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# Use of polymer-based sensors for monitoring the static and dynamic response of a cantilever composite beam

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Engineering polymeric materials offer a number of important advantages such as lightweight, immunity to electromagnetic interference, good chemical resistance, durability, low cost and ease of processing. In view of these benefits, polymer materials are being used in a wide spectrum of industries including aerospace, construction, electronics, transportation, packaging, fibre optics and sensor sectors. Indeed, the special properties exhibited by polymers are increasingly being exploited to provide highly competitive alternatives to conventional products and devices, such as plastic optical fibers and polymer-based transducers. In recent years, plastic optical fibre sensors and piezoelectric film, in particular, have been attracting considerable attention from the scientific community in view of their potential as sensing devices to monitor a variety of environmental parameters [1–5].

Polymeric materials which exhibit excellent optical properties such as polymethyl methacrylate (PMMA) are being used to produce plastic optical fibers (POF) for short distance data transmission, lighting, advertising and sensing applications. Diameter sizes of 0.25 to 3 mm are available, offering typical transmission losses in the region of 150 dB/km at 650 nm. Indeed, recent research using POFs has shown their potential as versatile and highly cost-effective passive sensors for structural health-monitoring [6, 7]. Their strain, vertical displacement and dynamic monitoring capability make them ideal sensors for mechanical systems. Compared to their glass-based counterparts, POFs offer simplicity in handling, ease of termination and are capable of high optical power delivery at a much lower cost (typically US$0.13/meter). In addition, POFs also exhibit a higher fracture toughness and flexibility than other comparable systems, making them much less susceptible to damage and fracture when operating in harsh engineering environments.

Polyvinylidine fluoride (PVDF) and its co-polymers, have been found to be very effective piezoelectric transducer materials converting mechanical stresses to electrical energy in the form of an electrical charge [8, 9]. Piezo film sensors are usually supplied in the form of a thin-film, typically ranging from 9 to 110 $\mu$m in thickness. Due to their very small cross-sectional area, a small load applied longitudinally along the plane of the film will result in a very large stress within the material. The electrical charge that is generated is proportional to the change in the mechanical stress. It is important however, to consider a PVDF film as a dynamic sensor due to the rapid decay of the induced charge. For the majority of applications, piezo films have been used in high frequency domains, typically 15 to 100 MHz and above [3, 10]. The lower bound of operation of a piezo film is characterized by its cut-off frequency, $f_C$, this being a function of the time constant (RC)—this is the frequency at which the magnitude of the piezo output falls to $-3$ dB. The cut-off frequency of a piezo film takes the form:

$$f_C = 1/(2\pi RC)$$

where $R$ is the load resistance and $C$ is the PVDF capacitance.

Operation of the PVDF film below its cut-off frequency (i.e., small $R$ and $C$) yields an output signal that is proportional to the *rate of change* of the mechanical stress. This phenomenon has been modeled analytically and the PVDF output voltage, $V_s(t)$, can be written as [11]:

$$V_s(t) = G\frac{dQ(t)}{dt} = G\{K_s\}^T\{\dot{X}\} \tag{1}$$

where $G$ is the constant gain of the charge amplifier, $\{K_s\}^T$ is a global coordinate system corresponding to the spatial integration of a complex function over the surface of the PVDF film, $Q(t)$ is the PVDF charge (which is a function of time) and $\{\dot{X}\}$ is the strain rate within the film sensor.

The above equation suggests the possibility of obtaining a measurement of the strain rate of the PVDF attached to the surface of a vibrating cantilever structure by simply measuring the voltage output of a PVDF film. However the values of $R$ and $C$ should be sufficiently small such that the cut off frequency is larger than the operating frequency. (When used as a

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strain/displacement sensor, a charge amplifier with a very large input impedance [e.g., $R = 10$ MOhm and $C = 10$ nF] is commonly used to ensure that the cut-off frequency is well below the operating frequency such that the sensor output is directly proportional to strain or displacement.)

In many applications, it would be desirable to obtain the displacement and velocity-time history of a vibrating structure directly via a standard laboratory instrument such as a multi-channel oscilloscope, without the need for further processing of the raw data. For example, further processing is required when analyzing accelerometer data (to obtain velocity data) and velocity data from a laser-Doppler velocimeter (to obtain displacement data). In addition, to realize the possibility of obtaining both the displacement and velocity-time trace at several points of a vibrating structure, an efficient and inexpensive manner is highly desirable. This is the case, for instance, in a modal analysis of a plate subjected to dynamic loading conditions. Due to the light weight of both POF and PVDF sensors, the response of the structure will not be significantly affected, this being a considerable advantage over other measuring systems such as accelerometers. In addition, POF and PVDF films are flexible and can be readily bonded to structures using a polymer-based adhesive such as an acrylic, a synthetic rubber resin, an epoxy or a cyanoacrylate. In view of these advantages, this letter investigates the possibility of using such inexpensive and rugged polymer-based devices as displacement and velocity sensors for monitoring the structural response of a cantilever beam subjected to a range of loading conditions.

The experimental set-up used in this study is illustrated in Fig. 1. Beams with dimensions of 13 mm × 5 mm × 250 mm were removed from a 16-ply woven carbon-fiber reinforced epoxy (Stesapreg EP121-C15-53 supplied by Stesalit Ltd., Switzerland). The POF used in this study was based on a 1 mm diameter multimode, step index fiber (ESKA CK40) supplied by Mitsubishi Rayon Co. Ltd. The POF consists of a super pure PMMA core (refractive index 1.492) and cladding made from fluorinated PMMA (refractive index 1.405). The POF sensing system relies on monitoring the modulation of light in the optical fiber. An intensity-based monitoring scheme is attractive as it is simple to implement and cost-effective. A 1 mW laser diode (centred at 655 nm) was used as the light source while the detection system consisted of a light-dependent resistor (LDR) and a fixed resistor in the form of a voltage divider circuit. As the incident light on the LDR varied, the voltage signal across the fixed resistor varied accordingly. A sharp razor blade was used to cleave the POF and this was polished using a silicon carbide polishing paper. The PVDF film (DT1-028K, capacitance 1.3 nF) was supplied by Measurement Specialities, USA. It had a 12 × 30 mm active area printed with silver ink electrodes on both surfaces, and was encased in a protective urethane jacket.

The POF and the PVDF film were bonded to the composite beam using a cyanoacrylate adhesive (Tokyo Sokki Kenkyujo Co. Ltd.). The data from the optical fiber and the PVDF film were acquired using an 8-bit 150 MHz digital oscilloscope (DL1540 supplied by Yokogawa Electric). The oscilloscope has internal impedance and capacitance of 1 MΩ and 25 pF respectively. The cut-off frequency of the PVDF sensor system was estimated to be approximately 122 Hz, this value was sufficient to ensure that the PVDF sensor operates below the cut-off frequency regime for the experiments conducted in this study.

The composite beam was subjected to an initial deflection, and its free vibration response (with and without end mass attached) were monitored using the POF and PVDF sensors. Fig. 2 compares the POF signal and the PVDF signal, clearly highlighting the ability of both the PVDF and POF sensors to monitor the dynamic response of the beam. Since the signal from the PVDF is proportional to the rate of the change of strain of the sensing film, one would expect that the value of the PVDF signal should correspond to the slope in the deflection-time trace. An examination of the two traces

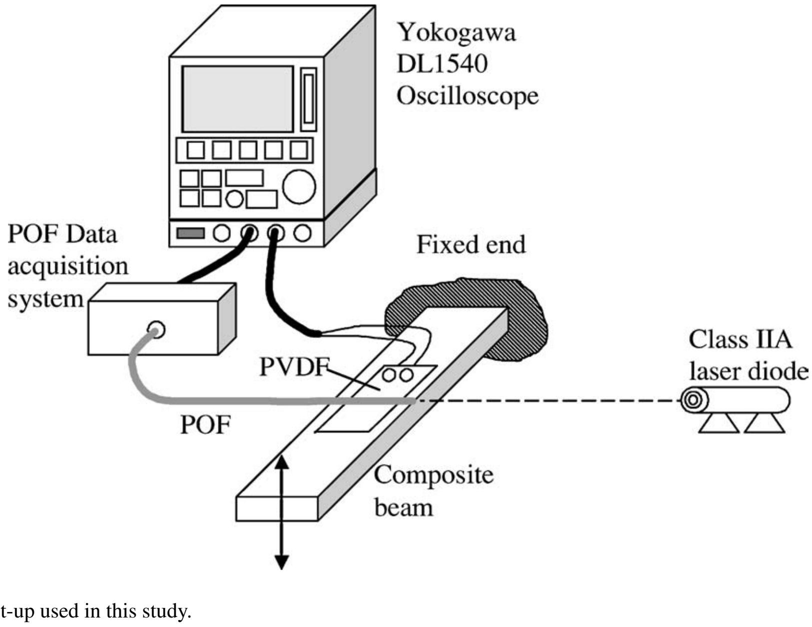

*Figure 1* Experimental set-up used in this study.

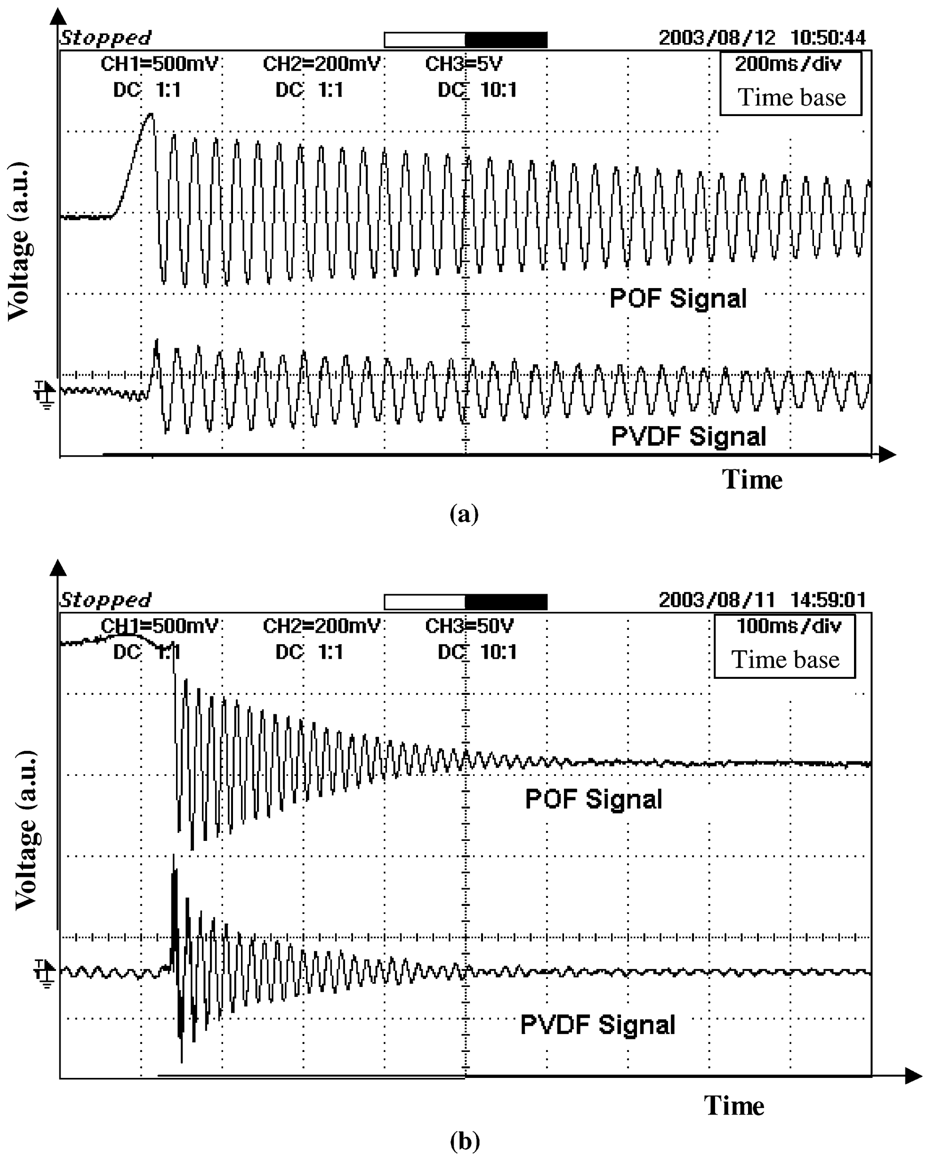

*Figure 2* Free vibration response of beam: (a) with end mass (approximately 20 Hz) and (b) without end mass (approximately 60 Hz).

shows that the peaks and troughs of the POF signal correspond very closely to the zero values in the PVDF response. The signals from both sensors were extracted and the area under PVDF signal was calculated for each cycle. The resulting integrated plot coincides with the POF signal as shown in Fig. 3. The integrated plot appears to be increasingly out of phase with the POF plot, this however is due to the integrating process involving a diminishing intensity of the PVDF signal with each cycle.

Further tests were carried out in which the beam was loaded gradually to compare the response of the POF and the PVDF sensor at very low rates of loading. Fig. 4a shows the response of both types of sensor when the beam was subjected to low frequency oscillatory deflections. It is evident that the amplitude of the PVDF sensor is significantly attenuated even though the deflection of the beam is larger than that used in Fig. 2. However, closer examination of the PVDF trace shows that the zero values coincide very well with the corresponding points of inflexion in the POF signal output. The beam was also loaded quasi-statically and these results are shown in Fig. 3b. As expected, no significant voltage output was detected from the film sensor during the deflection of the beam. Due to the finite time constant of the film sensor, the rate of decay of the electrical charge exceeds the rate of change of the mechanical stress during the static loading of the beam, hence no voltage signal was generated by the film.

Impact tests were also carried out to investigate the potential of each of these sensors to detect the structural response of the beam. The beam was impacted at its free end by either a metal or a rubber rod, and the results are illustrated in Fig. 5a and b respectively. It is evident from Fig. 5a that both sensors detected the impact event although the POF did not pick up the high frequency component of the beam response. The response of the beam when impacted by the rubber rod is presented in Fig. 5b. The PVDF signal clearly portrays a typical derivative-time trace of the POF signal, highlighting the potential of the PVDF and the POF to be used as a paired-sensor to acquire the displacement and velocity information of a vibrating structure.

The results presented in this study illustrate the potential of using POF-PVDF sensors for monitoring

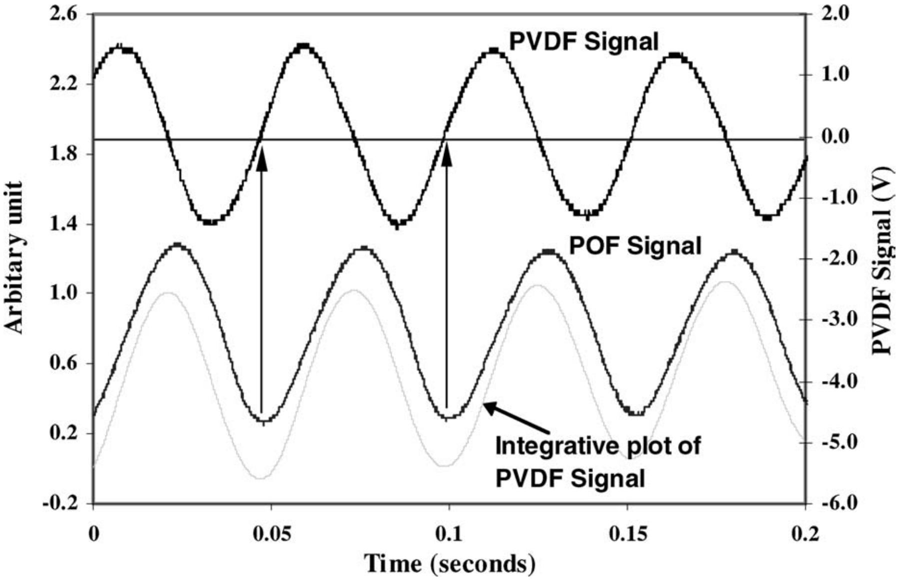

*Figure 3* Plot comparing the POF response with the result of the PVDF signal after an integrated operation.

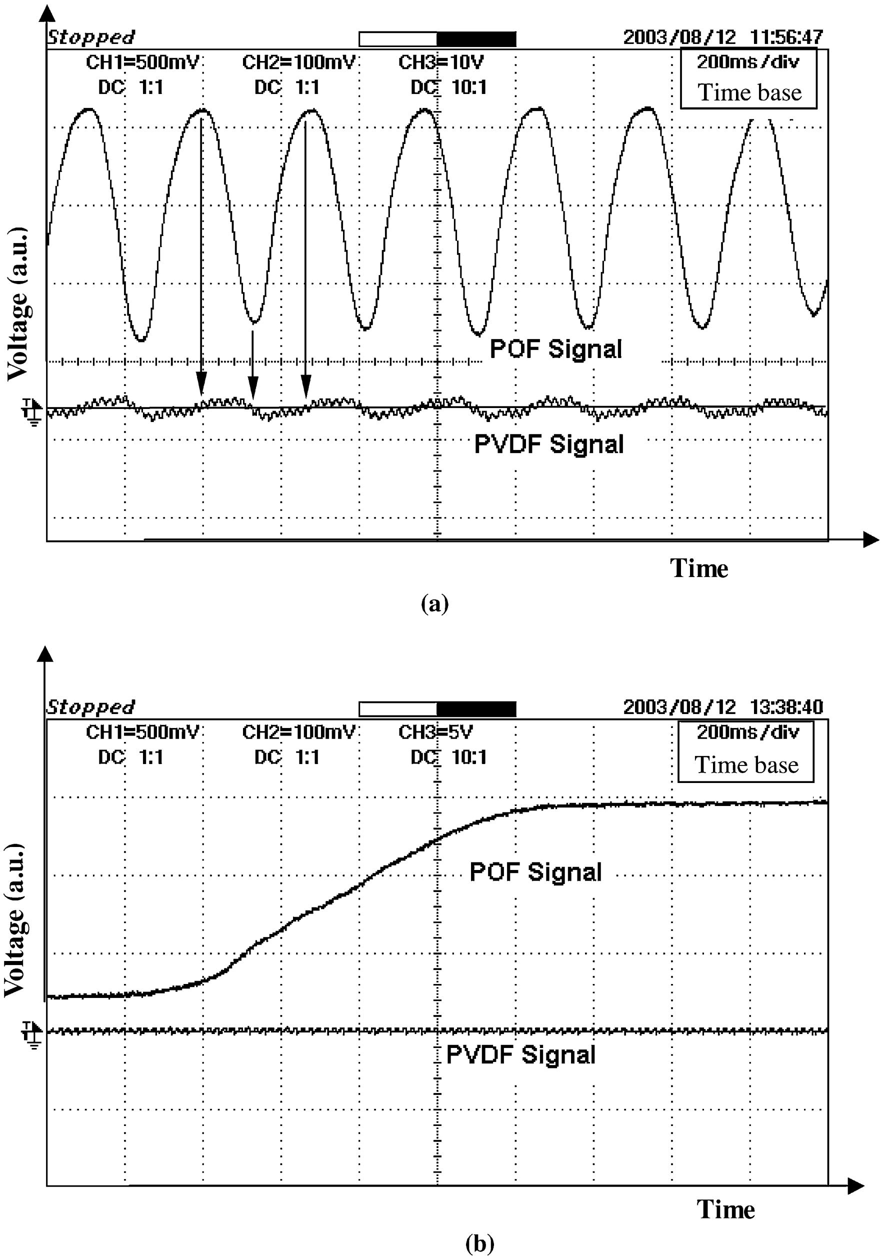

*Figure 4* Plot comparing the response of the POF and the PVDF sensor when the beam was subjected to: (a) a slow sine wave-type load (approximately 3.5 Hz) and (b) a quasi-static load.

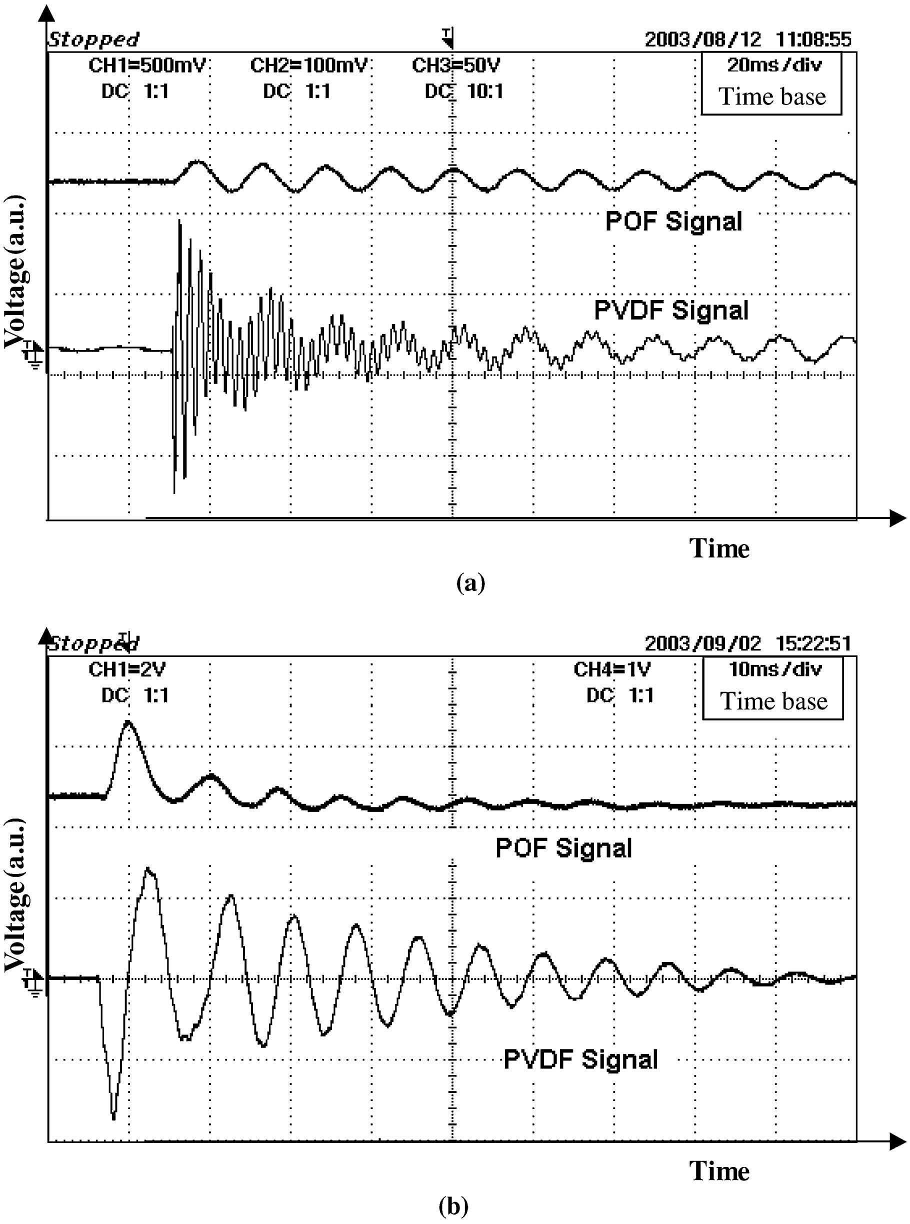

*Figure 5* Plot comparing the POF and PVDF sensor response of the beam was impacted with: (a) a metal rod and (b) a rubber rod.

low frequency loading conditions in load-bearing structures. The combined use of low cost POF and PVDF sensors for measuring fundamental parameters frequently encountered in structural analysis is encouraging, highlighting the synergistic value of using these two simple sensors that offer versatility in design and simplicity of operation.

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