Experimental and theoretical investigations on sensing and dynamic characteristics of PVDF thin film

Yu-Chih Lin 1,*, Yu-Hsi Huang 2, Chien-Ching Ma 2 and Chun-Kai Chang 2

1Department of Mechanical and Mechatronic Engineering, National Taiwan Ocean University, Keelung, Taiwan, Republic of China
2Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan, Republic of China

*Corresponding author: beatrice@mail.ntou.edu.tw

ABSTRACT

This research investigates both the steady-state and transient dynamic characteristics of polyvinylidene fluoride (PVDF), which is one of the most commonly used piezoelectric polymers. In steady-state vibration, the visible resonant mode fringe patterns are obtained using the amplitude-fluctuation electronic speckle pattern interferometry experiment, and the point-wise displacement data are measured by laser Doppler vibrometer–dynamic signal analysis. Finite element analysis is also performed, and the numerical results are compared with the experimental ones for the steady-state vibration. In a transient dynamic experiment, the history of dynamic impact generated by a steel ball is measured by the PVDF, and the experimental results are compared with the theoretical results obtained by the Hertz contact law. The comprehensive information about steady-state and transient dynamic properties of PVDF membranes obtained in this study is expected to contribute to the further development of the PVDF piezoelectric element.

KEYWORDS: polyvinylidene fluoride (PVDF), amplitude-fluctuation electronic speckle pattern interferometry (AF-ESPI), finite element analysis

1. INTRODUCTION

Piezoelectric materials have the special property of connecting the electrical and mechanical fields. When subjected to stress, they induce an electric charge, and conversely, when an electric field is applied, they generate strain. Pb(Ti,Zr)O 3 ceramic is one of the most widely used piezoelectric materials due to its low cost and large electromechanical coupling coefficient. However, ceramic is very brittle and cannot withstand large strain. Polyvinylidene fluoride (PVDF)—one of the piezoelectric polymers—has recently attracted considerable attention. PVDF and its copolymer were frequently used in the applications of piezoelectric materials. The superior properties of PVDF include a broad frequency response range, minimal resonant background noise, high strength and toughness, low chemical activity, low density, low acoustic resistance, simplicity of machining into various shapes and sizes according to the application demands and, especially, the proximity of its acoustic impedance to that of water and human tissue.

Bergman discovered the pyroelectric effect in 1971, but commercial implementation of PVDF only began in 1980. Hence, we believe that further investigation into the properties and potential applications of PVDF is required. Gerliczy and Betz [1] found that the mechanical forming, phase transformation, polarization processing and base material are important factors affecting the material properties of PVDF. They also found that the biaxially oriented membranes made under good processing conditions have better properties than the monoaxially oriented PVDF. Patterson and Nevill [2] used PVDF sensors to simulate the tactile sense of the fingertips and measured the recognition rates for different shapes under different conditions. Other medical applications of PVDF make use of its properties as a transducer in order to measure the strength and effect of ultrasonic waves in the human body during kidney stone removal operations [3,4]. Shan et al. [5] used PVDF to assess the characteristics of laser-generated ultrasonic signals in body tissue. This research considered the full-of-water environment of the human body and simulated it as a semi-finite fluid. Zahui et al. [6] developed a control technique to reduce the sound radiating from a vibrating beam structure. PVDF was used for beam vibration sensing. Sun and Mills [7] used PVDF as an actuator to control a rotating cantilever beam. They used the linear velocity feedback method, which is easier to implement and avoids modal truncation, effectively suppresses the main mode vibration and allows for high-speed motion compared with the angular velocity feedback method.

Petitjean and Legrain [8] used PVDF as a sensor to control the acoustic radiation of a composite plate. An array-type PVDF attached to a cantilever beam was used by Mao et al. [9] to sense acoustic vibration and actively control noise. Park et al. [10] compared three different sensor materials: lead zirconate titanate, PVDF and the poly(vinylidene fluoride-co-trifluoroethylene) copolymer to non-destructively investigate the capacities of composite materials. Additionally, large PVDF membranes have also been used as stardust sensors [11].

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For the purpose of monitoring the impact initiation and the crack evolution, a combination of PVDF thin-film sensors and piezoceramic-based smart aggregates was investigated by Qi et al. [12]. PVDF sensor array-based electronic skin characteristics were then measured by Seminara [13], and he suggested some possible developments for skin design and fabrication technology. The development of flexible tactile sensors—for mounting on electrical skin or other wearable devices—was also investigated [14].

The dynamic characteristics measured by PVDF were investigated in previous studies. Ma et al. [15] used both the PVDF sensor and the strain gauge to measure the transient responses of a cantilever beam. The sensing abilities for the PVDF sensor and the strain gauge were compared and discussed. The resonant frequencies measured by theoretical analysis, finite element analysis, PVDF sensor and strain gauge were also compared. They concluded that the sensitivity of the PVDF sensor was higher than that of the strain gauge. Chuang et al. [16,17] then investigated the history of impact loading of a cantilever beam by using the PVDF sensor. The transient strain responses obtained by PVDF and finite element analysis were also compared. The feasibility of measuring the transient behavior by PVDF was demonstrated. The liquid level detection was also performed by considering the vibration characteristics of an aluminum solid partially immersed in water [18]. The fiber Bragg grating sensor was used, and fast Fourier transform was performed for measuring the transient responses. This study provides the useful measurement techniques for the fluid–structure interaction vibration problems. Although many studies about PVDF exist in its sensor applications, detailed experimental results on its resonant properties are still lacking. A more thorough understanding of the resonant characteristics of PVDF requires the study of the resonant mode fringe patterns. In this research, the resonant frequencies and the full-field mode shapes were obtained via amplitude-fluctuation electronic speckle pattern interferometry (AF-ESPI) and laser Doppler vibrometer (LDV) experiments. The theoretical results were also calculated using finite element analysis for comparison. In order to measure the transient dynamic sensing ability of PVDF, this study also investigates the history of dynamic impact loading by experiment. In this experiment, an impact force generated by a steel ball on an aluminum block is computed by the Hertz contact law and compared with that obtained by a concept based on the metals’ conductivity. Then, the PVDF sensor is calibrated by an impact hammer experiment. Finally, the repeatability of the impacts of the steel ball on the cantilever beam is obtained from the transient responses of the PVDF sensor.

2. SPECIMENS AND EXPERIMENTAL SETUP

Three kinds of PVDF materials were used in this experiment: an LDT0-028K/L PVDF sensor, a PVDF thin film sheet with Ag coating on two surfaces (Piezotech®, Arkema-CRRA, Rue Henri Moissan 69496, Pierre-Benite Cedex, France) for a steady-state vibration experiment and a PVDF thin film (Measurement Specialties, 1-1004346-0) for transient dynamic measurement. Before the AF-ESPI experiment is conducted, there are two steps involved in assessing the steady-state sensor properties: (1) measuring the properties under constant voltage and different frequencies and (2) measuring the properties under constant frequency and different voltages. In both parts of the test, the PVDF sensor (MSI-LDT0-028K/L) was used. The LDT0-028K/L is a flexible sensor including a 28-μm-thick piezoelectric PVDF polymer thin film with screen-printed Ag ink electrodes. The sensor is then laminated to a polyester substrate, and the wire leads are attached. It is usually used as a vibration sensor, and its sensory properties were investigated in the experiment. Even though it is a well-known commercial sensor, some basic characteristics must be tested prior to performing the AF-ESPI technique for thorough investigation and verification. In the first part of the testing, two pieces of PVDF sensors were bonded together, an electrical voltage was applied to produce vibrations in one of the sensors and the output signal of the other sensor was measured. In the second part of the test, a constant frequency voltage was applied to excite the PVDF. Under different voltages, the vibration-induced voltages of the other PVDF sensor were obtained. The consistency of the input and output signals was measured to determine the sensor’s properties.

Then, the PVDF thin film sheet (12 cm × 12 cm × 25 μm, Ag coating on two sides, Piezotech®, Arkema-CRRA, Rue Henri Moissan 69496, Pierre-Benite Cedex, France) without plastic cover was used for optical measurements. The specimen was cut into 65 mm × 65 mm × 0.025 mm pieces for the experiment. The PVDF thin film was carefully attached to a square acrylic frame, thus introducing a fixed boundary condition to all four edges of the specimen. The vibrations of the PVDF thin film when excited by both electrical voltages and acoustic signals were investigated. The vibration characteristics of the PVDF film were investigated using the AF-ESPI, dynamic signal analysis and the finite element method (FEM) analysis techniques. The numerical and theoretical results were compared to test for any discrepancies. In the AF-ESPI experiment, both the resonant frequencies and the corresponding mode shapes were obtained. Hence, the sensory properties were more thoroughly understood with this technique. For the electrical energy excitation experiment, the piezoelectric thin film was excited by applying a sinusoidal voltage signal across its two surfaces. For the acoustic wave excitation experiment, the electrical voltages were input to the speaker, and the PVDF vibrated due to the acoustic vibration. When the frequencies of excitation were close to the resonant frequencies of the PVDF thin film, the specimen was in resonance and large displacement vibrations were induced.

The impact hammer (B&K Type 8204) is used to beat on the surface of a PVDF film (Measurement Specialties, 1-1004346-0) in the transient dynamic experiment to examine the linearity of the responses of the PVDF film. The dimensions of the PVDF film are 3 mm × 7 mm × 0.028 mm. The aluminum cantilever beam used in this experiment has the dimensions of 150 mm in length, 12 mm in width and 1.21 mm in thickness. The experimental setup for transient dynamic is shown in Fig. 1.

2.1 AF-ESPI experimental techniques

To obtain both the resonant frequencies and the mode shapes, the AF-ESPI technique was used. Ma and Huang [19] applied the AF-ESPI technique for three-dimensional vibration investigations of piezoelectric materials. This technique can be used in
real time, for a full field and without contact, so it can provide the overall characteristics of the vibration. The optical setup of the AF-ESPI system, as shown in Fig. 2, was used for measurement of the resonant frequencies and corresponding mode shapes of out-of-plane vibration. We used a He–Ne laser (Melles Griot 05-LHP-928) at 35 mW and a wavelength (λ) of 632.8 nm as the coherent light source. If the vibrating frequency is near the resonant frequency, clear fringe patterns can be observed in the monitor of the analyzing computer. If the vibrating frequency is not near the resonant frequency, only random speckles are displayed and no clear fringe patterns can be obtained. In the experimental procedure, the resonant frequencies and the full-field mode shapes were measured simultaneously.

2.2 Finite element analysis

ABAQUS finite element analysis software was used for the theoretical analysis of the vibration characteristics of the PVDF thin film sheet with dimension of 65 mm × 65 mm × 0.025 mm. Both shell and solid elements are used in this computation for comparison. Since piezoelectric analysis is not supported by the shell element in ABAQUS, we used both the S4R shell element without piezoelectric effect and the piezoelectric solid element C3D20RE to simulate the properties of the PVDF. The results obtained using finite element analysis were compared with the experimental results to understand the differences between theoretical and experimental techniques.

2.3 Hertz contact law

Hertz incorporated the local indentations near the contact point between two isotropic elastic materials with smooth surfaces [2021]. When the elastic wave motion can be neglected, the contact force $F$ and the indentation depth $\alpha$ have the following relationship:

$$ F = K a^{3/2}. $$

(1)

A reasonable approximation between the indentation depth $\alpha$ and the initial relative velocity $V_0$ has been provided by Hunter [22] as

$$ \alpha = \alpha_m \sin \left( \frac{0.68 V_0 t}{\alpha_m} \right). $$

(2)

We now consider a contact problem in which one elastic body is a sphere and the other an elastic half space. The parameters $K$ and $\alpha_m$ can be described as [20]

$$ K = \frac{4}{3} \sqrt{R \left( \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right)^{-1}} $$

(3)

and

$$ \alpha_m = \left[ \frac{15 m_1 V_0^2 \left( \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right)}{16 \sqrt{R}} \right]^{2/5}, $$

(4)

where $R$ is the sphere radius, $\nu$ is the Poisson’s ratio, $E$ is the Young’s modulus and the subscripts 1 and 2 denote the sphere.
Figure 3 The sensory behavior of PVDF sensors at different frequencies.
and the half space, respectively. After the assumption of the proportional relationship between $F$ and $\sin \frac{3}{2}[\left(\pi / T_c\right)/t]$, the contact time $T_c$ can be written as

$$T_c = 8.034R \left[ \frac{\rho_1 \left( \frac{1 - v_1^2}{\pi E_1} + \frac{1 - v_2^2}{\pi E_2} \right)}{\sqrt{V_0}} \right]^{2/5},$$

(5)

where $\rho_1$ is the sphere density, $V_0 = (2gh)^{1/2}$ for the case of free fall of the sphere, where $g$ is the gravitational acceleration and $h$ is the initial height of the sphere. We can write the equation of the relationship between the contact time and the initial height as

$$T_c = 5.97 \frac{R}{\sqrt{h}} \left[ \frac{\rho_1 \left( \frac{1 - v_1^2}{\pi E_1} + \frac{1 - v_2^2}{\pi E_2} \right)}{\sqrt{V_0}} \right]^{2/5}.$$

(6)
In the condition of hard materials and low impact speeds, the Hertzian model is valid, because the energy dissipation is not considered in this model [23]. The Hertzian model can be applied for the computation of the study since it is a steel ball free falling on the elastic structures, and the contact time can be measured through this equation.

3. RESULTS AND DISCUSSION

3.1 Behavior under constant voltage and different frequencies

The sensor behavior under different frequencies is shown in Fig. 3. The frequencies of the output signals measured by one PVDF sensor were identical to those of the input signals of the other sensor in the frequency range of 500 Hz to 1 MHz. This means that the sensor’s properties are excellent within this frequency band. At lower frequencies, the signal noises and lags were both more disruptive. When the frequency exceeded 1 MHz, the lag increased with frequency, and the voltages detected were unstable. The reason for this is that the bond between the two sensors deteriorates when the frequencies get higher and the sensors vibrate very fast; this means that the two sensors no longer lie flat against each other, and it introduces the measured voltage instability.

3.2 Behavior under constant frequency and different voltages

Although more noise was present at the lower excitation voltages, the linear relationship between the input and output voltage signals was significant, as indicated in Fig. 4.

3.3 Optical experiments for steady-state dynamic properties of PVDF

To analyze both the electrical energy and mechanical (acoustic) energy sensing properties of PVDF, we used both a speaker and electrical voltage to excite the PVDF thin film. When the PVDF vibrated, the resonant frequencies and the corresponding mode shapes were measured. Finite element analysis was also used to predict the resonant mode shapes. The theoretical and experimental results are listed in Fig. 5. The values listed below the mode shape graphs are the resonant frequencies and the voltages used to excite the materials.

The electrical energies used to directly excite the PVDF were larger than those used to excite the PVDF via the speaker. The PVDF was more sensitive to sound waves, an important insight into the PVDF capabilities. Comparing the results from the FEM and AF-ESPI experiments, it can be seen that the mode shapes obtained through theoretical and experimental analysis were almost identical. Although not all of them were very clear, the shape structure could generally be observed. In the first, second and fifth modes, the resonant frequencies were very close under electric and acoustic excitation modes. The mode shapes at high frequencies were hard to produce compared with the piezoelectric ceramic experiments of our previous studies [19] because the PVDF membrane is very thin and soft. When bonding the PVDF thin film to the acrylic frame, the membrane boundaries were not sufficiently flat. As such, perfectly fixed boundary conditions were not easy to achieve in the experiment. Despite the mode shapes obtained from the experiment not always being clear, the coincident shapes for FEM and AF-ESPI results could be observed (Fig. 5). The second, fourth and fifth modes in Fig. 5 may be degenerate modes for the four-edge-fixed square

Figure 4 The sensor behavior under different electrical voltages.
Figure 5 The resonant mode shapes obtained using the FEM and ESPI techniques.
plate vitiation. The degenerate modes obtained in the experiment may be caused by the unstable vibration of the whole structure, the imperfect fixed boundary condition and the interaction of displacement of different modes with close frequencies. The degenerate modes can be identified by specifying the normalized boundary data at different boundary points. The detailed acoustic mode shapes of a square cavity are investigated analytically and numerically in the research of Chen et al. [24]. The singular integral equation (UT method) and the hypersingular integral equation (LM method) are used for obtaining these modes.

The second optical experiment used the LDV (AVID, Ahead Optoelectronics Inc., Chung-Ho, Taipei, Taiwan). It is a point-wise displacement measurement technique used to measure the out-of-plane vibration characteristics of the PVDF. Figure 6 shows the LDV output gain spectrum of the out-of-plane vibrations for the PVDF membrane. The horizontal axis represents the frequency and the vertical axis represents the signal gain. The first resonant frequency that is obvious to identify in this curve was 164 Hz, very close to 170 Hz, which was the lowest resonant frequency measured in the AF-ESPI experiment. Some differences were observed in the other resonant modes. As the frequency of function generator was increased to attempt to find the local maximum output voltages and verify the resonant frequencies, we find out that the frequencies are closer to those obtained by the AF-ESPI experiment than by LDV measurement. This may be due to the softness of the PVDF thin film and the imperfection of the boundary conditions in the experiment; using a point-wise laser LDV may also cause some vibrational signals of other points on the thin film sheet to be excluded. From this experiment, the full-field optical measurement technique was found to be very suitable for analyzing the vibration of piezoelectric membranes. The vibrational properties of the thin film sheet can be observed more comprehensively by the AF-ESPI technique.

Table 1 Comparison of the contact time between the Hertz contact theory and the conductivity method under different experimental conditions.

| (Diameter, initial height) | Hertz contact theory (μs) | Conductivity method (μs) | Error (%) |
|---------------------------|--------------------------|-------------------------|-----------|
| (D, H) = (3.1 mm, 30 mm)  | 14.9                     | 17                      | 14.1      |
| (D, H) = (3.1 mm, 70 mm)  | 13.7                     | 15                      | 9.5       |
| (D, H) = (6.3 mm, 30 mm)  | 30.3                     | 31                      | 2.3       |
| (D, H) = (6.3 mm, 70 mm)  | 27.8                     | 29                      | 4.3       |
| (D, H) = (9.4 mm, 30 mm)  | 45.3                     | 46                      | 1.5       |
| (D, H) = (9.4 mm, 70 mm)  | 41.6                     | 43                      | 3.4       |

3.4 Transient dynamic responses

We use the “conductivity method” to determine the contact time by dropping a steel ball on an aluminum block. The circuit will be conducted when the steel ball impacts the metal; hence, the contact time can be measured. Three steel balls with diameters of 3.1, 6.3 and 9.4 mm and two initial heights of 30 and 70 mm are considered in this experiment. The aluminum block on which the steel ball is impacted has the dimensions of 200 mm in length, 190 mm in width and 75.6 mm in thickness. Table 1 lists the contact time predicted by the Hertzian model and the experiments. The errors are <5% except for the case when the diameter of the steel ball is 3.1 mm. This error might come from the fact that the small duration of contact for the steel ball of 3.1 mm diameter makes the influences of the enamel wire under disturbance on experimental results more obvious. Since for the steel balls of other diameters the errors are acceptable (i.e. <5%), the conductivity method can still be considered reliable.

Figure 7 shows the relationship between the voltage obtained from the PVDF film and that of the impact hammer, indicating good linearity. The horizontal axis represents the maximum
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Figure 7 Calibration of the PVDF film with the impact hammer.

Figure 8 Repeatability of the impact loadings history obtained from the PVDF film when three types of loadings are generated by impact hammers: (a) Type 8204, (b) Type 8206-002 with an aluminum tip and (c) Type 8206-002 with a plastic tip.

Since the linearity of the PVDF film between its output voltage and intensity of the impact loading has been confirmed, we next detect history of the dynamic impact loadings with the PVDF film. Figure 8 shows the measuring results of the history of the impact loadings obtained from the PVDF film when loadings are generated by three types of hammers (B&K Type 8204, B&K Type 8206-002 with an aluminum tip and B&K Type 8206-002 with a plastic tip, respectively). From Fig. 8, we can see that the repeatability of the experiments is demonstrated.

Then, the duration obtained from the steel ball falling experiment based on the conductivity method is substituted in the Hertzian model and the predicted history is compared with that obtained from the PVDF film, as shown in
Fig. 9. Although the Hertzian model considers the ideal case when an elastic sphere impacts a half space, excellent agreement between the two results (i.e. the PVDF-based method and the conductivity method) can still be obtained in our experiment.

Finally, the history of impact loading on the cantilever beam is investigated. Figure 10 shows the history of the impact hammer obtained from a built-in piezoelectric force transducer in the tip of the hammer, the inverse response obtained from the top PVDF film and the response obtained from the bottom PVDF film, respectively. For the purpose of comparison, here the response obtained from the top PVDF film is inversed. It can be seen that the history of the impact loadings can be separated by performing shifting, normalization and addition operations on the signals obtained from the two PVDFs.

A steel ball with 1/8 in. diameter is freely released on the cantilever beam and at the location where the PVDF pair is bonded. The initial height of the ball is 45 mm. Figure 11 shows the repeatability of the impacts of the steel ball obtained from the transient responses of the bottom PVDF, indicating that steel balls are good sources of impact loadings.

4. CONCLUSIONS

Two experimental techniques, AF-ESPI and LDV, and one theoretical method, FEM, were applied to analyze the steady-state dynamic characteristics and sensory properties of the PDVF membrane. The resonant mode shapes observed by AF-ESPI agreed with the FEM results. The resonant frequencies obtained via AF-ESPI and LDV techniques had some matching modes.
Figure 11 Repeatability of the transient response induced by impact loadings from the steel ball.

The thinness and softness of PVDF thin films make it more difficult to conduct practical experiments when compared to the other piezoelectric materials we have studied. The difficulties of the optical experiment for the vibration of membranes are overcome in this study. The full-field mode shapes obtained using the AF-ESPI method, the finite element calculation results and LDV measurement provide a comprehensive understanding of the steady-state sensory characteristics of the PVDF. The sensing ability of impact loading history is proved through the transient dynamic experiment by using two PVDFs on the cantilever beam. The repeatability of the impacts of the steel ball on the cantilever beam is also obtained from the transient responses of the PVDF sensor. This research presents the suitable techniques for obtaining complete information for the application of PVDF in the fields of tactile sensing, wearable devices, array microphones, smart speakers and the elements for other types of intelligent systems.

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REFERENCES

1. Gerliczy G, Betz R. SOLEF® PVDF biaxially oriented piezoelectric films for transducers. Sensors and Actuators 1987;12:207–223.
2. Patterson RW, Nevill GE. The induced vibration touch sensor—a new dynamic touch sensing concept. Roboticca 1986;4:27–31.
3. Coleman AJ, Kodama T, Choi MJ, Adams T, Saunders JE. The cavitation threshold of human tissue exposed to 0.2-MHz pulsed ultrasound: preliminary measurements based on a study of clinical lithotripsy. Ultrasound in Medicine & Biology 1995;21:405–417.
4. Cleveland RO, Lifshitz DA, Connors BA, Evan AP, Willis LR, Crum LA. In vivo pressure measurements of lithotripsy shock waves in pigs. Ultrasound in Medicine & Biology 1998;24:293–306.
5. Shan Q, Dewhurst RJ, Kuhn A, Pang KF, Payne PA. Modelling of a photoacoustic probe designed for medical applications. Ultrasonics 1996;34:575–577.
6. Zahir MB, Naghshineh K, Kamman JW. Narrow band active control of sound radiated from a baffled beam using local volume displacement minimization. Applied Acoustics 2001;62:47–64.
7. Sun D, Mills JK. Control of a rotating cantilever beam using a torque actuator and a distributed piezoelectric polymer actuator. Applied Acoustics 2002;63:885–899.
8. Petijean B, Legrain I. Active control experiments for acoustic radiation reduction of a sandwich panel: feedback and feedforward investigations. Journal of Sound and Vibration 1990;252:19–36.
9. Mao Q, Xu B, Jiang Z, Gu J. A piezoelectric array for sensing radiation modes. Applied Acoustics 2003;64:669–680.
10. Park JM, Kong JW, Kim DS, Yoon DJ. Nondestructive damage detection and interfacial evaluation of single-fibers/epoxy composites using PZT, PVDF and P(VDF-TrFE) copolymer sensors. Composites Science and Technology 2005;65:241–256.
11. Blum J, Giovane F, Tuzzolino AJ, McKibben RB, Corsaro R. The large-area dust detection array (LADDA). Advances in Space Research 2003;31:307–312.
12. Qi B, Kong Q, Qian H, Patil D, Lim I, Li M, Liu D, Song G. Study of impact damage in PVA-ECC beam under low-velocity impact loading using piezoceramic transducers and PVDF thin-film transducers. Sensors 2018;18:671.
13. Seminara L. Modeling electronic skin response to normal distributed force. Sensors 2018;18:459.
14. Wang X, Sun F, Yin G, Wang Y, Liu B, Dong M. Tactile-sensing based on flexible PVDF nanofibers via electrospinning: a review. Sensors 2018;18:330.
15. Ma CC, Huang YH, Pan SY. Investigation of the transient behavior of a cantilever beam using PVDF sensors. Sensors 2012;12:2088–2117.
16. Chuang KC, Ma CC, Chang CK. Determination of dynamic history of impact loadings using polyvinylidene fluoride (PVDF) films. Experimental Mechanics 2014;54:483–488.
17. Chuang KC, Huang KC, Liou HC, Ma CC. Investigation of transient behavior of a cantilever plate based on elastic loading history detection using polyvinylidene fluoride film sensors. IEEE Sensors Journal 2016;16:1565–1574.
18. Chuang KC, Ma CC, Wang CY. The measurement of dynamic strain and resonant frequency for three-dimensional solids partially immersed in water using free-edge bonded fiber Bragg grating sensors. Sensors and Actuators A 2016;247:65–74.
19. Ma CC, Huang CH. The investigation of three-dimensional vibration for piezoelectric rectangular parallelepipeds using the AF-ESPI method. IEEE Trans Ultrason FerroelectrFreq Control 2001;48:142–153.

20. Goldsmith W. Impact: The Theory and Physical Behavior of Colliding Solids. London: Edward Arnold, Ltd, 1960.

21. Sun CT, Yang SH. Contact Law and Impact Responses of Laminated Composites. NASA CR-159884. Washington, DC: NASA, 1980.

22. Hunter SC. Energy absorbed by elastic waves during impact. Journal of the Mechanics and Physics of Solids 1957;5:162–171.

23. Gilardi G, Sharf I. Literature survey of contact dynamics modeling. Mechanism and Machine Theory 2002;37:1213–1239.

24. Chen JT, Chen KH, Chyuan SW. Numerical experiments for acoustic modes of a square cavity using the dual BEM. Applied Acoustics 1999;57:293–325.