New Paradigms in Piezoelectric Energy Harvesting from Civil-Structures

Naveet Kaur and Suresh Bhalla

Abstract In this paper, the recent advances in the field of energy harvesting from piezoelectric transducers have been presented. The energy harvesting from the piezoelectric material using the d_{33} mode has been done enormously in the literature. However, in this paper the energy harvesting feasibility using the d_{31} mode, which has been recently explored, is discussed. The proposed study in this paper provides a proof-of-concept experimental demonstration of achieving energy harvesting from the PZT patch (a) surface bonded on steel beam and (b) embedded concrete vibration sensor (CVS) in reinforced concrete (RC) beam. The CVS has been specifically designed for RC structures. This packaged sensor (CVS) can withstand the harsh conditions encountered during construction due to its unique packaging characteristics. The laboratory experiments for voltage generation by the PZT patches (a) surface bonded on steel beam and (b) embedded CVS in RC beam have been demonstrated. In both cases, a real life sized simply supported beam has been considered as the host structure. The experimental results have been compared with the proposed analytical model. While the experiments provide a proof-of-concept feasibility of employing the d_{31} mode, it is also concluded that the shear lag effect must be taken into consideration in the electro-mechanical coupling model.

Keywords Energy harvesting · Piezoelectric device · Sensor

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1 Introduction

Energy harvesting from piezo sensors have attracted numerous researchers since last two decades due to development of less power consuming electronic systems [1–4]. Energy can be harnessed from two different modes namely, d_{33} mode and d_{31} mode of vibrations of piezo sensors. In d_{33} mode, the dynamic force application and the voltage generation are in direction 3 (polarization, out of plane) of the piezo patch. In d_{31} mode, on the other hand, the dynamic force is applied in direction 1 (along length, in plane) and the voltage is measured across direction 3. The piezoelectric coefficient of the d_{31} mode is much less than d_{33} mode, hence the latter mode has been frequently used for energy harvesting from piezo sensors in literature. However, for civil structures d_{31} mode is more natural way of excitation [5–7], hence, in the present work, d_{31} mode of vibration experienced by thin piezo (PZT) patches has been utilized for energy harvesting. The energy harvesting capabilities of the PZT patches in the real life sized steel and reinforced concrete (RC) beam has been investigated. The main objective of this paper is to explore the possibility of energy harvesting from PZT patches bonded to a steel and RC beam operating in the d_{31}-mode. The results presented in this paper are based on the detailed experimentation and analytical modelling covered in the recent publications [8, 9] of the authors.

2 Laboratory Experimentation

Experiments were carried out in the laboratory environment to measure the voltage generated by a surface bonded PZT patch when the host structure undergoes vibrations. A real life sized simply supported (a) steel I section beam and (b) RC beam have been considered to demonstrate the energy harvesting potential of PZT patches operating d_{31} mode. The properties of the beam are listed in Table 1. The complete experimental set-up for the steel beam and RC beam is as shown in Fig. 1a, b respectively. A commercially available PZT patch of 10 × 10 × 0.3 mm size conforming to grade PIC 151 [10] was surface bonded on steel beam [8] and embedded in RC beam {in the form of concrete vibration sensor (CVS, [9])}using

Table 1 Properties of host structure

Property	Steel beam	RC beam
Length, L (m)	3.2	4
Cross section	Flange: 0.070 m × 0.006 m Web: 0.133 m × 0.004 m	0.210 m × 0.160 m
Flexural rigidity modulus, EI (N m^2)	1.01×10^6	3.9×10^6
Characteristic strength of concrete, f_{ck}	–	40
Characteristic strength of reinforcement, f_y	–	415

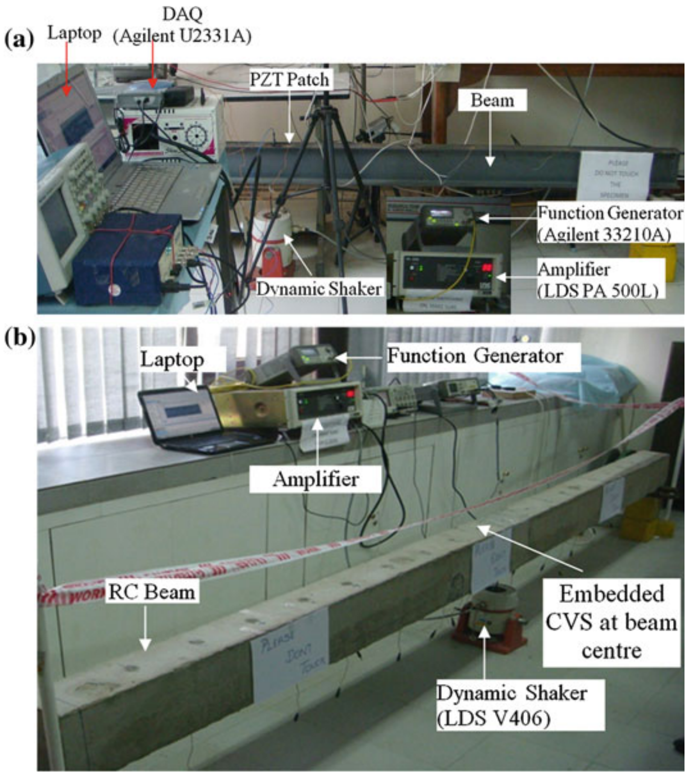

Fig. 1 Complete experimental setup for voltage measurement for **a** surface bonded PZT on steel beam and **b** embedded CVS in RC beam

two part araldite epoxy adhesive at the centre of the beam. The beam was excited using LDS V406 series portable dynamic shaker. A function generator (Agilent 33210A) was employed to generate an electrical signal, which was amplified by a power amplifier (LDS PA500L) and transmitted to the shaker, which converted it into mechanical force the oscilloscope has been used to measure the voltage generated by the PZT patch.

3 Results and Discussions

A coupled electro-mechanical model analytical model has been developed for estimation of the voltage generated by the PZT patch (a) surface bonded [8] and (b) embedded [9] inside the simply supported beam at its centre considering the effect of adhesive layer. The shear lag effect, which occurs due to presence of bond layer deforming in shear mode between the PZT patch and the host structure, was found to be the main contributor to the voltage loss [8]. The relation between the voltage V_p^S generated by the PZT patch considering the shear lag effect can be expressed as, [8]

$$V_p^S = \in K_p K_b S_q^* \tag{1}$$

This equation was employed for estimation of the PZT output voltage. The symbols used in above equation hold different meanings for surface bonded and embedded CVS as explained in [8, 9]. The variation of voltage generated by (a) surface bonded on steel beam and (b) embedded CVS in RC beam is shown in Fig. 2.

Shear lag effect was incorporated for varying thickness of adhesive bond layer (note that *h* is the thickness of the PZT patch in Fig. 2). It can be observed that with increase in bond layer thickness, the predicted theoretical voltage significantly reduces. The actual thickness of bond layer was measured to be 0.015 mm (=0.5*h*) for the surface bonded PZT patch and 3 mm (10*h*) for the embedded CVS, experimentally. It can be concluded from this analysis that effect of shear lag must be taken into account in the electro-mechanical coupling model. In embedded CVS, in addition to the shear lag effect, other factors are also possibly contributing. Investigations are underway to unearth these factors. The reader may refer to the related publications [8, 9] for modelling details. Typical values of power achieved by this configuration were measured to be 0.270 μW for surface bonded case and 0.017 μW for CVS in the lab environment.

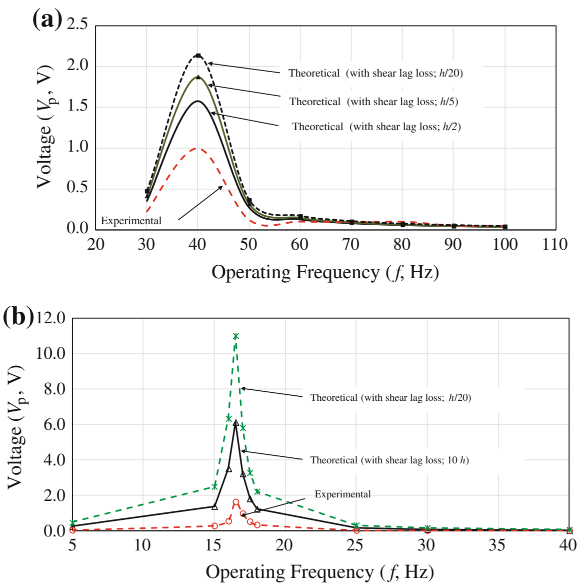

Fig. 2 Comparison of experimental and theoretical voltage incorporating the effect of shear loss for PZT patches **a** surface bonded on steel beam and **b** embedded CVS in RC beam (*h* thickness of PZT patch)

4 Conclusions

The recent advances in the field of energy harvesting from piezoelectric sensors in civil structures achieved at Smart Structures and Dynamics Laboratory [11] have been reported. The laboratory experiments for voltage generation by the PZT patches (a) surface bonded on steel beam and (b) embedded CVS in RC beam have been demonstrated. A real life sized simply supported beam has been considered as the host structure for both the cases. The experimental results have been compared with the proposed analytical model. The study established the feasibility of employing the d_{31} mode for energy harvesting. Typically, power in the microwatt range is achievable from the PZT patches in real-life structures [8, 9]. It is also concluded that the shear lag effect must be taken into consideration in the electro-mechanical coupling model.

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