Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

# Vibration and impact monitoring of a composite-wing model using piezoelectric paint

Lae-Hyong Kang[a]
[a] LANL-CBNU Engineering Institute Korea, Department of Mechatronics Engineering, Chonbuk National University, 567 Baekje-daero, Deokjin-gu, Jeonju 561756, Republic of Korea
Published online: 25 Nov 2013.

To cite this article: Lae-Hyong Kang (2014) Vibration and impact monitoring of a composite-wing model using piezoelectric paint, Advanced Composite Materials, 23:1, 73-84, DOI: 10.1080/09243046.2013.862390

To link to this article: http://dx.doi.org/10.1080/09243046.2013.862390

*Advanced Composite Materials*, 2014
Vol. 23, No. 1, 73–84, http://dx.doi.org/10.1080/09243046.2013.862390



# Vibration and impact monitoring of a composite-wing model using piezoelectric paint

Lae-Hyong Kang*

*LANL-CBNU Engineering Institute Korea, Department of Mechatronics Engineering, Chonbuk National University, 567 Baekje-daero, Deokjin-gu, Jeonju 561756, Republic of Korea*

(*Received 30 March 2013; accepted 20 June 2013*)

This study investigates a piezoelectric paint sensor for large area sensing applications, and its sensing characteristics under dynamic loading conditions such as impact and vibration. The piezoelectric paint is composed of the $Pb(Nb,Ni)O_3$-$Pb(Zr,Ti)O_3$ (PNN–PZT) powder and epoxy resin. The PNN–PZT is a kind of soft piezoelectric material that offers many advantages such as high piezoelectric properties, easy poling, and so on. The PNN–PZT/epoxy paint sensor can be easily applied to various engineering structures, even to those having a complex geometry or curved shapes because of its flexibility. In this study, the PNN–PZT/epoxy paint was coated on a composite-wing model. One electrode was made on the upper surface of the piezoelectric paint, while the graphite/epoxy composite structure itself was used as the other electrode. Then poling was conducted at room temperature (20 °C) under a 4 kV/mm electric field for 10 min. When the composite-wing model was subjected to free-vibration, its vibration response was monitored by measuring the output voltage of the piezoelectric paint sensor; when the composite-wing model was impacted by an impact hammer, its impact signal was also measured by the piezoelectric paint sensor. The vibration and impact test results showed that the PNN–PZT/epoxy paint sensor captured the dynamic responses of the composite-wing structure very well. We believe that the piezoelectric paint sensor can be useful in many engineering applications such as real-time vibration and impact monitoring, damage detection, nondestructive structural health monitoring, and so on.

**Keywords:** piezoelectric; composite; 0–3 connectivity; paint; impact; vibration; monitoring; sensor; structural health monitoring

## 1. Introduction

Composite materials are widely used for many engineering structures due to its advantageous material properties, such as low density (lightweight), high stiffness, high strength, and so on. As composite structures have replaced conventional metallic structures, composite materials with sensing capability can also be used as replacement for lightweight, integrated sensor systems. One example of a composite sensor is the piezoelectric material–polymer composite, and there exist various combinations of the composite sensor according to the connectivity. In this study, a piezoelectric paint sensor, one of the 0–3 connectivity piezoelectric composites,[1] has been studied for large area sensor application. Because a piezoelectric material generates electrical charges responding to mechanical loads without any external power source, piezoelectric paint sensors can be

*Email: reon.kang@jbnu.ac.kr

applied to many engineering structures, especially to those whose power consumption is significantly constrained, under minimum mechanical loading.

A piezoelectric paint is a kind of piezoelectric 0–3 composite material, in which the first and second numbers in the connectivity denote the continuity of the piezoelectric and polymer phases, respectively. The 0–3 composites can be made by a homogeneous distribution of piezoelectric ceramic particles within a polymer matrix. The main advantage of a piezoelectric paint is that it can be formed into various and complex shapes, while retaining its piezoelectricity. However, it cannot be sufficiently poled or is difficult to be poled because the ceramic phase is not self-connected in the poling direction.[2]

Some researchers [3–10] have developed piezoelectric paint sensors and investigated the poling techniques of the piezoelectric paint sensors. White et al. [3] used the PZT5A-type powder provided by Morgan Electro Ceramics Ltd., and the water-based acrylic produced by Rohm and Haas, and investigated PZT powder-lacquer compositions with weight ratios between 1:1 and 4:1. They conducted poling under an electric field of 5–10 kV/mm at a high temperature between 40–50 °C by placing a 150 W lamp close to the sensor for 1–5 s (sometimes up to 1000 s). Zhang and Li [4,5] used PZT5A powder and epoxy resin (weight ratio of PZT:resin = 7:3 (equal to 24:76 vol.%) or volume ratio of PZT:resin = 42:58) to form a piezoelectric paint sensor, and conducted poling at a high temperature between 70–80 °C under an electric field of 6.5 kV/mm for 1 h. Egusa and Iwasawa [6] mixed PE-60A (Fuji Titanium Industry Co., Ltd.) and epoxy resin (Epikoto 1001, Yuka Shell Epoxy K K) at the weight ratio of 88:12 to form the piezoelectric paint sensor, and conducted poling under an electric field of 5–25 kV/mm at room temperature. Lahtinen et al. [7] made the paint with 60 vol.% piezo powder (PZ27 produced by Ferroperm Electroceramics A/S, Denmark) and 40 vol.% epoxy resin, and conducted poling of the piezopaint layer under an electric field of 12.5 kV/mm electric field for 15 min at room temperature. Payo and Hale [8,9] used PKI–502, commonly known as 'Navy type II' and similar to PZT5A, of Piezo Kinetics Inc. and the acrylic paint base (weight ratio of PZT:resin = 13:7) provided by Rohm and Haas with various additives (coalescent, plasticizer, dispersant, surfactant, deformer, and neutralizer) to make a viable paint. Their piezoelectric paint was poled under an electric field of 5 kV/mm at room temperature for 10 s (after some tests at various poling times). They also investigated on the sensitivity of the piezoelectric paint sensor according to various parameters: the poling electric field (1–9 kV/mm); the poling time (~60 s); the coating thickness (24–80 μm); the electrode area (50–250 mm$^2$); and the concentration of PZT by weight (50–70 wt.%). In Li's work,[10] which included summaries of the works of other researchers, poling was generally performed under an electric field of 3–25 kV/mm at 60–150 °C for 5–60 min.

Piezoelectric paint sensors are still expensive and heavy due to the mixing ratio of the piezoelectric powder and the resin (the piezoelectric powder is much heavier than the resin), and their poling usually need to be carried out under a large electric field at a high temperature (costly for the equipments). In order to perform poling at low temperatures under low electric fields, a piezoelectric material softer than the conventional PZT5A was used in this study, and the weight percent between the resin and the PZT powder was set to 2:1 for weight and cost reduction.

A composite-wing model was selected as the target structure in the evaluation of the sensing characteristics of the piezoelectric paint sensor because lightweight, flexible composite structures are prone to failures due to vibration, impact, and cyclic vibration/impact fatigue.[11] Furthermore, unlike conventional metallic structures, composite structures generally have a high damping coefficient, which suppresses vibration or impact transmission. In other words, a local vibration or an impact signal cannot be monitored if the sensors are located far from the event point. Therefore, distributed sensing is necessary to detect such a local vibration and impact, which sometimes induce a whole structural failure. There are several types of distributed sensors, such as fiber optic sensors,[12] scanning laser sensors,[13] and optical imaging sensors,[14,15] but the best sensor for not missing such local vibrations and impact signals during a structural operation would be a sensor that can cover the whole surface of the structure. For this reason, the piezoelectric paint sensor has been newly developed in this study for large area sensor applications, and for vibration and impact signals monitoring.

## 2. Fabrication of the piezoelectric paint sensor

Piezoelectric materials can be simply divided into two groups: soft type piezoelectric materials and hard type piezoelectric materials. A soft type piezoelectric material can be obtained using donor ions ($La^{3+}$ into the A site, or $Nb^{5+}$ or $Sb^{5+}$ into the B site) as additives in the $ABO_3$ perovskite structure. It has a larger electromechanical coupling factor and a larger piezoelectric strain coefficient than a hard type piezoelectric material, and can be poled easily.[2] Due to its easier polarization and higher electromechanical properties, a soft type piezoelectric material is more suitable than a hard type for making the piezoelectric paint.

We made the soft type piezoelectric ceramic powder from five raw materials: PbO, $TiO_2$, $ZrO_2$, which are basic to PZT ceramic fabrication, $Nb_2O_5$ for softening,[16,17] and NiO to reduce the sintering temperature [17] (all from Sigma Aldrich). Table 1 shows the weight percent of each material in the PNN–PZT ceramic powder, and the overall test procedure is summarized in Figure 1. The powder was sintered at 1000 °C in the high-temperature muffle furnace (DF–3A, DAEHUNG.SCIENCE Corp.), and the sintered PNN–PZT powder is shown in Figure 2(b) for comparison with the mixture of the five raw materials shown in Figure 2(a).

Epoxy was selected as the binder of the piezoelectric paint sensor due to its advantages, such as low density, high electric strength, moderate viscosity, high impact resistance, water resistance, and no shrinkage during curing. The sintered PNN–PZT powder was mixed in the epoxy matrix (Epoxy Quick Set™, Loctite), and the resulting piezoelectric paint was cured at room temperature. One sample of the cured piezoelectric paint is shown in Figure 2(c), and the weight ratio of the epoxy to the piezoelectric powder was chosen as 2:1 for this study to reduce the total weight of the sensor. The density of the epoxy in the study was 1140 $kg/m^3$, and that of the piezoelectric paint was measured to be about 1500 $kg/m^3$. Note that the densities of typical piezoelectric ceramics range between 7000 and 8000 $kg/m^3$, and the density of the PNN–PZT ceramic was measured as 7200 $kg/m^3$. The PNN–PZT/epoxy paint, as shown in Figure 2(c), is not piezoelectrically active until it is poled under a high electric field. For the poling process, a silver paste (ELCOAT P–100, CANS) was coated on the top surface of the paint sensor to form an electrode, and the surface of the target structure itself became

Table 1. Weight percents of 5 raw materials constituting PNN–PZT ceramic powder.

| Material | PbO | $Nb_2O_5$ | NiO | $ZrO_2$ | $TiO_2$ |
|---|---|---|---|---|---|
| Weight percent (wt.%) | 66.91 | 14.46 | 6.10 | 4.99 | 7.54 |

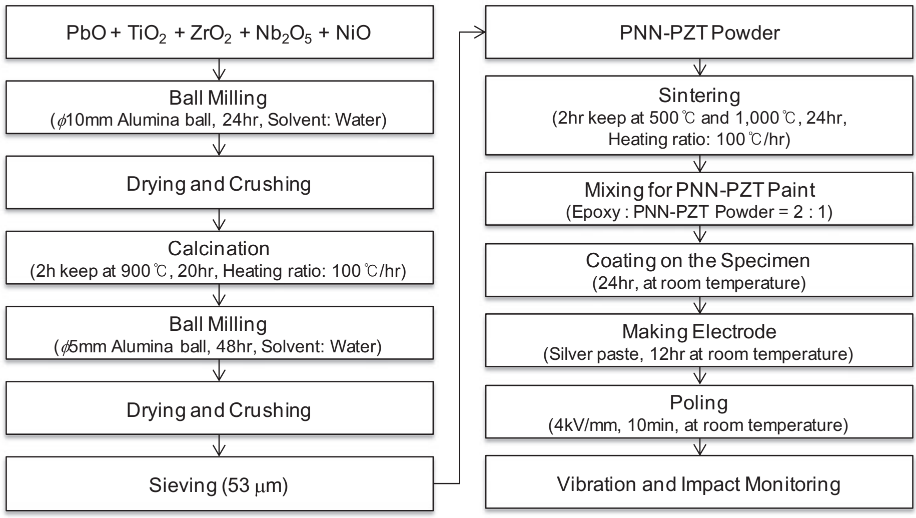


Figure 1. Overall experimental procedure for the PNN–PZT paint sensor tests.

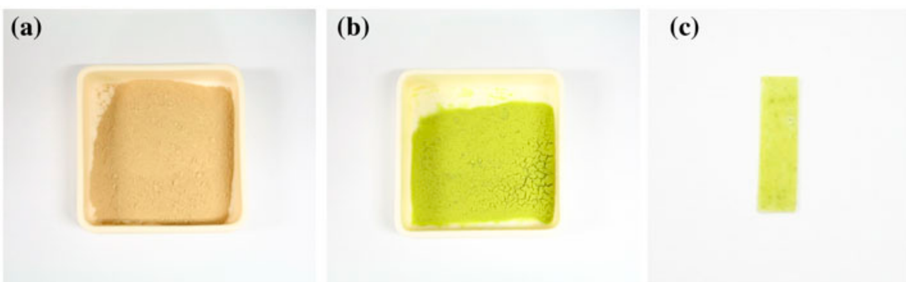


Figure 2. Piezoelectric powder and the PNN–PZT paint during fabrication: (a) the mixture of five raw materials; (b) the sintered PNN–PZT powder; and (c) the cured PNN–PZT paint sample before wiring.

the other electrode in this study. The poling was performed successfully at room temperature (20 °C) using a DC power supply (P3030D, Advantek Corp.) and the piezoelectric amplifier (Model 623B, Trek), under an electric field of 4 kV/mm (the sensor thickness was 0.3 mm and the applied poling voltage was 1.2 kV) for 10 min.

## 3. Vibration and impact monitoring of the composite-wing using the PNN–PZT paint sensor

A graphite/epoxy (CU–125NS, Hankuk Fiber Co., Ltd.) composite-wing having $[90_2/0_2]_s$ lay-up was manufactured in order to demonstrate the capability of the piezoelectric paint sensor to sense vibrations and impacts on the composite structure. The dimensions of the composite-wing applied with the piezoelectric paint sensor are illustrated in Figure 3. The wing was clamped on a fixture, as depicted in Figure 3(a). The PNN–PZT/epoxy paint sensor was coated along the center line of the wing, not on the whole surface of the composite-wing, to compare sensing signals according to the location – on the paint sensor or not – of the impact points. For comparison with the paint sensor output, the strain and velocity at certain points as shown in Figure 3(a) was measured simultaneously by a strain gage (FLA-1-11-1L, Tokyo Sokki Kenkyujo Co., Ltd.) and a laser Doppler vibrometer (LDV) (Head: OFV 303; Controller: OFV 3001, Polytec), respectively. Figure 4 shows the overall test setup for vibration and impact testing, including an FFT analyzer (PULSE 3560-B-040, Brüel & Kjær), a data acquisition board (DS1104, dSPACE), an impact hammer (086B01, PCB Piezotronics, Inc.), an ICP sensor signal conditioner for the impact hammer (Model 442B101, PCB Piezotronics, Inc.), a strain gage indicator (SDA-810C, Tokyo Sokki Kenkyujo Co., Ltd.), and the LDV. Modal testing was performed first, and the measured natural frequencies were compared with those from finite element analysis. The finite element analysis (30 × 10 quadratic hexahedral elements) was conducted using MSC/NASTRAN, and the material properties that were used for the analysis are shown in Table 2. Table 3 summarizes the first 5five natural frequencies; the first natural frequency is 24.3 Hz.

In order to verify the vibration sensing capability of the piezoelectric paint sensor, free-vibration testing was carried out, with the wing tip having a certain initial out-of-plane deformation. The composite-wing started to vibrate after the initial



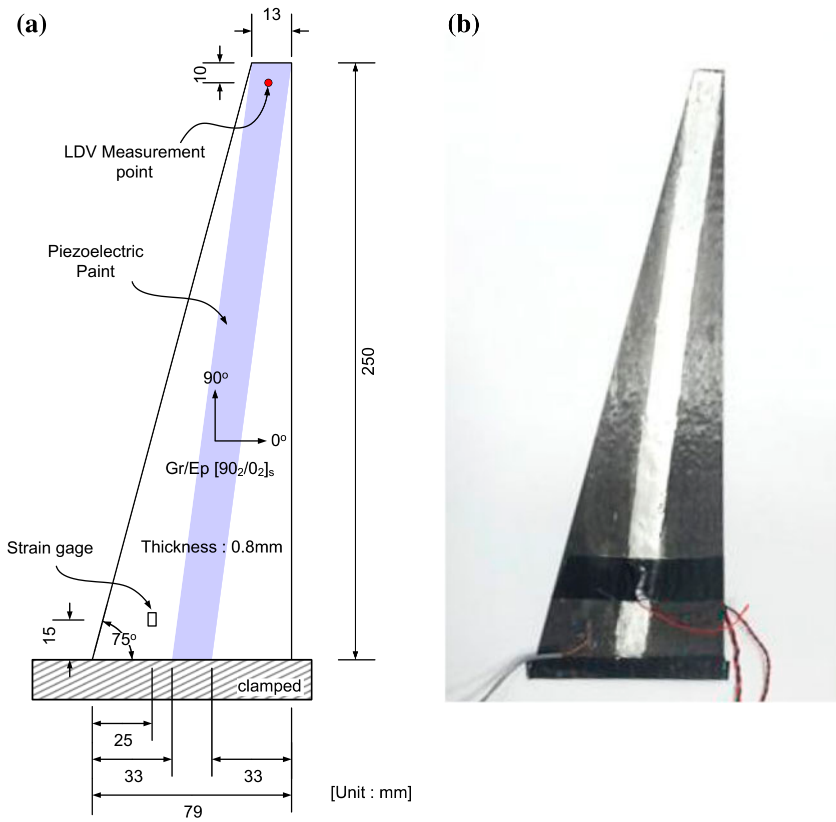


Figure 3. Composite-wing model with piezoelectric paint sensor: (a) dimensions and measurement points of the composite-wing model; (b) a real composite-wing model.

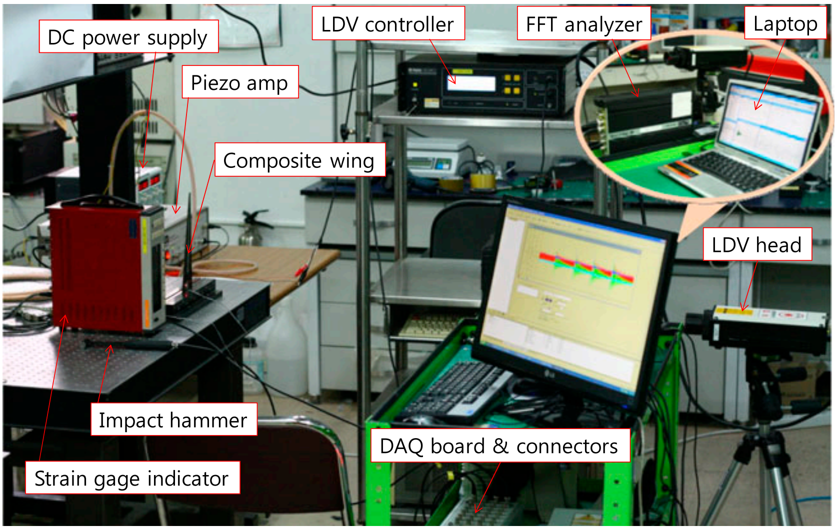


Figure 4. Overall test setup for vibration and impact measurement.

deformation was removed, and the output voltage of the PNN–PZT/epoxy paint sensor and the velocity near the wing tip, 240 mm from the wing root, were measured using the LDV and compared, as shown in Figure 5. The output signal of the typical piezoelectric sensor having high resistance and low capacitance is proportional to the time differential of charge, which is generated by the deformation; therefore, the signal from the PNN–PZT/epoxy paint sensor matches with the velocity (time differential of deformation). The maximum noise level (max. magnitude) of the piezoelectric paint sensor was about 2.5 mV, and minimum detectable velocity is set to the corresponding

Table 2. Material properties of CU-125NS.

| Material properties of CU-125NS | |
|---|---|
| Elastic modulus, $E_1$ | 119 GPa |
| Elastic modulus, $E_2$ | 8.67 GPa |
| Shear modulus, $G_{12}$, $G_{13}$ | 5.18 GPa |
| Shear modulus, $G_{23}$ | 3.29 GPa |
| Poisson's ratio, $v$ | 0.31 |
| Density, $\rho$ | 1570 $kg/m^3$ |
| Layer thickness, $t$ | 0.1 mm |

Table 3. Natural frequencies of the composite-wing model.

| Natural freq. | Experiment (Hz) | Analysis (Hz) | Error (%) |
|---|---|---|---|
| 1st | 24.3 | 24.9 | 2.3 |
| 2nd | 108.5 | 109.8 | 1.2 |
| 3rd | 166.4 | 147.9 | 11.1 |
| 4th | 272.3 | 280.8 | 3.1 |
| 5th | 397.3 | 371.5 | 6.5 |

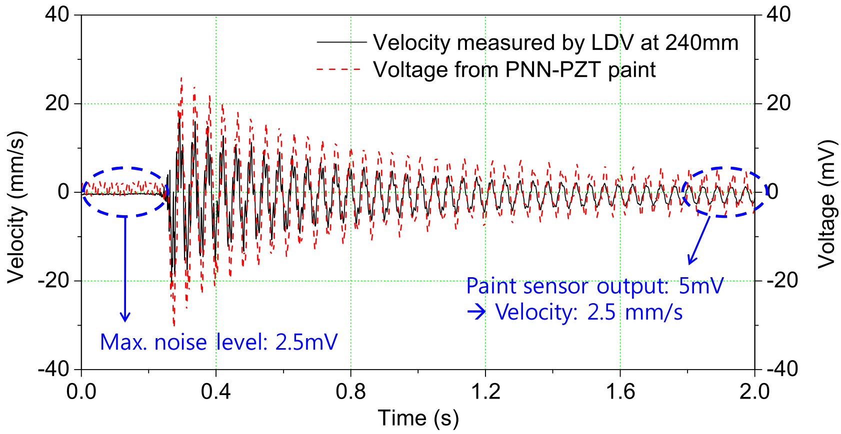


Figure 5. PNN–PZT paint output voltage and velocity for the case of free-vibration.

velocity when the paint sensor output is twice of the maximum noise level. The minimum detectable velocity at 240 mm is 2.5 mm/s when the piezoelectric paint sensor output is 5 mV. The FFT (Fast Fourier Transform) of the voltage signal is shown in Figure 6; the free-vibration frequency measured from the piezoelectric paint sensor is 23.93 Hz and the value is exactly the same as that from the LDV sensor.

For impact testing, 9 points were hit using an impact hammer, as illustrated in Figure 7. The force from the impact hammer, the velocity and strain, and the voltage output from the piezoelectric paint sensor were monitored simultaneously at 10 kHz

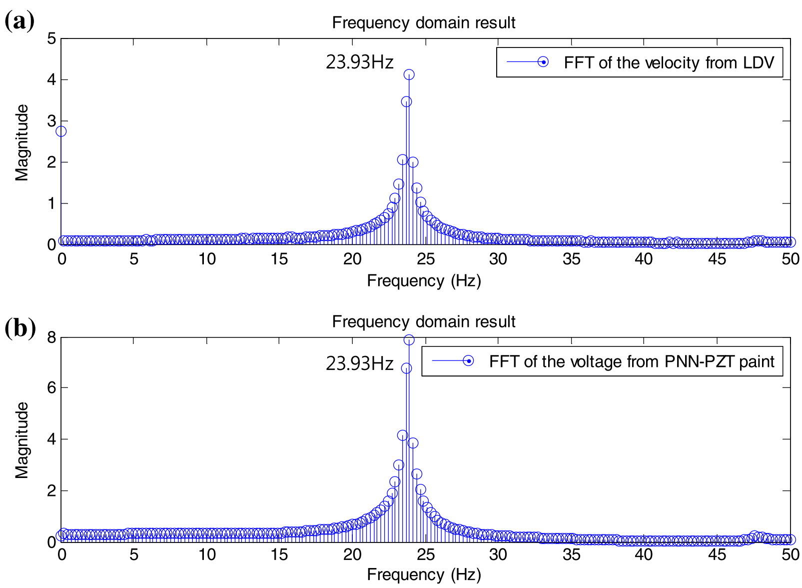


Figure 6. FFT analysis results for the case of free-vibration: (a) a result from the velocity measured by LDV; (b) a result from the voltage of the PNN–PZT paint sensor.

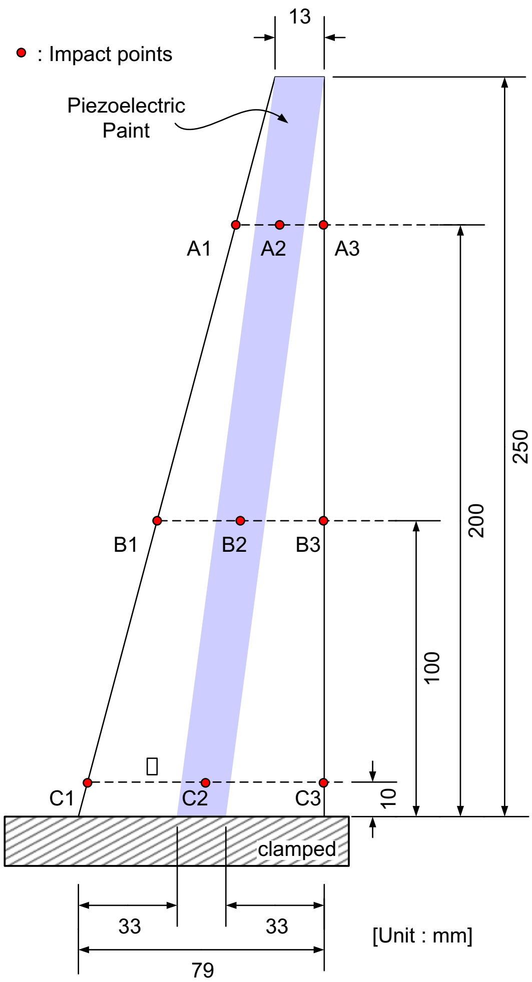


Figure 7. Nine impact points on the composite-wing model.

sampling frequency. Figures 8–10 show the impact test results for locations A1–A3; the voltage from the paint sensor and the LDV signal were more sensitive to the impact, not the subsequent vibration (transient vibration after impact), as the voltage output signal is related to the velocity component, the changes of deformation (strain). The voltage output was much more sensitive to the impact in the case of A2 compared with the cases of A1 and A3, because the impact occurred directly on the paint sensor. Other impact test results for B1–B3 and C1–C3 are also shown in Figures 11 and 12, and the variations of the voltage output were investigated according to impact location and impact strength. As in the free-vibration test, the minimum detectable impact signal level was calculated based on the signal of twice the noise level, and is summarized in Table 4. As expected, an impact on the center line coated with the piezoelectric paint was captured successfully by the paint sensor, and the threshold of the paint sensor output was the largest in the case of impact near the wing root (C1 and C3). For actual

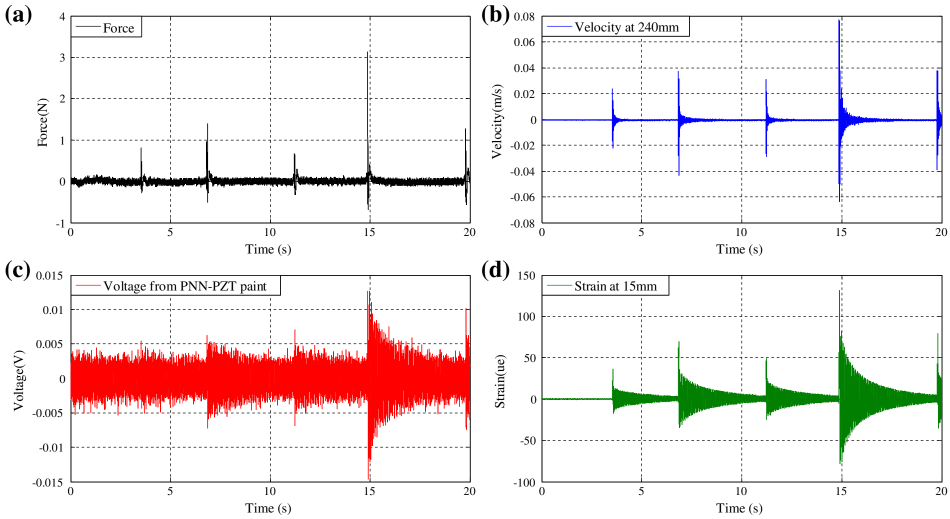


Figure 8. Impact test results at A1: (a) force; (b) velocity; (c) paint sensor output; (d) strain.

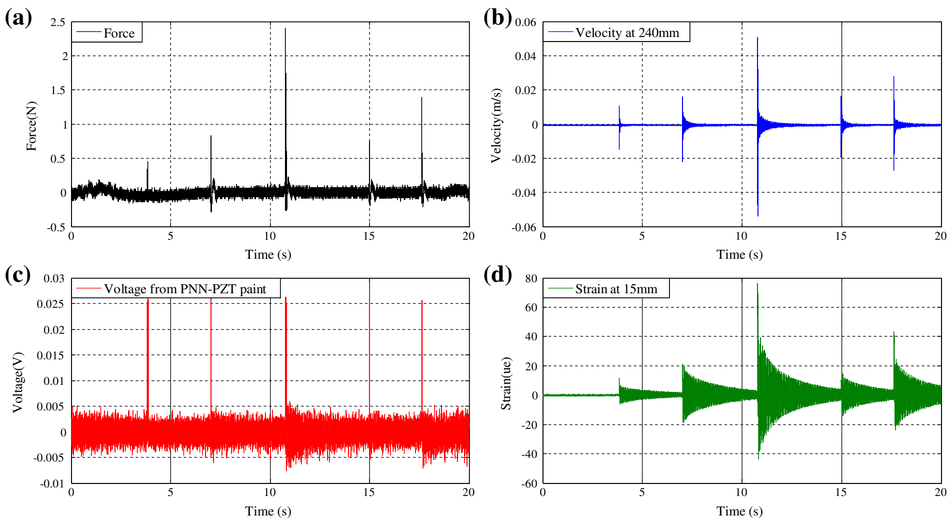


Figure 9. Impact test results at A2: (a) force; (b) velocity; (c) paint sensor output; (d) strain.

application, the paint can be coated on the whole surface of a structure to increase its sensitivity to vibration and impact. Even though the noise level can increase a little as the coating area increases, we expect that the threshold of the output signal at the leading edge and trailing edge can be significantly reduced; thus, smaller vibration and impact on the structure can be monitored more clearly according to the results in Table 4.

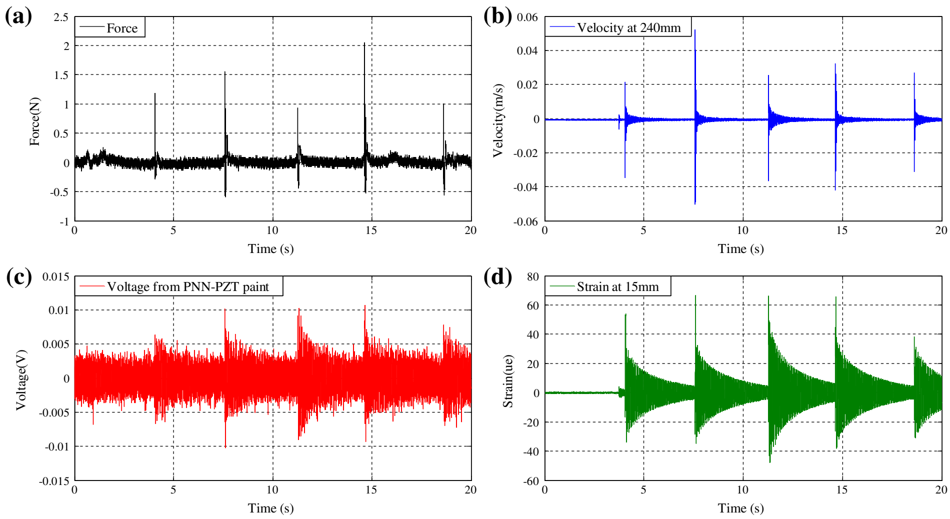


Figure 10. Impact test results at A3: (a) force; (b) velocity; (c) paint sensor output; (d) strain.

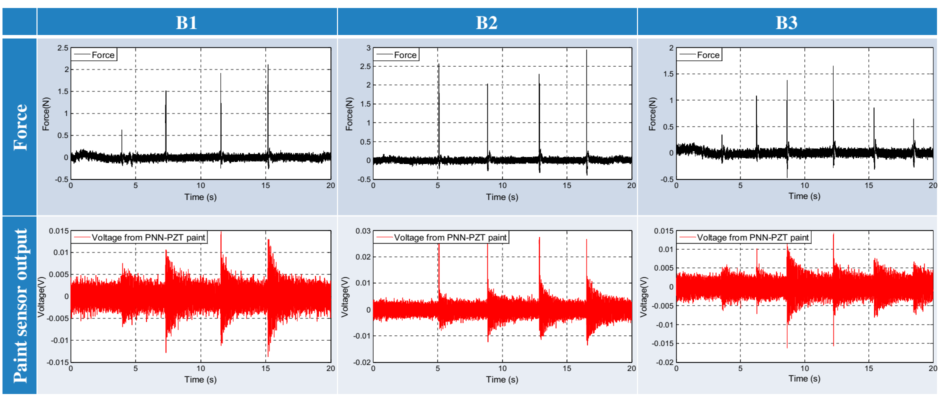


Figure 11. Impact test results at B1, B2, and B3.

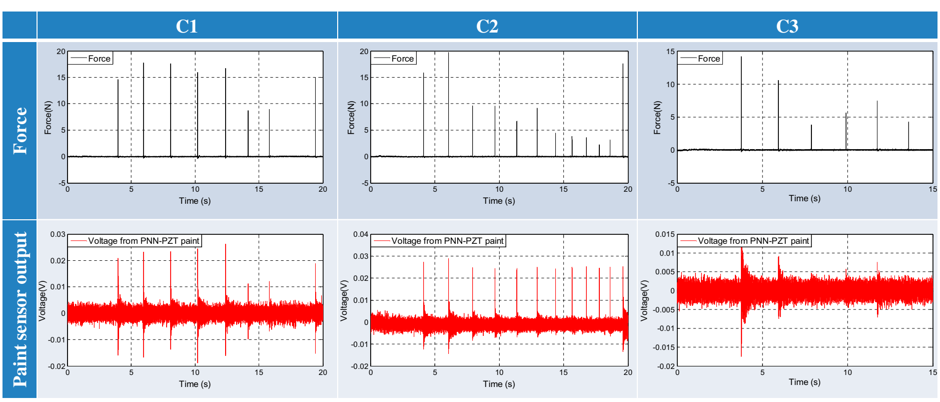


Figure 12. Impact test results at C1, C2, and C3.

Table 4. Minimum detectable signal level (the signal of more than twice the noise level) for impact monitoring.

| Event point | A (200 mm) | B (100 mm) | C (10 mm) |
|---|---|---|---|
| 1 (leading edge) | 2 N | 1.5 N | 8 N |
| 2 (center) | $<0.5$ N | $<2$ N | $<2$ N |
| 3 (trailing edge) | 1.5 N | 1.5 N | 10 N |

## 4. Conclusion

In this paper, the PNN–PZT/epoxy paint was studied as a sensor for vibration and impact monitoring of a lightweight composite structure. For fabrication of the PNN–PZT paint, first the PNN–PZT powder, a kind of soft type piezoelectric material, was manufactured by 1000 °C sintering process in the laboratory. Then, the PNN–PZT powder was mixed with epoxy resin (the ratio of powder to resin was 1:2), and the mixture – piezoelectric paint – was coated on a composite-wing model. After curing of the paint, an electrode was made on the paint by coating with a silver paste, and poling was conducted successfully under an electric field of 4 kV/mm at room temperature for 10 min.

The composite-wing model having fixed-free boundary was subjected to free-vibration and impact conditions, and the voltage responses were monitored. When the composite-wing structure was under the free-vibration condition, the output signal from the paint sensor matched the velocity signal measured by the LDV. For the impact tests, an impact hammer was controlled to hit nine points on the composite structure, and of these points, three points were located on the piezoelectric paint sensor. The results showed that the PNN–PZT paint sensor captured the impact signals, even those of very small magnitude (~10 N), and especially, those that resulted from impact on the piezoelectric sensor ($<2$ N).

The presented PNN–PZT/epoxy paint sensor can be a promising sensor for wide area or distributed sensing applications, real-time vibration and impact monitoring, damage detection, nondestructive structural health monitoring, etc. In addition, it would be very useful especially for applications where power supply is significantly limited because the sensor can monitor vibrations and impacts without the use of any external power sources and amplifiers.



## Acknowledgment

The author wishes to thank Prof. Jae-Hung Han in KAIST for providing measurement systems. This research was supported by Leading Foreign Research Institute Recruitment Program through the National Research Foundation of Korea funded by the Ministry of Science, ICT and Future Planning (2011-0030065), and supported by research funds of Chonbuk National University in 2012.

## References

[1] Newnham RE, Skinner DP, Cross LE. Connectivity and piezoelectric–pyroelectric composites. Mater. Res. Bull. 1978;13:525–536.
[2] Schwartz M. Encyclopedia of smart materials. New York (NY): John Wiley and Sons; 2002.
[3] White JR, de Poumeyrol B, Hale JM, Stephenson R. Piezoelectric paint: ceramic-polymer composites for vibration sensors. J. Mater. Sci. 2004;39:3105–3114.
[4] Zhang Y. In situ fatigue crack detection using piezoelectric paint sensor. J. Intell. Mater. Syst. Struct. 2006;17:843–852.

[5] Li X, Zhang Y. Analytical study of piezoelectric paint sensor for acoustic emission-based fracture monitoring. Fatigue Fract. Eng. Mater. Struct. 2008;31:684–694.
[6] Egusa S, Iwasawa N. Piezoelectric paints as one approach to smart structural materials with health-monitoring capabilities. Smart Mater. Struct. 1998;7:438–445.
[7] Lahtinen R, Muukkonen T, Koskinen J, Hannula S-P, Heczko O. A piezopaint-based sensor for monitoring structure dynamics. Smart Mater. Struct. 2007;16:2571–2576.
[8] Payo I, Hale JM. Dynamic characterization of piezoelectric paint sensors under biaxial strain. Sens. Actuators, A. 2010;163:150–158.
[9] Payo I, Hale JM. Sensitivity analysis of piezoelectric paint sensors made up of PZT ceramic powder and water-based acrylic polymer. Sens. Actuators, A. 2011;168:77–89.
[10] Li X. Electroelastic properties of piezoelectric paint for ultrasonic guided wave sensing and damage detection. Ann Arbor: ProQuest LLC; 2011.
[11] Jang B-W, Park S-O, Lee Y-G, Kim C-G, Park C-Y. Detection of impact damage in composite structures using high speed FBG interrogator. Adv. Compos. Mater. 2012;21:29–44.
[12] Kim H-I, Kang L-H, Han J-H. Shape estimation with distributed fiber Bragg grating sensors for rotating structures. Smart Mater. Struct. 2011;20:035011_1–035011_11.
[13] Di Maio D, Ewins DJ. Measurement and comparison of operational deflection shapes (ODSs) using a scanning LDV system in step or continuous scanning mode. Proceedings of the IMAC-XXVII; 2009 Feb 9–12; Orlando, FL, USA.
[14] Fleming GA, Gorton SA. Measurement of rotorcraft blade deformation using projection moiré interferometry. Proc. SPIE. 1998;3411:514–527.
[15] Schneider O. Analysis of SPR measurements form HART II. Aerosp. Sci. Technol. 2005;9:409–420.
[16] Qiu J, Tani J, Yanada N, Kobayashi Y, Takahashi H. Fabrication of $Pb(Nb,Ni)O_3$–$Pb(Zr, Ti)O_3$ piezoelectric ceramic fibers by extrusion of a sol-powder mixture. J. Intell. Mater. Syst. Struct. 2004;15:643–653.
[17] Lee M-W, Kim S-J, Yoon M-S, Ryu S-L, Kweon S-Y. Low temperature sintering of PNN–PZT ceramics and its electrical properties. J. Korean Inst. Electr. Electron. Mater. Eng. 2008;21:1077–1082.