MONITORING OF A TRAFFIC SIGN STRUCTURAL SUPPORT VIBRATIONS

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Traffic signs and signals are vital communication components on highways and urban roads. They convey the rules, guidance, warnings, and other information to the millions of drivers and soon driverless vehicles. The structural supports of these signs and signals are often subjected to weather induced failures mainly damage caused by vibration loads from wind. The types of structures that experience these failures include straight and cantilever members, utility poles and others. Various vibration mitigation devices have been proposed for these structural supports with no clear solution on how to assess or monitor their effectiveness. One proposed method is the real time measurement of the vibration displacement curve of the cantilever support structures. This paper shows that the displacement curve of a cantilever traffic signs support can be monitored through the use of a set of PVDF sensors. To examine the proposed sensors, a reduced model of a cantilever traffic signal support structure is fabricated along with the surface sensors, and subsequently tested. The measured values obtained using the PVDF sensors are compared to those obtained using an accelerometer measurements array. It is shown that the sensors are sufficiently accurate for sensing the displacement of the vibrating support structure at low frequency.

Keywords: PVDF, vibration, wind load, traffic signs

1. Introduction

Traffic signal and luminaires support structures are typically characterized by high flexibility and extremely low damping because of their long span length and relatively small cross sectional area and mass. These properties make the support structures very susceptible to large amplitude vibration and fatigue failure under wind loading [1]. The wind loadings comprise galloping, vortex shedding, natural wind gusts and/or truck induced wind gusts [2, 3]. These four types of wind loadings greatly contribute to the fatigue damage of the sign structures. Galloping is an aeroelastic phenomena in which unstable aerodynamic damping forces are created due to structural vibration-induced variations in the angle of attack of the wind flow [4]. Vortex shedding is caused by the passage of turbulent eddies in a regular, alternating pattern on opposite sides of a structural element. It typically occurs during steady, uniform flows and produces resonant oscillations in a plane normal to the direction of flow. Natural wind gusts arise from the naturally occurring variability in the velocity and direction of air flow. Changes in velocity and direction of air flow produce fluctuating pressures on the sign structure, which can cause it to vibrate. Finally Truck-induced wind gusts are produced by the passage of trucks beneath sign structures and act on the front area facing the oncoming traffic and underside of the members of the sign structures. Galloping and vortex shedding often creates quasi constant-amplitude vibrations at the support natural frequencies creating short fatigue life of the sign structure. On the other hand, natural wind gusts and truck induced gusts cause vibrations that can produce accumulated fatigue damage over the life of the structure.

Stop signs that are often subject to high wind load can be classified in five basic categories including the cantilever structure with single-mastarm or double-mastarm, the overhead bridge, the monotube structure, the wire cable span structure, and the variable message sign. Each type of the sign structure is prone to fatigue failure and must undergo periodic inspections to detect potential problems and avoid catastrophic failures. In order to alleviate these failures, engineers have proposed to design structures that can better resist wind forces, perform periodic inspections, use effective vibration mitigation devices, and/or provide full scale continuous monitoring of the structures [5, 6].

The objective of the proposed work is to use sensors fabricated from PVDF film to continuously monitor the vibration response of traffic signal and luminaires support structures. The sensors are relatively inexpensive and easy to manufactures. They can be attached to the surfaces of the structure under consideration and the measurement signals wirelessly transmitted to a remote location. They will permit to monitor the vibration deflection curves of the receiving structure. The information can then be related to the design fatigue life allowing the timely maintenance of the structures.

2. Sensor description

Many applications of PVDF based sensors can be found in literature in active noise and vibration control [7] Material characterization [8], Medical field [9] etc. The PVDF is usually in the form a film bonded to the structure. The film is very flexible compared to the structure to which it is bonded such that the strain transferred to the structure is negligible. The PDVF sensor is often shaped to extract the structural dynamic properties of interest. The proposed sensor measures the slopes of the vibration curve of the structure simultaneously at multiple locations to yield the instantaneous real time vibration curves. Important mechanical properties such as strains, stresses, and fatigue life can be readily computed from the deflection curves making the proposed sensor an invaluable asset for traffic sign structure structural health monitoring. Dynamic properties such as natural frequencies and mode shapes can also be calculated from the instantaneous deflection curves. Figure (1) shows the concept layout of the sensor n patches on a beam and Eq. (1) is used to calculate the dynamic beam deflection [10].

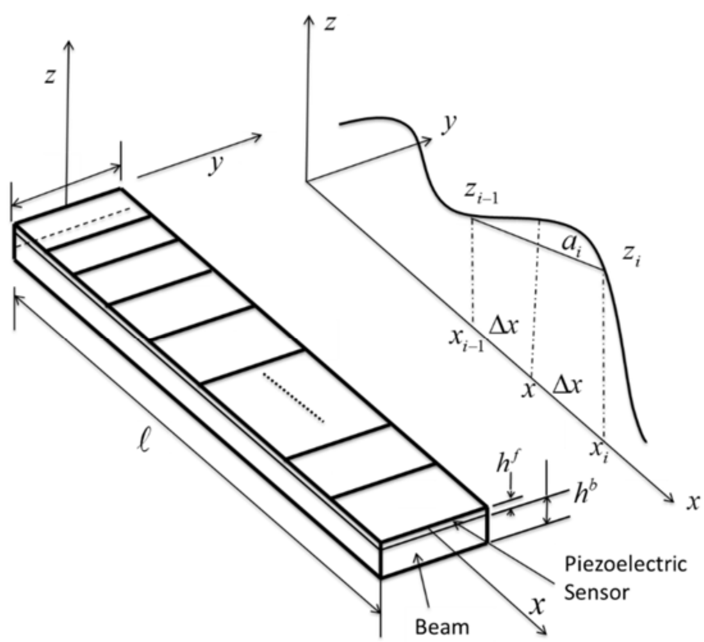

Figure 1: Beam covered with PVDF film and Beam deflection curve

$$z_i = -2\frac{\phi_i \ell^2}{h^f h^b h_{31} n^2} + z_{i-1} \tag{1}$$

where ϕ_i is the output charge of the i^{th} patch of PVDF film and z_i is the value of the deflection at the center of the i^{th} patch. The h^b and h^f are respectively the thickness of the beam and the film. Finally h_{31} is the stress charge coefficient of the film.

3. Experiment Setup

The sensor described above is proposed to be used to monitor traffic sign support structures structural health. As stated previously, there are multiple types of sign support structures, however in this paper a stop sign support is considered as a proof of concept. A reduced model of the stop sign system is tested in a wind tunnel using accelerometer and the proposed PVDF sensor measurements. Similitude is used to calculate the parameters of the experiment [11]. In general, elastic models can be easily built to give high correlation with the prototype, as long as the model is designed, loaded, and interpreted according to a set of similitude requirements that relate the model to the prototype. Using independent scale factors such as mass, length, and time with the Buckingham Pi theorem, geometric, kinematic, and dynamic similarities can be determined as shown in Table 1. $S = L_p / L_m$ in the table is the dimensional scale factor of the prototype over the model where the subscripts (p) and (m) are used respectively for the prototype or real system and the experiment model.

Table 1: Similitude Relations

Prototype Parameters	Symbol	Scale Factor
Dimension	L_p	S
Area	A_p	S^2
Volume	V_p	S^3
Linear Displacement	U_p	S
Moment of inertia	I_p	S^4
Frequency	f_p	$S^{-1/2}$
Young's Modulus	E_p	S_E
Density	ρ_p	S_E / S
Point load	F_p	$S_E S^2$
Line load	F_p^L	$S_E S$
Uniformly distributed surface load	P_p	S_E
Shear force load	V_p	$S_E S^2$
Moment	M_p	$S_E S^2$
stress	σ_p	S_E

Table 2 shows the similarity values of the prototype and the model used in the experiment. The model is validated using theoretical and finite element modelling. In general, standard stop signs are supported by perforated square steel tubing. However, because the model is made of aluminium bar with rectangular cross section and one of the surfaces needs to be at least 12.7 mm wide in order to receive the sensor film, the height of the prototype is used to calculate the scale factor. Then using the moment of inertia of the prototype and setting the width of the model to 12.7 mm, the thickness of the model is calculated. Figure (2) shows the prototype and the model with a scale factor of $S=4$. The model is made with aluminium plate riveted to an aluminium bar.

Table 2: Similitude values

	$L(mm)$	$W(mm)$	$b(mm)$	E(GPa)	$I(mm^4)$	$\rho(kg/m)$	$\delta(mm)$	$F(Hz)$
Prototype	2896	762	50.8	200	$1.2e^{-7}$	2.96	32.9	6.1
Model	724	190.5	12.7	70	$4.8e^{-8}$	0.264	8.2	12.1

To validate the model, the deflection of the support modelled as a cantilever beam is calculated along with the first natural frequency. The results in the table indicate that the model can be used to assess the dynamic behaviour of the prototype. The scale factor calculated from the frequency values using $S^{-1/2}$ from Table 1 yields $S=3.93$ while the deflection ratio gives $S=4$. These values are at par with the initial dimension scale of $S=4$. Also when the aluminium polygon plate is attached to the beam of the model, the finite element simulation shows natural frequencies of 4.3 Hz and 50.2 Hz for the first and second modes. These frequencies are experimentally confirmed in section 4.

The sensor is fabricated using etching techniques. A template is cut out of a self-adhesive vinyl sheet by a printer-cutter in the pattern shown in the drawing of Fig. (2). The film is bonded to the template of Fig. (3a) and a thin art brush is used to apply the etching chemical to the exposed part of the film Fig. (3b). The resulting sensor with 29 segments of PVDF patches on one face and a continuous electrode on the other is partially shown. Using a multi-meter, the continuity between the patches is checked to ensure that the 29 patches are electrically isolated from each other. Then, the sensor is bonded to the support of the stop sign with a double sided tape and the tabs connected to the data acquisition unit with alligator clips and BNC connectors as in Fig. (3c). The back side of each clip is isolated with an electrical tape.

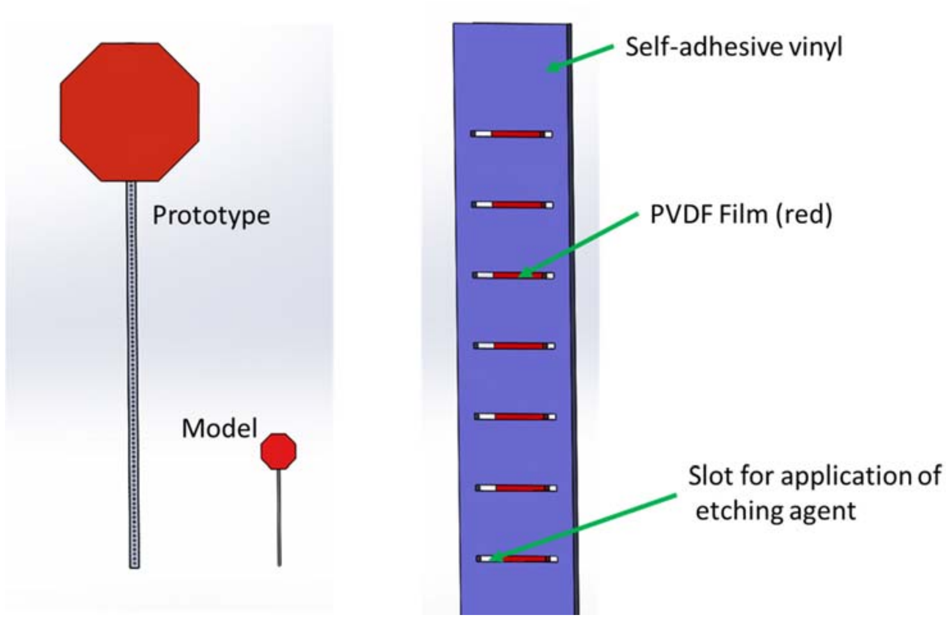

Figure 2: Prototype and Model; Sensor template

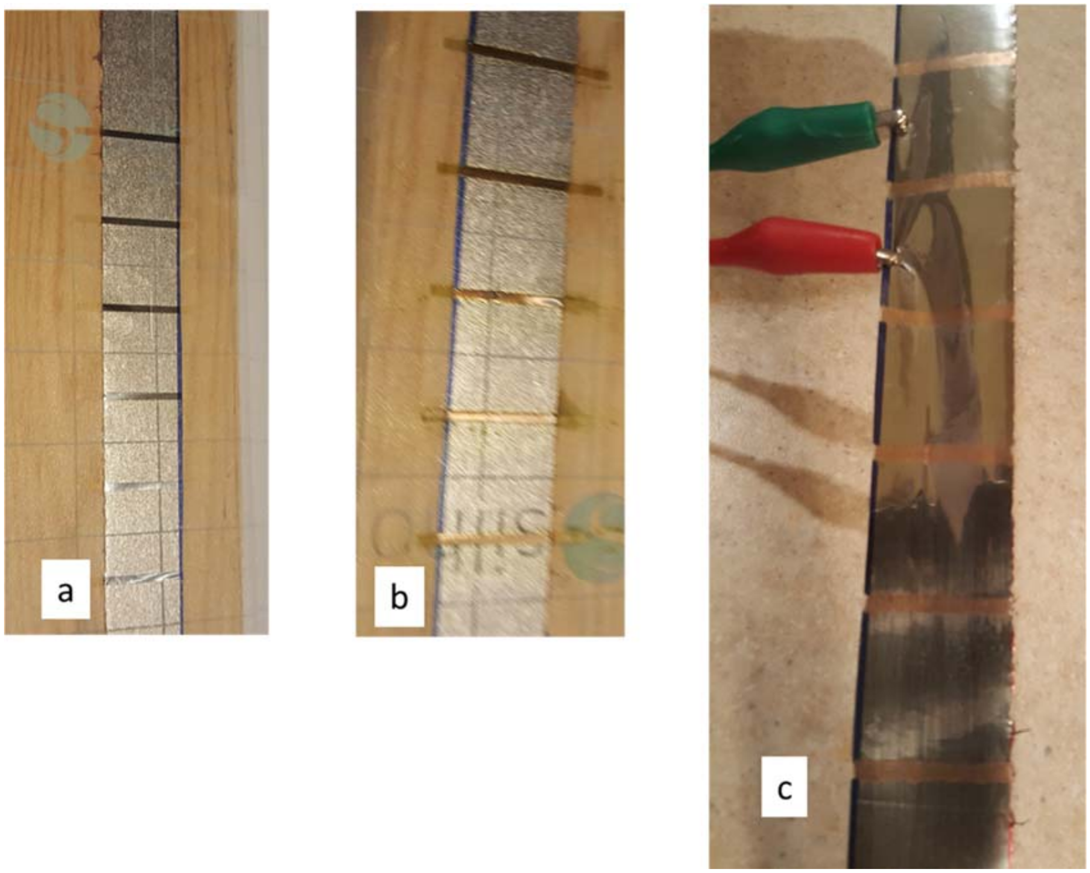

Figure 3: Sensor fabrication details

4. Experimental Procedure and Results

The main purpose of this experiment is to monitor the structural health of a stop sign support under wind loading mainly vortex loading. It has been shown in literature that wind speed greater than $5m/s$ [12] will induce noticeable vibrations. The flow fields of the prototype and model are kinematically similar therefore the wind velocity ratio using the information in Fig. (2) and Table 2 is $S = 4$. Thus, the wind speed corresponds to $20m/s$ in the wind tunnel through Reynold number similarity. A wind speed of $20m/s$ is therefore applied to the model shown in Fig. (4). Twenty nine measurements from the 29 sensor patches are recorded and processed to retain the values at the support first two natural frequencies. Figure (5) shows the response spectrum of the support at a patch location with the first two natural frequencies compared to the response spectrum of an accelerometer at the center of the patch. The shown natural frequencies confirme the finite element results of section 3. The measurement data is subsequently processed to calculate the deflection of the support shown in Fig. (6) using Eq. (1). Next, a single tri-axial accelerometer is used to measure the acceleration at the center the 29 sensor patches along the support. The z-axis of the accelerometer is pointed in the direction of the wind. The response in the x and y directions are very small, therefore it can be concluded that the predominant deformation of the support is bending in the direction of wind. Figure (5) shows the response spectrum of the support with the first two natural frequencies. The power spectral density of the signal from the accelerometer is measuring the horizontal acceleration of the stop sign model while the PVDF patch measures the bending strain of the stop sign model. The strain is then converted into displacement using Eq. (1). Assuming the motion to be harmonic at each frequency, the acceleration values are transformed into displacement by dividing the acceleration at the i^{th} frequency by $-\omega_i^2$. The displacement curves of Fig. (6) are similarly calculated with

$-\omega_1^2 = -799.4$ for the first mode. The blue line in the figure is the curve fit of the displacement data. The results indicate that the PVDF film sensor can be used to effectively monitor the structural health of the support structure of a stop sign.

Figure 4: Experimental setup

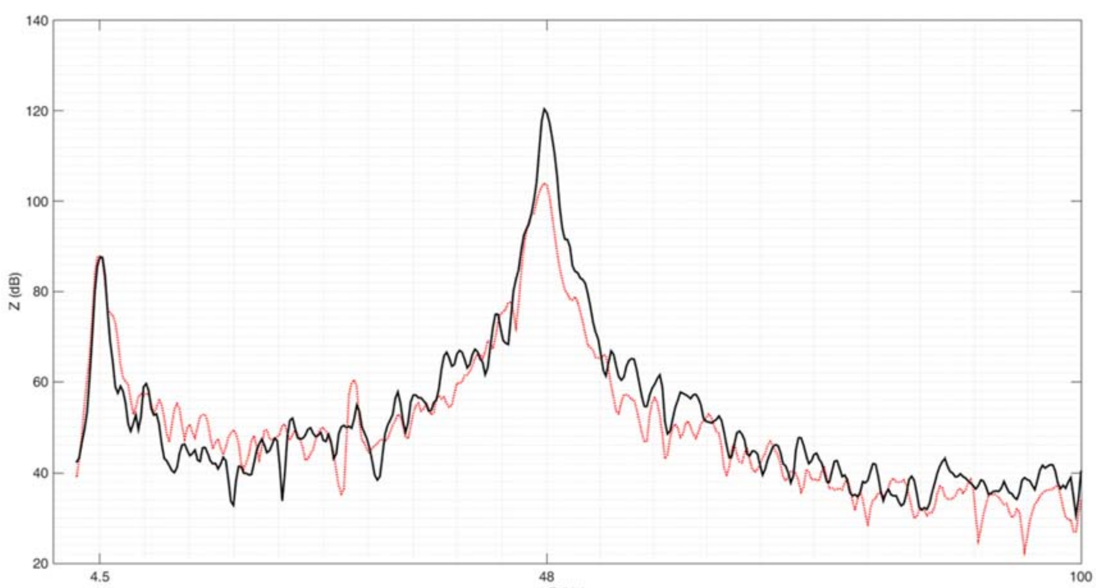

Figure 5: Power spectrum density of the model stop sign; Accelerometer (Black line), PVDF Sensor (Red line).

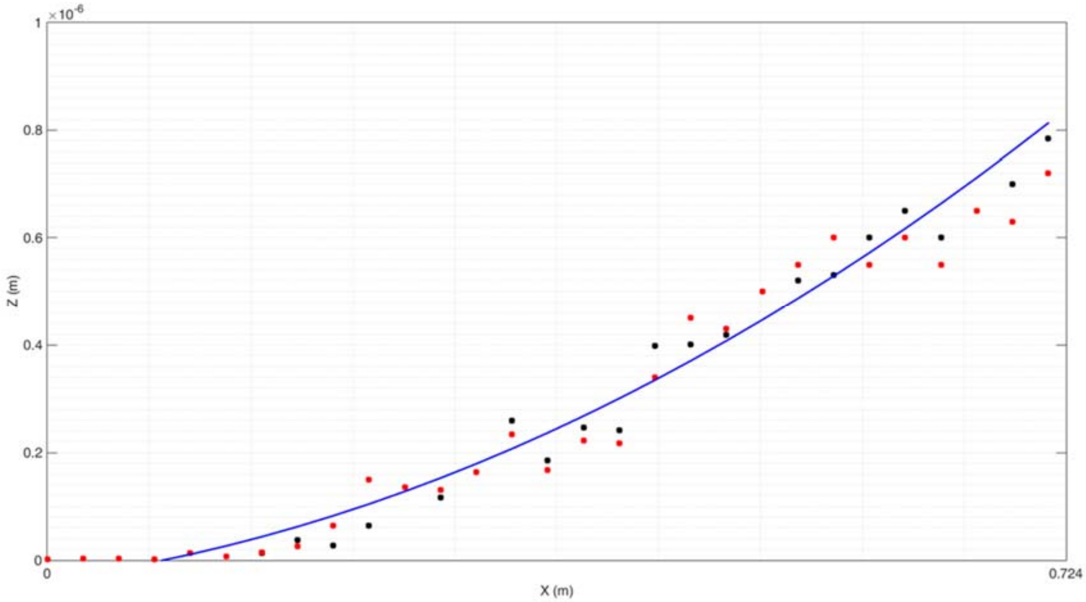

Figure 6: Model stop sign deflection as a function of the distance from its clamped end or ground; calculated based on Accelerometer signal (Black dots), calculated based on PVDF patches signal (Red dots). Data curve fit (Blue line)

5. Conclusion

This paper describes the use of PVDF films to monitor the structural health of a model traffic stop sign system. Using similitude, a reduce model of a prototype is defined and the model vibration characteristics are compared to those of the prototype using theoretical calculation and finite element modelling. The deflection and the natural frequencies are matched through the similitude scale factor. The model is then fabricated along with the sensor and tested in a wind tunnel. The outputs of the sensor are compared to the accelerometer measurements. The results indicate that the proposed inexpensive sensor can be used to monitor the vibrations of traffic stop sign systems. Future work will involve the field testing of the sensors and the extension of its application to other type of traffic sign support structures in order to predict and prevent vibration and fatigue damages

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