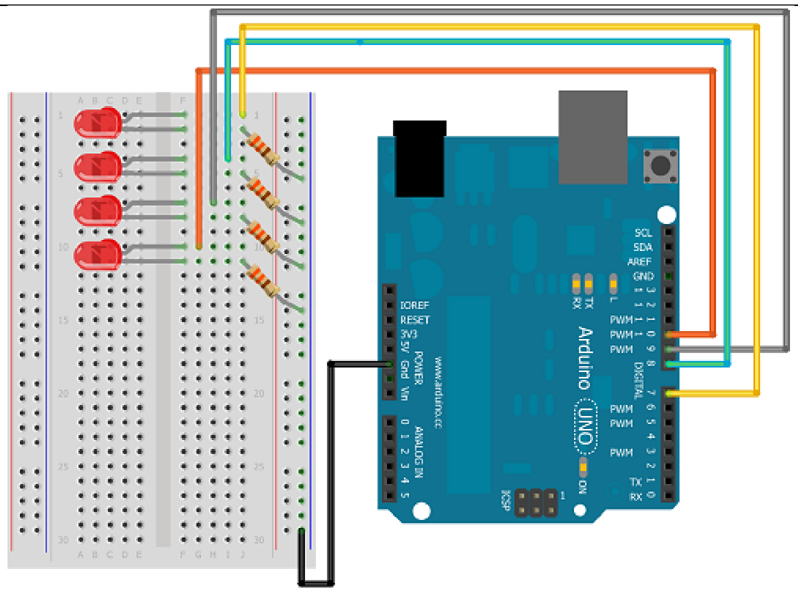


Figure 3. LEDs are observable on the left side; the top LED is number 1 and the others are number 2, 3 and 4, respectively.

2.4 Validation of the device

A quasi-isotropic SE-70 composite laminate with the following configuration $[0_2, 90_2, +45_2, -45_2]_2$ was used as the structure and the PVDF sensor connected to the designed circuit was mounted on it. A room temperature curing epoxy adhesive was used for bonding the PVDF to the samples. Later an experiment was conducted to validate the circuit consistency and the sensor's functionality. An experimental setup was conducted using Laser Doppler Vibrometer (LDV) experiments. The composite panel was clamped at one end and the beam was vibrated by using a stinger from a shaker. The setup is shown in Figure 4. The shaker is defined to run random load signals. The signals are random in nature but are predefined by the author with certain number of peaks to validate the counter circuit. The shaker can level schedules to run various durations and can be changed while the test is in progress. The PE-PVDF sensor was placed 20 mm from tip. The load levels experienced by the structure is below the endurance limite of the composite and would not result in failure. Here, the author has defined a load as harmful as an example to check the validity of the circuit.

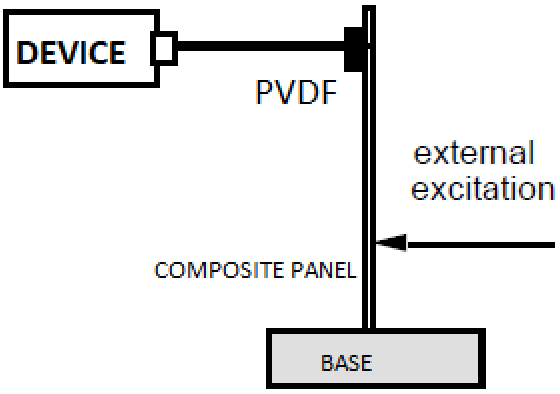


Figure 4. Experimental setup for validation of circuit.

3- RESULTS AND DISCUSSION

3.1 Comparing voltage output of the PVDF with a strain gauge

Figure 5 displays the impulse response from both the sensors. It is important to note that the data shown here are unfiltered and show strain converted from raw voltage values. The working principle of a strain gage is based on the Wheatstone Bridge circuit. As the voltage values obtained is in order of micro-volts, the ratio of signal to noise is not sufficient. This is where PVDF gives a major advantage over the strain gages; for scenarios where the structures are subjected to low strain or high noise level, it provides excellent signal-to-noise ratio.

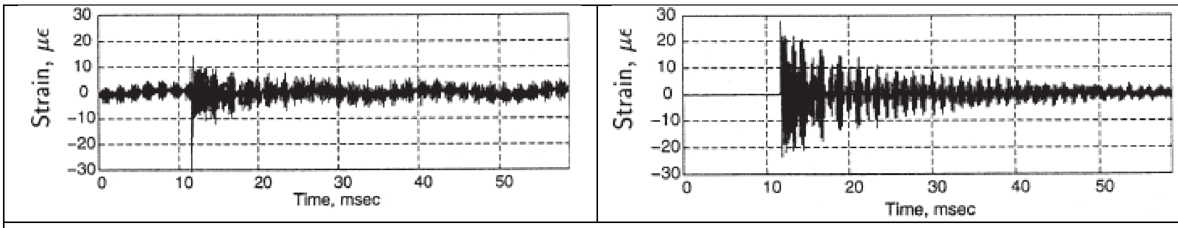
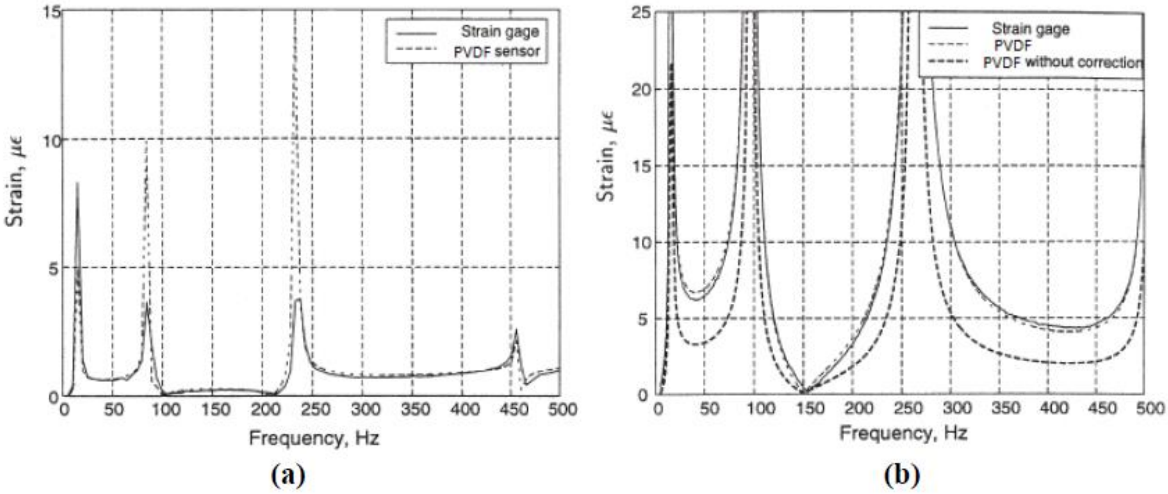


Figure 5. Impulse response from strain gage (left side) and PE-PVDF sensor (right side).

Figure 6 shows the outputs from the PE-PVDF and the strain gauge over different frequency ranges. A good agreement between the results is observable for the low-strain values (Figure 6 (a), whereas by increasing the strain level (figure 6(b)), there is a need for a correction factor to match the results. Therefore, the PE-PVDF output should be calibrated in order to have reliable results. The strain responses are similar apart from the specific points where the strain gauge is not sensitive enough to detect the peaks at low strain levels in figure 6, hence, showing better performance of the PE-PVDF sensors at low strain levels.



(a) (b)

Figure 6. (a) Correlation between sensors for low strain levels (b) Correlation between sensors with and without correction factor of PVDF

3.2 Validation of circuit

The panel was subjected to various pre-set loadings levels. Even though the circuit has been designed to meet the requirements of the structure, after conducting the experiment various flaws were seen. The circuit is usually developed by set of theoretical guidelines available in the literature. So, unless the experiment is conducted it is hard to foresee the issues. The authors have tried to understand the underlying problems and developed the device accordingly.

After successfully removing the flaws, the experiment was performed four times to check the reliability with the input data and was seen consistent every time and the corresponding LED was switched on in the specified load level. However, the device was showing an output delay of approximately 2 minutes. If more time is invested in designing the device and a higher microprocessor is chosen it would be possible to reduce the delay considerably.

4. Conclusions

This study was an effort to design a load-spectrum monitoring device using PVDF as the data acquisition sensor and a custom designed circuit to classify different load levels. The following conclusions are drawn:

- PVDF piezoelectric sensors are a good alternative to conventional strain gauges and are capable to be used as a sensor for monitoring loading history of engineering structures, without any power for the excitation of the sensor. However, the PVDF sensor needs to be calibrated to find the correlation between the applied load and the output voltage.
- The designed circuit successfully monitored a sinusoidal loading applied on a composite plate and could distinguish different load levels by lightening the specified LEDs designed for the designed load levels.
- The designed load spectrum monitoring device was showing an output delay of approximately 2 minutes. A better design process using a higher microprocessor is needed to reduce the delay time for *in-situ* monitoring purposes.

Acknowledgments

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