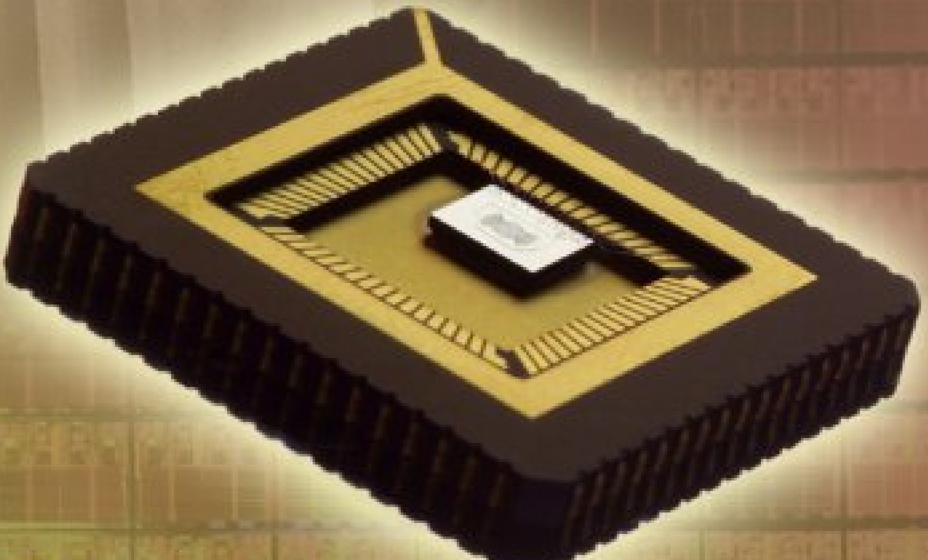
ISSN 1726-5479

SENSORS & TRANSDUCERS

vol. 127
4/11



MEMS and Modern Technologies

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 127, Issue 4, April 2011 **www.sensorsportal.com** **ISSN 1726-5479**

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).

Sensors & Transducers Journal

Contents

Volume 127
Issue 4
April 2011

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com
Please visit journal's webpage with preparation instructions: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm

Sensors & Transducers Journal, Vol. 127, Issue 4, April 2011, pp. 45-55

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Inspection of Pipe Inner Surface using Advanced Pipe Crawler Robot with PVDF Sensor based Rotating Probe

[1]Vimal AGARWAL, [2]HARUTOSHI Ogai, [2]KENTAROU Nishijima and [3]Bishakh BHATTACHARYA

[1] System Engineer, Infosys Technologies Limited, Bangalore, India
Tel.: +91-9620770832
[2]Department of Mechanical Engineering, Indian Institute of Technology Kanpur, India-208016
Tel.: +91-0512-2597824
[3] Graduate school of Information, Production and Systems, Waseda University,
2-7 Hibikino, Wakamatsu-Ku, Kitakyushu-shi, Fukuoka, Japan
Tel.: +81-93-692-5147
E-mail: vimal_agarwal01@infosys.com, ogai@waseda.jp, kentaronishijima@fuji.waseda.jp, bishakh@iitk.ac.in

Received: 18 March 2011 /Accepted: 22 April 2011 /Published: 30 April 2011

Abstract: Due to corrosive environment, pipes used for transportation of water and gas at the plants often get damaged. Defects caused by corrosion and cracking may cause serious accidents like leakage, fire and blasts. It also reduces the life of the transportation system substantially. In order to inspect such defects, a Polyvinyledene Fluoride (PVDF) based cantilever smart probe is developed to scan the surface quality of the pipes. The smart probe, during rotation, touches the inner surface of the pipe and experience a broad-band excitation in the absence of surface features. On the other hand, whenever the probe comes across any surface projection, there is a change in vibration pattern of the probe, which causes a high voltage peak/pulse. Such peaks/pulses could give useful information about the location and nature of a defect. Experiments are carried out on different patterns, sizes and shapes of surface projections artificially constructed inside the pipe. The sensor system has reliably predicted the presence and distribution of projections in every case. It is envisaged that the new sensing system could be used effectively for pipe health monitoring. *Copyright © 2011 IFSA.*

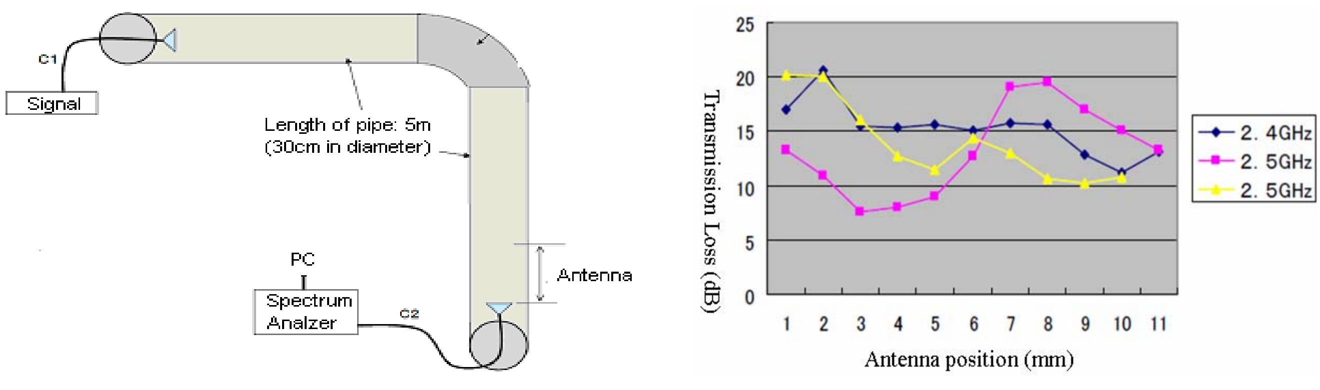
Keywords: Pipeline inspection robot, Smart sensors, PVDF, Structural health monitoring, Wireless signal transmission.

---

1. Introduction

Very often, it is necessary to monitor the surface roughness of the pipes which transport water and gas for cracks, obstructive growths as well as shape deformation on a regular basis to forestall any accident. In cylindrical pipes, traditionally, the surface integrity is checked either manually or by using laser probes [1]. While the manual inspection relies heavily on human skill, the laser sensing system is quite expensive. Hence, it is convenient and economic to have a setup that can move inside the pipe and make such inspection automatically by using a rotating probe. Crawler robots are being developed for pipe –health monitoring, but most of them rely on wired signal transmission which causes problems with the movement of the robot inside the pipe. Dongmei Wu *et al*. [2] have proposed an inspection robot using a wireless radio communication system useful for long complex pipes. The communication properties of radio signals inside pipes of diameter 30 cm and length 10 cm was measured using such device.(see Fig. 1-a).

A wireless radio signal from the steel pipe inlet was emitted and it was measured in the steel pipe outlet as shown in Fig. 1. The Radio signal at different antenna positions was measured. The transmission loss from transmitting antenna input to the corresponding receiving antenna output was 14±6 dB in 2.4 GHz band. Typical output corresponding to different band and position of antenna are shown in Fig. 1-b.



(a) (b)

Fig. 1. (a) Transmission test in steel pipe; (b**)** Measurement result in steel pipe.

The experiments have proved that signals could be transmitted well in steel pipes within 100 m. The objective of this paper is to establish the usability of a new PVDF based cantilever smart probe as a sensor to sense finite sized discontinuities over a surface using the above mentioned inspection robot [2]. This is done by conducting a series of experiments by testing the beam against surfaces with known projections and studying whether any meaningful results are obtained. The probes are made up of spring steel and used in cantilever mode. A PVDF patch is bonded to the cantilever for sensing vibration of the cantilever. The rotating probe is attached with the robot and rotated by a motor as shown in Fig. 4. Whenever the system touches the defected area, the PVDF film could detect the presence of defect due to the change in dynamic strain. This strain change of the PVDF film can be measured as voltage change. Thus, the feature of the defect can be predicted by observing the voltage peak/pulse.

2. Previous Work

The idea of using cantilever beam for surface roughness measurement is already in use in atomic force microscopes, at a very high precision level. In these systems, deflection is measured by the reflection of a laser ray off the beam, falling on a photodiode. Beaulieu *et al.* [3] have analyzed such laser beam deflection based systems used with cantilever probes. It is apparent and is also suggested by them that in addition to the point at which the laser beam hits the cantilever, the slope also has to be taken into consideration to determine the position where the ray gets reflected to. The slope of the cantilever varies with position and as deflection changes, the point of reflection shift. However, with proper choice of different parameters, it is possible to obtain a near linear relationship between Photo Sensitive Diode signal and the actual deflection of the cantilever. Work has been done in determining the sensitivity of a cantilever depending upon its length, stiffness of the contact surface and the shape of the cantilever [4]. Stiffness of the contact surface plays an important role in determining the sensitivity of the beam with respect to its shape. Two shapes of the beam were considered straight (uniform) and "V" shaped. However, it was observed that for stiff materials, response of both the shapes tends to converge. The beam deflection considered is quasi static in nature.

It is frequently observed that when a string/beam is oscillating, the vibrating parts are seen blurred. This motion blur is highest near the antinodes and decreases as we approach the nodes. This phenomenon is studied analytically by Slangen *et al.* [5]. When coherent light falls on an optically rough surface, the grainy aspect detected is known as the speckle of the surface. The size of the speckle depends on the focal length and the aperture diameter of the optical system, Speckle interferometry is used to detect and measure such vibration mode shapes. Another technique of measuring deflection of cantilever using optical method is developed by Wong [6]. He has used a CCD camera instead of simple Photo sensitive strip. The lens of the camera is focused at a plane behind the reflecting surface and the change in intensity of the light reflected on the camera is recorded to measure surface roughness. Once the sensing is carried out, it is required to transfer the signals to the analyzer. Use of onboard data recorder like EPROM is used as one of the options [7]. After the completion of scanning, the chip is removed and the data can be retrieved using a decoder.

3. Properties and Function of PVDF

Shirinov *et al.* [8] report PVDF as low cost polymer pressure sensor. The output signal is of the order of few volts and the circuit required for signal detection is fairly simple. The measurement accuracy is usually limited by environmental conditions like temperature and humidity, as well as internal variations like pyroelectric effects and creep. Creep however can be taken care of by pre-stressing the composite in which the sensor is embedded. And if the environment is controlled, other variations can be neglected. PVDF thus forms a good pressure sensor. Piezo film sensors are usually supplied in the form of thin-film, typically ranging from 9 to 110 µm thicknesses. Due to the small cross-sectional area, a small load applied longitudinally along the plane of the film results in a very large axial stress in the film.

The electrical charge that is generated in the PVDF strip is proportional to the change in the mechanical stress [9]. If the sensor is bonded to the structure then the sensor output is proportional to changes in surface displacement. Hence this material can be used to detect variations in structural systems. Hua *et al.* [10] have discussed why PVDF film is better than other conventional health monitoring sensors like strain gauge, linear variable differential transducers (LVDT) and clip gauge from the point of view of external power supply.

The output response of the PVDF is proportional to the rate of change of the strain. The PVDF output voltage, V_s (t) can be written as [11].

$$V_s(t) = G\frac{dQ(t)}{dt} = G\{K_S\}^T\{\dot{X}\}, \quad (1)$$

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

The constitutive equation suggests the possibility of obtaining the measurement of the strain rate of the PVDF attached to the surface of the vibrating cantilever structure by simply measuring the voltage output of the PVDF film. The charge generated by PVDF is converted to voltage by a charge amplifier whose details are given in Section 5.

4. Details of Pipe Crawler Vehicle

A pipe crawler vehicle as shown in Fig. 2 is designed with the specifications provided in Table 1.

Table 1. Specifications of the Pipe Crawler vehicle.

Parameters	Values
Size	Length: 370 mm, Width: 180 mm, Height: 160
Working speed	13.7 m/min
Driveling mode	Double Motor
Electric Power	Rechargeable Batteries 7.2 V
Wireless Frequency	Apply to 2.4/5 GHz and Data Transmission

The vehicle is based on belt –driven translation mechanism. There are three basic elements in the vehicle .The front section carries the payload like camera, obstacle avoidance system etc. The central position drives the system as well as contains the processing unit containing microcontroller unit, wireless module and motor drivers. The end part contains four rotating probes of spring steel with embedded PVDF sensor.

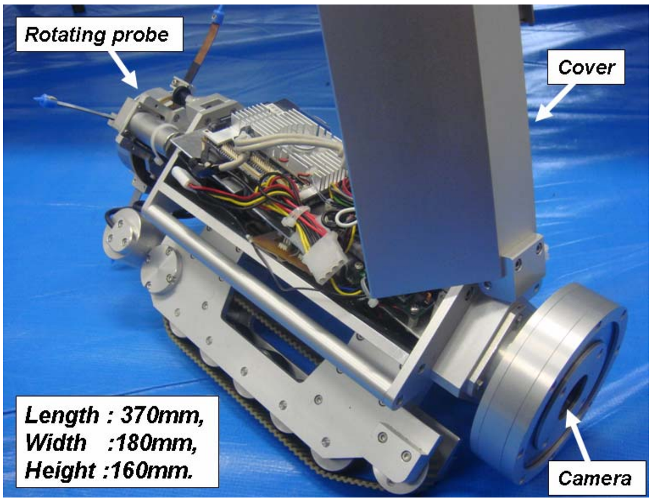


Fig. 2. Design of Pipe Crawler Robot**.**

The probe is positioned at the back of the robot. The rotating probe consisted of cantilever beam and PVDF film is fixed on the probe for the sensing as shown in Fig. 3. To control the cable of the rotating probe, a slip ring is used. The movement of the rotating probe is explained in the following section.

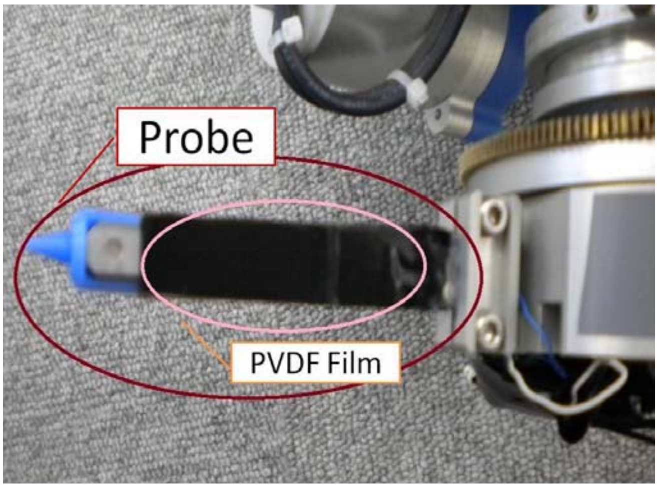


Fig. 3. Rotating probe with PVDF sensor.

4.1. Movement of the Rotating Probe

During tests, radius of the scanning tip is kept slightly less than that of the actual base radius of the tube. Therefore, the beam does not slip over the base surface. Whenever an obstacle comes in the way, the beam hits it, and starts bending, rubs over it and finally shoots out. The following series of figures (Figs.4 & 5.) give an idea as to how this process takes place.

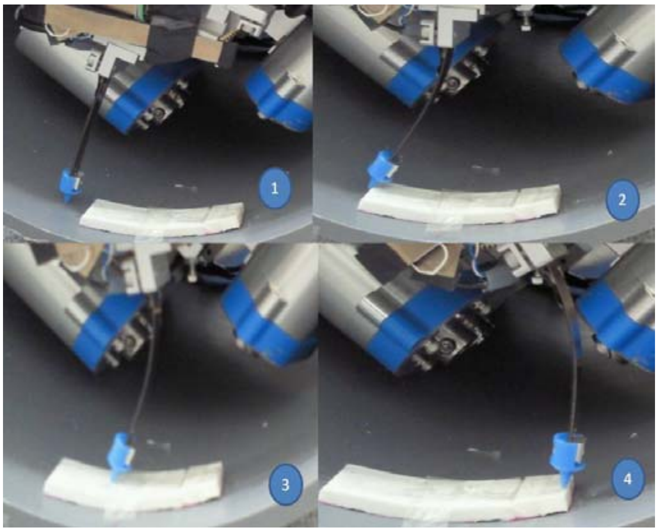


Fig. 4. Sequence of steps showing the beam going past a typical obstacle. (1) Free beam approaching defect of width 70 mm; (2) Beam starting to touch the defect; (3) Beam rubbing over the defect; (4) Beam about to shoot off.

The angular velocity of the stepper motor determines the rate at which the probe runs across the surface. Variation in the rate of scanning plays an important role when the strain is sensed by piezoelectric materials. Unlike strain gauges, piezoelectric materials are dynamic in nature i.e. the rate at which they are strained strongly affects the nature and quality of signal that they produce. In the simplest form, a piezowafer may be compared to a capacitor that displaces charge upon actuation. Hence, faster/stronger actuation causes it to displace more charge and thus generate a stronger signal and vice-versa. However , the angular velocity of the stepper motor should not be very high otherwise it will not rub the surface of the defect.

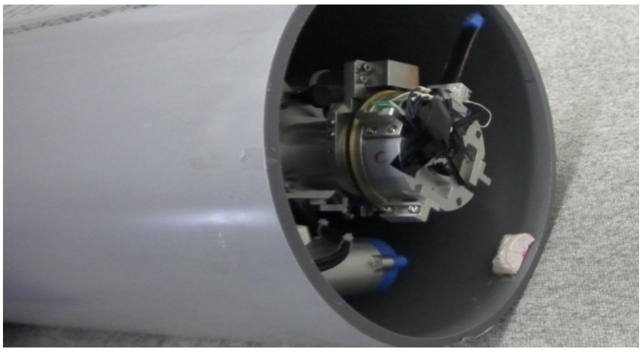


Fig. 5. Test in PVC pipe of diameter 25 cm.

5. Rotating Probe in a PVC Pipe

PVDF generates a charge in response to a stress which can be converted to voltage and then amplified. PVDF generates an output in the range of pico coulombs with very high impedance. It needs to be transformed into a low impedance voltage signal, for processing the signal by standard measuring equipment. Charge amplifier is designed and implemented for this purpose.

To amplify the small voltage signal obtained by the charge amplifier we have used an amplifier, AD8607A, with a gain of 100. The voltage output of the PVDF is captured into the microcomputer by A/D converter. The main computer of the robot reads the data through serial transmission using an RS-232 cable. The sampling cycle of the A/D converter is 0.01 seconds. The set of experiments are performed to check the response of the PVDF film when the probe collides with the obstacles.

6. Experiments

All the experiments are performed on resting robot in a clean vinyl chloride pipe of 250 mm diameter, as shown in Fig. 5. To imitate hollow cylindrical tubes with growths, inside the cylinder, pieces of the rubber was fixed to create artificial projections**.** Experiments were performed with the setup as shown in Fig. 6. The height, width, and separation between projections are represented as h, b_p, and p_p respectively.

The response of the sensor when it is subjected to a projection of width 10 mm and height 3 mm, 6 mm and 10 mm respectively are shown in Fig 7-a,b and c.

The probe first touches the projection, then it bends, due to this bending which is shown in step 2 of Fig. 3; strain is developed in the probe. The PVDF sensor fixed on the probe senses this strain and gives voltage corresponding to the rate of change of strain, which is very high at the instant when the probe first touches the defect and thus a peak is observed in all the three experiments. After the impact it rubs the width of the defect and finally shoots out showing free vibrational response. When the probe touches the surface of projection (bp), there is less voltage recorded. This is due to the fact that during that time there is less rate of change of strain developed on the probe because the bending of probe almost remains the same when the probe first touched the surface of projection (shown in step 3 and 4 of Fig. 4). In all the three cases there is damping effect of vibration, this occurs when the probe shoot outs of the projection.

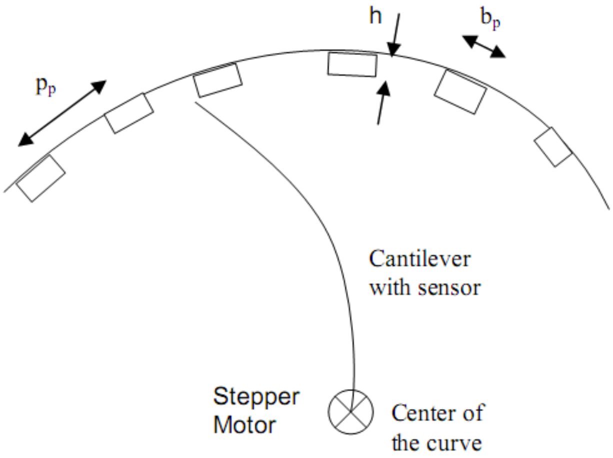
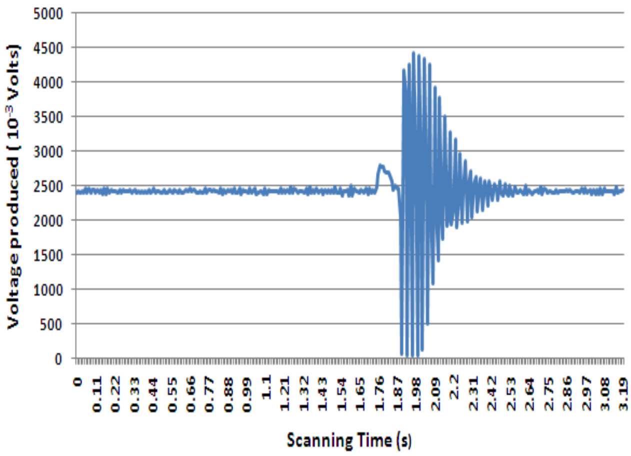
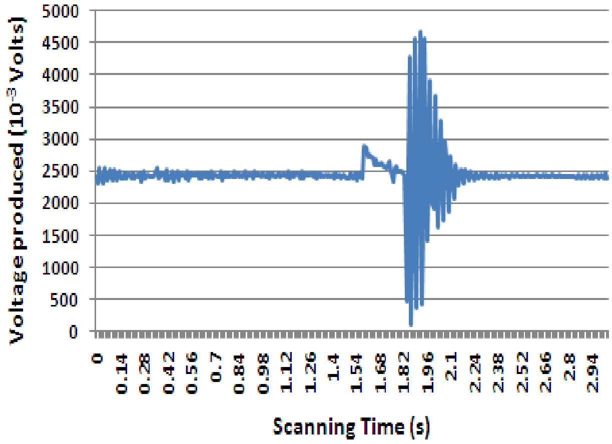


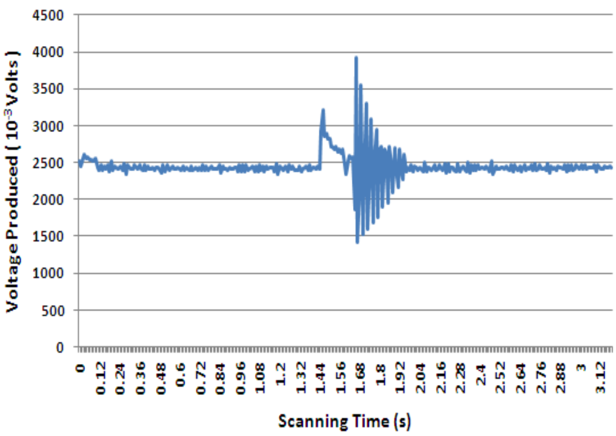
Fig. 6. A schematic of the moving cantilever probe against the obstruction.



(a)



(b)



(c)

Fig. 7. Graph between voltage Vs. Scanning time for a projection of width 10 mm and height (a) 3mm; (b) 6mm; (c) 10mm.

It is observed that the voltage recorded at the instant when the probe first touches the defect is the highest at 10mm height. This is due to the reason that higher projection caused greater bending of probe and thus a higher initial strain is developed and due to that a high voltage is recorded. The vibration effect is the

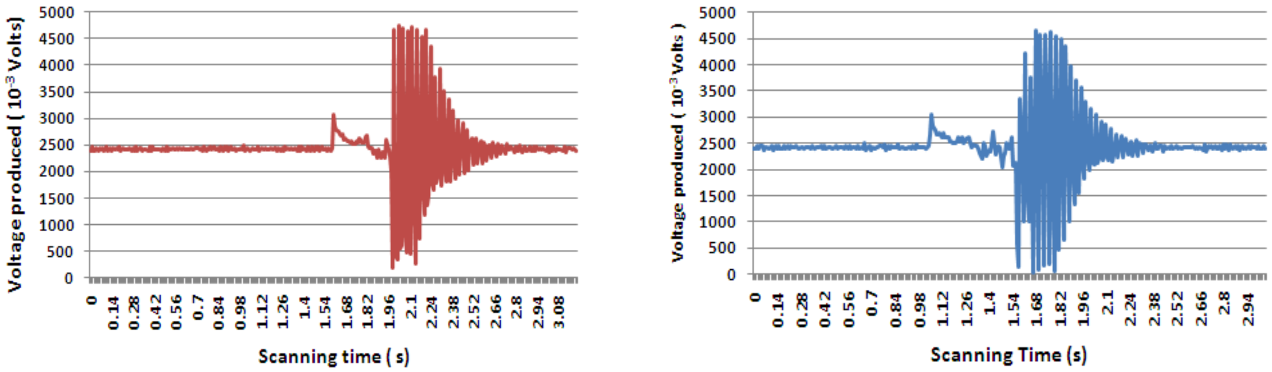
highest in the case of 3mm projection because the higher height of the projection reduced the speed of the probe and thus after shooting off from the projection, it vibrates with less intensity.

The peak voltage recorded for different height projections is provided in Table 2.

Table 2. Peak voltage value corresponding to height of projection for a constant width of projection as 10 mm.

Height of Projection(in mm)	**Peak Output Voltage(in mV)**
3	2800
6	2873
10	3205

The response of the PVDF sensor when the probe rubs with projections of width 30 mm and 50 mm are shown in Figs.8-a and b. The height for both projections was kept constant as 10 mm**.**



(a) (b)

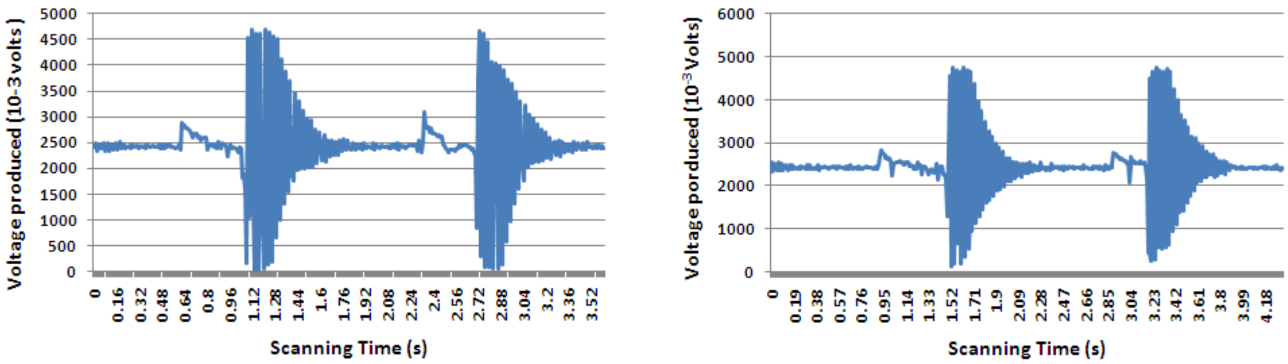
Fig. 8. Plot of Voltage vs. Scanning Time for projection of height 10 mm and (a) width 30 mm; (b) width 50 mm.

The change in width of the defect can be observed by observing the time elapsed between the instant when the first peak in voltage signal is recorded and the instant when the vibration effect starts. During that time duration, the probe rubbed the width of the projection. The recorded time instants of position when the first rise in voltage is observed (T_1) and start of vibration effect (T_2) are shown in Table 3. The difference of T_2 and T_1 is the time during which the probe rubbed the width of the projection and is denoted as T_3.

The response of the probe when it is subjected to two projections in a rotation is studied next. Fig. 9-a presents the voltage produced by PVDF vs. Scanning time for two projection of height 5 mm and 10 mm, width same as 50 mm. Fig. 19-b presents the voltage output for width 50 mm and 30 mm, for a common height of 10 mm.

Table 3. Recorded time instants corresponding to width of projection for a constant height of projection as 10 mm.

Width(mm)	**T_1(in sec)**	**T_2(in sec)**	**T_3 (in sec)**
10	1.45	1.56	0.11
30	1.60	1.99	0.39
50	1.06	1.55	0.49



(a) (b)

Fig. 9. (a) Voltage output for two projection of height 5 mm and 10 mm, width same as 50 mm; (b) Voltage output for two projection of width 50 mm and 10 mm, height same as 10 mm.

Fig. 10 presents the results of the PVDF sensor output when successively five projections of height 10 mm and width 10 mm were uniformly placed on the circumference of the pipe.

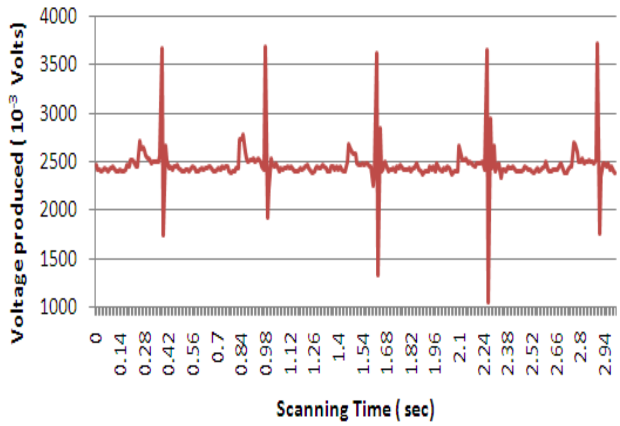


Fig. 10. Voltage output for five projections each of height 10 mm and width 10 mm.

It is observed from the Fig. 9-a that peak voltage due to defect of height 10 mm is greater than the defect of height 5 mm. This suggests that the height of the projection can be estimated by observing the peak voltage of the scanning results. In Fig. 9-b, it is shown that for the same height, when the width is increased, there is a time elapsed between the voltage peak observed due to bending and start of the vibration effect. This experiment suggests that the width of the projection can be estimated by observing this time elapsed. In Fig. 10, there is a pattern that repeats 5 times, this is because of the five projections on the surface of the pipe. The peaks are uniform as the projections were created at a uniform distance.

The response of the PVDF sensor is checked when it is subjected to projection of semicircle and triangular geometry. Fig. 11 shows the bending of probe for these experiments. Fig. 12-a presents the results of scanning with a projection of semicircle geometry with diameter 30 mm and Fig. 12-b presents for Equilateral triangle with side of 20 mm.

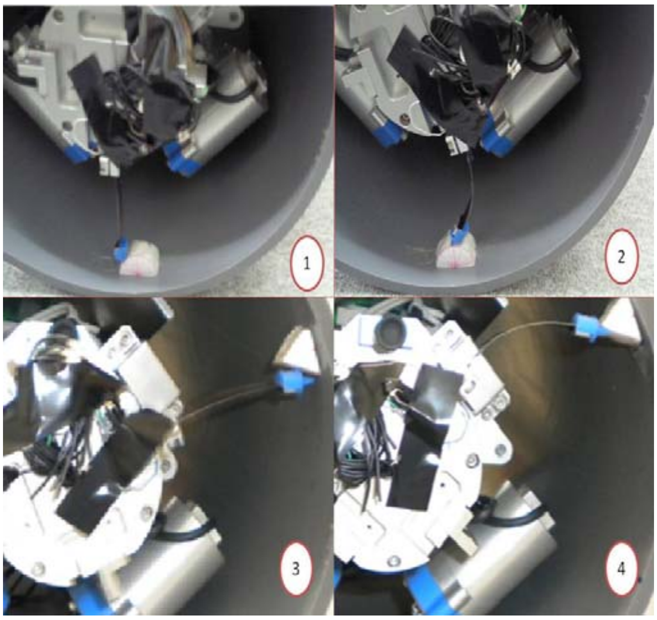
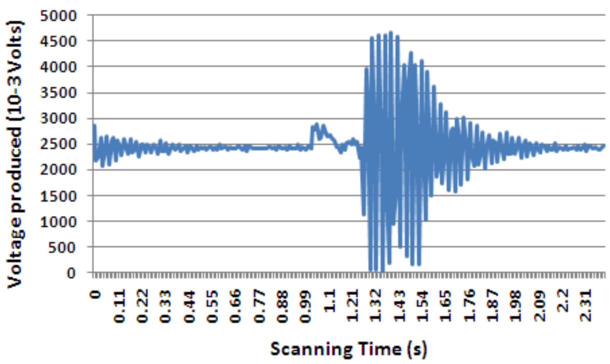
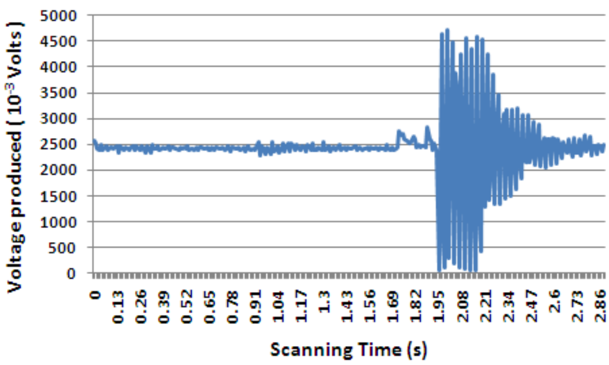


Fig. 11. (1) Probe touching the semicircle type projection; (2) Probe ready to shoot off from top of projection; (3) Probe touching the triangle type projection; (4) Probe ready to shoot off from top of projection.



(a)



(b)

Fig. 12. (a) Voltage output for projection of semicircle geometry of diameter 30 mm; (b) Voltage output for projection of Equilateral triangle with side of 20 mm.

Results shown in Fig. 13-a, b are pointing towards the property of PVDF sensor that it gives voltage proportional to rate of change of strain. When the probe rubbed the surface of a semicircle, due to change in surface, the probe experienced different bending and thus different strain and thus a plateau kind of structure is obtained before the vibration effect starts. In Fig. 13-b, when the probe rubbed the height of projection of triangle a voltage is produced at the very instant. Two peaks are observed before the vibration. The first one is obtained when the probe touched the projection for the first time and the other when the probe touched the top of the projection.

7. Conclusion

The present work provides a useful insight as to how, without using very sophisticated setups, a simple rotating probe with a PVDF film patch can be used as a fairly good sensor to sense finite sized projections in a pipe. The width, height and spacing of such projections are reliably predicted by the touch sensor. Further experiments can be carried out to check the response of the PVDF sensor with different angular speeds of the probe. The voltage obtained by PVDF sensor can also be calibrated in term of degree of roughness.

References

[1]. Duran, O., Altheofer K., Seneviratne L. D., Laser Profiler model for robot based pipe inspection, *Automation Congress*, June 2009, pp. 353-358.
[2]. Dongmei, W., Harutoshi, O., Yichun, Y., Katsumi, H., Takahiko, A. and Gunkichi, S., Pipe inspection robot using a wireless communication system, *Artificial Life Robotics*, Vol. 14, 2009, pp. 154–159.
[3]. Beaulieu, L., Godin, M., Laroche, O., Tabard-Cossa, V. and Grutter, P., A complete analysis of the laser beam deflection systems used in cantilever-based systems, *Ultramicroscopy*, Vol. 107, Issues 4-5, April-May 2007.
[4]. Haw-Long, L., Win-Jin, C. and Yu-Ching, Y., Flexural sensitivity of a V-shaped cantilever of an atomic force microscope, *Materials Chemistry and Physics*, Vol. 92, Issues 2-3, 2007, pp. 438-442.
[5]. Slangen, P., Leon, B., Christophede, V., Jean-Claude, G. and Yves, L., Digital Speckle Pattern Interferometry (DSPI) A Fast Procedure to Detect and Measure Vibration Mode Shapes, *Optics and Lasers in Engineering*, Vol. 25, Issues 4-5, 1996, pp. 311-321.
[6]. Wai-On, W., Vibration Analysis by Laser Speckle Correlation, *Optics and Lasers in Engineering*, Vol. 28, Issue 4, 1997, pp. 277-286.
[7]. Franco, R. A. and Ingram, K. J., A Very High Shock Data Recorder, *IEEE Transactions of the Southeastcon*, Vol. 1, 1991.
[8]. Shirinov, A. V. and Schomburg, W. K., Pressure sensor from a PVDF film, *Sensors and Actuators: A Physical*, Vol. 142, Issue 1, 2008, pp. 48-55.
[9]. Roger, V. and Stephen, C. G., Use of PVDF Strain Sensors for Health Monitoring of Bonded Composite Patches, *DSTO Aeronautical and Maritime Research Laboratory*.
[10].Gu, H., Zhao, Y. and Wang, M. L., A wireless smart PVDF sensor for structural health monitoring, *Structural control and Health Monitoring*, Vol. 12, 2005, pp. 329–343.
[11].Kuang, K. S. C., Quek, S. T., and Cantwell, W. J., Use of polymer-based sensors form monitoring the static and dynamic response of a cantilever composite beam, *Journal of Material Sciences*, Vol. 39, 2004, pp. 3839–3843.

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

Advertising Information

Advertising orders and enquires may be sent to sales@sensorsportal.com Please download also our media kit: http://www.sensorsportal.com/DOWNLOADS/Media_Kit_2011.pdf