Typical Properties and Specific Applications of Piezoelectric Polymer

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Abstract: Piezoelectric materials have been an area of focus for developing sensors and actuators for almost a century. Polyvinylidene Fluoride (PVDF) is a ferroelectric fluoro-polymer with excellent piezoelectric as well as pyroelectric properties. It has been in use for various applications demanding flexibility and good chemical resistance. These properties make it extremely well suited for the aerospace and automotive industry, in areas of Non-destructive testing, vibration control, sensing material in strain rosettes, to name a few. Apart from these PVDF is widely accepted in medical applications and in distance ranging applications. But, there are certain areas where PVDF has unique advantage over other materials. This paper is an attempt to compile such unique properties of PVDF, from literature, at one place while discussing the typical applications of PVDF.

Key words: PVDF, Piezoelectric, pyroelectric, applications.

1. Introduction

Polyvinylidene Fluoride (PVDF) is an Electro-active fluoro-polymer exhibiting wide variety of characteristic mechanical and electric properties, such as piezoelectricity (the largest among the synthetic polymers), pyroelectricity, nonlinear optical property etc. It has excellent chemical resistance and solvent resistance, high abrasion resistance, high dirt shedding, low flame and smoke characteristics, low permeation to most gases and fluids (extremely important for mil-grade Micro Electro Mechanical Systems (MEMS) applications), high dielectric strength & volume resistivity, high thermal stability, resistant to gamma and e-beam radiation, high mechanical strength at elevated temperatures. It is readily processable, formable and weldable, superior melt processing characteristics. Their melt processibility along with other exceptional properties enables the polymer to stand apart from its counterparts.

These properties make PVDF highly adaptable for applications in a wide range of industries, spanning aerospace, automotive, civil engineering, bio-medical and healthcare. They are extensively used in structural health monitoring systems, vibration and noise control, distance ranging and navigation, security systems. In all these systems, PVDF predominantly plays role of sensor and/or actuator. Apart from these, PVDF also plays role as the electrolyte in polymer fuel cells, insulation of the electrical harness, micromanipulators and high-energy storage devices. The five most frequently described areas of application of PVDF are- as actuators, for vibration control, in medical ultrasound, as single-element pyroelectric infrared sensors, and in strain and acceleration measurement devices. Fig. 1 indicates the approximate distribution of papers published on various applications.

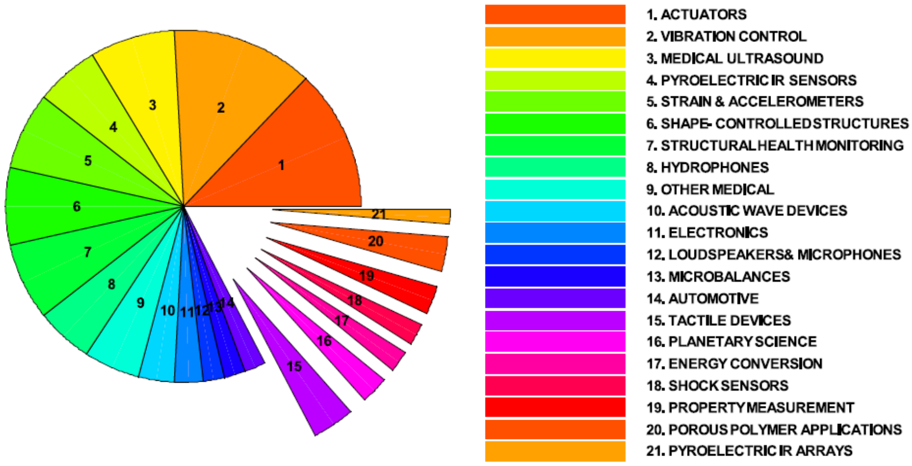

Fig. 1. The approximate distribution of papers published on various applications, Adapted from Lang [1]

This paper is an attempt to discuss certain typical applications of PVDF, appropriately highlighting the unique advantage of using PVDF in these cases, as a preferred material for the application.

2. Typical Properties of PVDF

PVDF is a typical member of the family of alkenes exhibiting high piezoelectric properties. The high piezoelectric properties are due to the presence of highly electronegative fluorine atoms. The high piezoelectric properties of PVDF were first reported in the year 1969 by Kawai [2]. Unlike the commonly available piezoelectric materials like barium titanate and PZT (Lead zirconate titanate) which are brittle, PVDF was found to be flexible, non-toxic and readily formable at a low cost.

A typical advantage of its flexibility can be witnessed in structural health monitoring applications. The previously available methods such as LVDT (Linear Variable Differential Transformers) etc. are not flexible [3]. Many of the parts had to be removed from the installed system for crack evaluation. But PVDF on the other hand, being flexible and conformable to any shape and size, can be used for real time health monitoring. Also unlike PZT which detects only A0 mode waves PVDF film can detect both S0 (in-plane plate deformations) as well as A0 (flexural waves) lamb waves [4].

In case of endoscopic applications, previously PZT probes were used [5-8]. But they are not only brittle but are also toxic in nature due to the presence of heavy metals like lead. There PVDF can replacing as the newer choice of material [9, 10]. The added advantage of PVDF over other flexible piezoelectric material is that it is non-toxic. It has been in use in the food industry for determination of food spoilage [11]. Thus, the material is accepted and tested for non-toxicity on contact with humans.

PVDF can be prepared into films (thick or thin), needles, tubes, fibers, paints, probes, coating on substrates and coating on a Carbon Nano Tube (CNT) (for optical applications) or formed into a sensor package itself. Thus, based on the application and space available, PVDF can be fabricated into various shapes and sizes. Also, despite the advancement in technology for ceramic fabrication such as bulk micro-machining, laser machining, lost mold techniques and freeform fabrication, the process continues to be extremely costly. Par contra, PVDF can be fabricated at a low cost. Thus, in applications demanding a disposable sensor, PVDF is predominantly used. Additionally, PVDF can be used for sensing over a localized as well as a large area.

PVDF transmitters exhibit Omni-directional horizontal beam directivity and broad band characteristics. These characteristics lend unique solutions in many applications such as two-dimensional positioning, digitizer, object detection, and distance measurement. The rising time and the signal decay time are much faster than the conventional ceramic transmitters. This characteristic makes it suitable for high speed data acquisition or high speed digitizer applications.

PZT has high acoustic impedance and necessitates a use of matching layer. On the contrary, PVDF has low acoustic impedance with value matching the human tissue and water. This makes it suitable for applications involving humans and underwater applications.

Visible light and near IR radiation are not absorbed and therefore cannot give rise to any sort of disturbances. The film is additionally protected from moisture, which could otherwise reduce the high impedance output signal. PVDF has a high creep strength, low moisture absorption (<0.02%), abrasive resistance and resistance to harsh environments. PVDF is totally resistance to sunlight degradation. PVDF is unaffected by ultra violet (UV) radiation and, consequently, can be used outdoors without need to specially pigment or otherwise protect the material (In use by National Aeronautics and Space Administration (NASA) for cosmic dust particle detection and allied studies). PVDF being an excellent insulator with strong inertness to environment is extensively used for insulation of the electrical harness.

The impedance spectra of PVDF indicate no spurious modes over a wide range of frequency. Thus, it can be also used in fiber form for various data and signal transfer with very little loss. These probes can also be developed as sensors for energy measurements of optical radiation.

PVDF doped with PANI (Polyaniline) can provide flexible conducting polymers with application in high-energy storage density devices. These conducting polymers can as well be used for wide range of roles in actuators dedicated to manipulation applications, especially for micro fluidic applications and 'lab on chip' devices.

Thus, we have a flexible material with excellent chemical resistance and solvent resistance, high abrasion resistance, high dirt shedding, low flame and smoke characteristics, low permeation to most gases and fluids (extremely relevant for mil-grade MEMS applications) along with having dielectric strength & volume resistivity, high thermal stability, resistant to gamma and e-beam radiation, high mechanical strength at elevated temperatures, readily processable, formable and weldable, superior melt processing characteristics, which can be used for developing sensors of the following types- impedance type sensors, semiconductor device based type sensors, resonant sensors, calorimetric sensors, fibre optic sensors (optrode-style, core-based, coating-based or interferometric) apart from applications in electrochemical cells, fuel cells. Many of these applications enlisted above are feasible by only PVDF (as a piezoelectric material) due to their inherent flexibility apart from other properties.

2.1. PVDF Actuator Configured for Sound Radiation Control-Smart Foam

Porous sound absorbing materials find use in buildings, machinery enclosures, aircrafts etc. to reduce the structural sound radiation. It is impractical to rely completely on passive damping, especially at low frequencies. Gentry et al. [12] developed the smart foam (Fig. 2(a)), which is a compact arrangement consisting of cylindrically curved sections of PVDF film embedded in partially reticulated polyurethane acoustic foam. The PVDF actuator is configured to behave in a linear sense and to couple in-plane strain associated with piezoelectric effect with out-of-plane motion needed to radiate sound from the foam surface. Thus, the PVDF acts as an active element (effective at low frequencies) while the foam acts as a passive element (effective at high frequencies) to reduce the sound by simultaneous absorption. It is significantly different from common ASAC (Active Structural Acoustic Control) and even the ANC (Active Noise Control) techniques that use secondary acoustic sources (loud speakers) in arrays around the primary noise source because the smart foam is actually located on the surface of the vibrating structure.

Partially reticulated polyurethane foam is an acoustical grade, open cell, flexible ester based urethane foam designed to give maximum sound absorption per given thickness [13]. The curvature of the half-cylinder configuration was determined by a simple analytical model and was intended to couple the predominantly in-plane strain associated with the piezoelectric effect and the out-of-plane motion, which is required to accelerate fluid particles and hence radiate sound away from the surface of the foam.

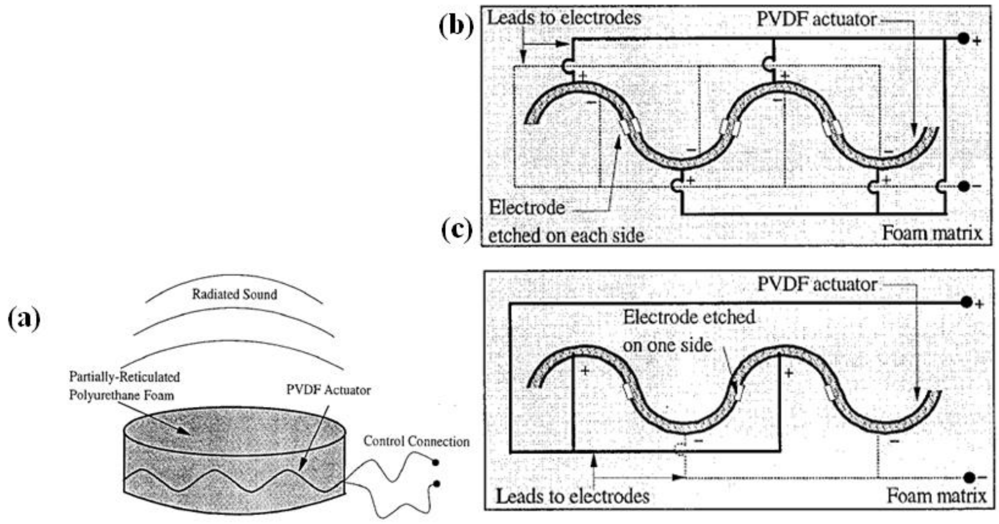

Fig. 2. (a) Smart foam; PVDF actuator configurations (b) Parallel; (c) Series-parallel

The silver electrode on the film is chemically etched to remove or erase thin portions of electrode at points where the physical polarity (curvature) of the actuator changes [14], to overcome the undesirable nonlinear dynamic behaviour appearing in the form of higher-order harmonic distortion in the acoustic frequency response spectrum. In the parallel actuator arrangement, the top and bottom electrodes are connected in parallel with phase reversal, as shown in Fig. 2(b). Therefore, the PVDF film is activated such that neighbouring cells are driven by the same voltage amplitude with a 180° phase difference leading each cell to move in the same out-of-plane direction yielding net volumetric source strength. In the series parallel actuator configuration, shown in Fig. 2(c), only the bottom electrode is divided into independent transducers, which are then wired 180° out of phase. This arrangement also results in a more efficient radiator as compared to the configuration of flat PVDF film as the entire film is moving in the out-of-plane direction. The PVDF actuator was configured to behave in a linear sense as well as to increase its sound radiation efficiency. PVDF in all these three circuit configurations was tested in an anechoic chamber for successful attenuation of low- and high-frequency sound, passive effect of foam and active-passive broadband control, harmonic distortion and linearization by varying the resonant frequency as well as the input voltage to the signal generator.

PVDF due to its high sensitivity, flexibility, wide band operation and resistance to environment was adaptable for this application. The application is extremely relevant for protecting the various electronics systems from interfering, apart from the noise absorption and control.

2.2. PVDF Sensor for Structural Health Monitoring

Structural health monitoring is an important field in the engineering community for structural engineers from civil, aviation as well as automotive sector. Some of the commonly used crack detection techniques like optical inspection, use of liquid penetrant, use of magnetic particles, ultrasonic inspection, and eddy currents are time-consuming, expensive and many times require disassembly of the parts. Thus, they are not effective for real time health monitoring. Especially, for structural health monitoring in areas involving variable contours the commonly used LVDT cannot be employed, as the metal casing of the LVDT is not flexible. The another disadvantage of conventionally used sensors, such as strain gauges, LVDT and clip gauge, is that, they require external power source for excitation, in turn increasing the cost of the equipment. Compared with the ceramic-based piezoelectric material such as PZT, which has a brittle nature, PVDF sensors are reusable and can be removed from the monitored structures without damaging them [15]. Additionally, PVDF's high sensitivity renders PVDF sensor elements suitable, to be integrated into low-power wireless systems, which reduces noise signals, lowers the overall cost, and enables full-scale real-time monitoring. The PVDF wireless sensor systems have been developed and have undergone field tests on Kishwaukee Bridge [16]. The wireless systems are found as reliable and as accurate as a tethered monitoring system [17].

Damages such as matrix cracking, delamination, transverse cracking, and fibre breakage release energy and causes transient elastic waves. For plate-like structures, the propagation characteristics of waves depend on properties such as plate thickness, boundary conditions, elastic properties, and material density. The analysis of wave propagation provides critically useful information about composite laminate materials [15, 17, 18] such as location of source.

Lamb waves can travel for long distances and have been investigated for a number of years to determine the propagation of cracks and other defects in a structure. Lamb waves [19] refer to elastic perturbations propagating in a solid plate with free boundaries, for which displacements occur both in the direction of wave propagation and perpendicularly to the plane of the plate. Starting from the Lamb wave equation, one can find two solutions: one symmetric solution and another anti-symmetric solution. The corresponding modes of the Lamb waves are symmetric-plate waves (S mode), often called extensional waves because the in-plane plate deformations are symmetric about the mid-plane of the plate; anti-symmetric plate waves (A mode) or flexural waves, because the out-of-plane deformations are asymmetric about the mid-plane of the plate. For structural health monitoring, the A mode and S mode waves are used to understand the characteristic of wave propagation and location of crack. As the S0 and A0 mode waves propagate at distinctly different velocities, they can be distinguished by analyzing signals measured at a single sensor. The low dielectric constant (εr) and low electromechanical coupling constant (kt) of PVDF make piezoelectric ceramics better suited for low-frequency. But for applications in aviation, automotive and astronautics where in the flexibility is required; in civil engineering applications where large area is required, PVDF is the preferred choice.

Gu et al. [3] developed a wireless PVDF sensor system for structural health monitoring. It involves a wireless system, powered by portable power supplies (batteries), decentralizing the computational responsibility from central data servers in turn reducing the overall energy consumption [17]. The wireless sensor system employs a mother board and a child board. The major components of the mother board are an embedded micro-converter, data acquisition and pre-processing unit, and a wireless transceiver. ADUC832 from Analog Devices was employed as the micro-converter. A half duplex transceiver from Linx technologies was used for the wireless transmission. The block diagram of the wireless sensor is shown in Fig. 3.

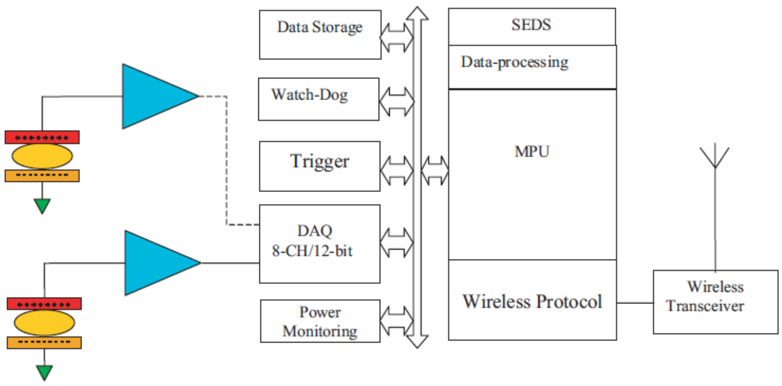

Fig. 3. Wireless smart sensor, developed by Gu et al. [3]

The temperature compensation for the PVDF was provided by using a dummy gauge method. A dummy gauge method involves use of another piece of PVDF of same size and its length is perpendicular to the stretch direction, as a dummy gauge. The positive electrode of the active gauge is connected to the negative electrode of the dummy gauge and the negative electrode of the active gauge is connected to the positive electrode of the dummy gauge, as shown in Fig. 4. The equal charges produced because of the pyroelectric effect cancel each other since these two gauges have the same size and are oppositely connected. In addition, the electrode area parallel to the stretch direction develops a signal about 10 times stronger than the electrode perpendicular to the stretch direction. Thus, subtracting the signals yields a pure piezo response. Each unit was found to be capable of an operational range of 60 m.

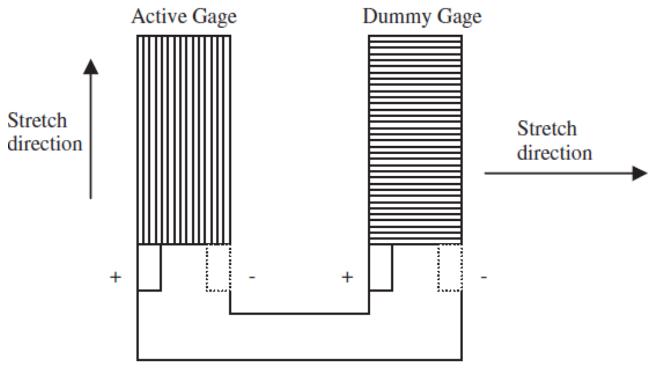

Fig. 4. Dummy gauge method for temperature compensation, developed by Gu et al. [3]

2.3. PVDF Array Sensor for Ultrasonic Imaging

Ultrasonic imaging techniques have been developed in medical and non destructive testing (NDT) fields. The major goal in these applications is high lateral resolution apart from transducer efficiency and bandwidth. The conventional techniques for such application achieve a good lateral resolution only when a large transducer is used. Additionally, for robotic applications, such as in robot end-effectors, the area under investigation is very small and limited. For such applications, the ultrasonic imaging system needs to be small size, light and exhibit good transducer efficiency to cover a range up to 40 cm.

The frequencies of operation can range from 0.3 MHz to 50 MHz [20]. The difficulties in machining PZT ceramics [21-23] have led to maximum range of operations of <20 MHz for pure PZT; Patterned zinc oxide (ZnO) [24] has been used to as high as 100 MHz; however, ZnO do not possess the very high piezoelectric and/or favorable acoustic properties of PVDF/PZT composites. Thus, in order to increase the maximum range of operations and obtain larger lateral resolution, linear and phased array transducers are used.

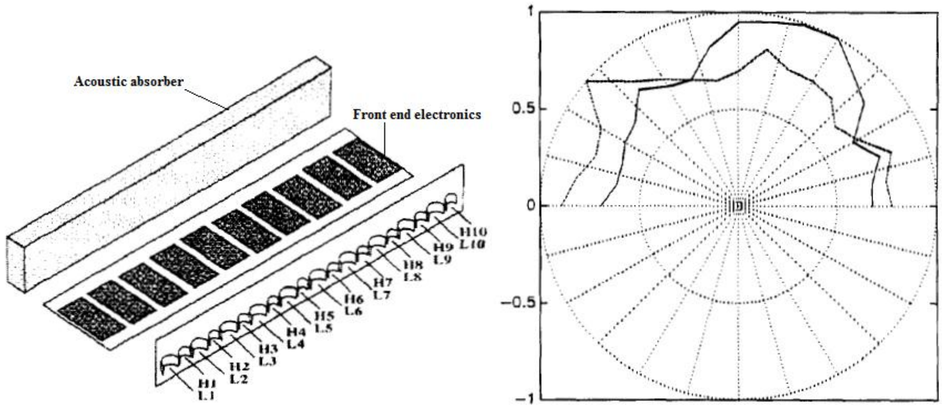

Fig. 5. (a) Exploded view of the double frequency array. (b) Averaged lobes of 10 elements. Continuous line 60 kHz, dashed line 86 kHz [25]

PVDF sensors can be built to operate over a large bandwidth which otherwise is obtainable with more sophisticated and expensive fabrication technologies. L. Capineri *et al*. [25] made an interlaced array of transducers with different resonant frequencies in order to further enhance the bandwidth. They were able to achieve a spatial resolution of 3mm in both lateral as well as axial directions. This was achieved by developing PVDF into hemicylindrical resonator (as shown in Fig. 5 (a)).

PVDF has a Q factor of seven and a wide main front lobe as shown in Fig. 5(b). This is seen as a drawback while using PVDF in pulse-echo mode. However, when the transducer is used in a multi-element configuration according to SAFT reconstruction (synthetic aperture focussing technique), it becomes the primary quality [26]. The low Q factor means that the rising time and the signal decay time are much faster than the conventional ceramic transmitters. This characteristic is suitable for high speed data acquisition or high speed digitizer applications. Thus, the transducer element permits a high sampling rate.

2.4. PVDF Array Sensors for Human Body Detection (Pyroelectric)

PVDF sensor has excellent pyroelectric properties. The PVDF based pyroelectric sensors depend on both thermal and pyroelectric phenomena; yet are different from thermal detectors as it behaves essentially with pure capacitance due to its high resistivity. Also these sensors can respond only to time dependent radiation and do not respond to continuous radiation. The use of single sensor, two sensors or array sensors depends on, whether, we want to determine only the presence of a human being or also want determine the direction of motion and velocity.

The salient sensor array parameters to be taken into account when selecting a suitable sensor material for infrared (IR) detectors are- pyroelectric signal voltage, response speed and lateral thermal resolution. The human body emits about 60W of infrared radiations onto its surroundings [27]. The pyroelectric coefficient (Pu) provides a measure of the signal voltage which in turn determines the range of operation of the sensor. An IR detector with more thickness will have a better operational range. The high lateral thermal conductivity of PVDF leads to a very high lateral resolution. These principle sensor properties was compared for some common sensors based on the literature values [28-30] by Freitag and Meixner [27] with lithium tantalite taken as standard (the pyroelectric material most commonly used up to now) and is shown in the Fig. 6.

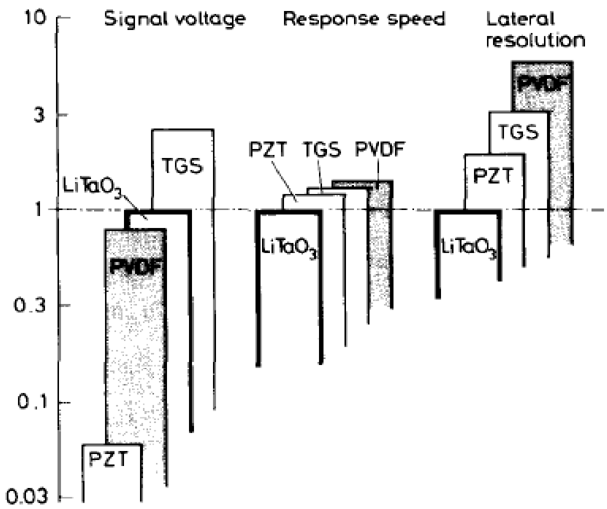

Fig. 6. Principal sensor properties normalized to the values of LiTa03 of identical thickness [27]

The PVDF provides the highest lateral resolution and response time despite giving just 80% of the signal voltage obtained. None of the known pyroelectric materials are as well suited as PVDF.

2.5. PVDF Doped with Pani for High Energy Density Capacitor Material

High capacity charge and electric energy storage materials find wide application in capacitors, gate dielectrics, memories and power-storage devices [31-34]. Energy storage capacitors have been the focus of increasing attention due to their advantages such as high efficiency and environmental friendliness [31-36]. As the energy density of the linear dielectric material is proportional to the product of permittivity and the square of applied electric field, it is essential to develop materials with high dielectric permittivity and high electric breakdown field (Eb). Ceramic materials are easily fractured under stress and have poor flexibility, high production cost and large density. Therefore, they are not suitable to fabricate large area thin film. Conventional high εr materials such as Barium titanate (εr = 2500) can be processed into thin films by chemical solution deposition. But the high sintering temperature is incompatible with most of the materials. Par contra, polymer dielectrics have good processibility with high electric breakdown field, which is suitable for high energy density capacitors. But the low permittivity of PVDF is a drawback for these applications unless the application relies more on the high electric breakdown field. To overcome this drawback, conducting materials can be incorporated into the polymers. The percolative composite exhibits a marked improvement in the dielectric permittivity at the percolation threshold, and without any adverse effect on the mechanical flexibility of polymer due to the relatively low filler loading [36-38]. PVDF is a well-known material because of its relatively high room temperature relative dielectric permittivity (7-13 at 1 kHz) and superior ferroelectric performances, which endows PVDF with potential applications in power-storage devices. PANI is chosen as the conductive filler due to its tuneable conductivity and low elastic modulus, and more importantly, good compatibility with polymer matrix even at high filler loading and thus reducing the dielectric loss and maintaining the high electric breakdown field of polymer matrix.

The increment in dielectric permittivity in PANI/PVDF composite as it reaches percolation threshold is governed by the micro-capacitor model and not the insulating-conducting transition like other percolative composites [36-41]. The micro-capacitor structure gives an advantage that the high energy density can be tailored in a wide PANI content range.

2.6. PVDF as a Touch or Tactile Sensor

Touch or tactile sensing has been gaining increasing awareness due to the necessity of development of artificial skin for future robots and for measurement of forces between the plantar surface of the foot and the shoe for the diagnosis and treatment of various foot disorders. Relatively little progress has been made in the direction of pressure recognition compared with area of sight and voice recognition, mainly because good artificial ‘‘electronic skin’’ with a large area and mechanical flexibility is not yet available. The fabrication of a sensitive skin consisting of thousands of pressure sensors would require a flexible switching matrix that cannot be realized with present silicon-based electronics.

The light weight, formability into really thin sheets, good mechanical properties and easy metallization of electrodes are the salient properties that have led to the use of PVDF as a tactile sensor. Organic field-effect transistors [42-52] can substitute for the conventional electronics as they are inherently flexible and potentially ultralow in cost even for a large area [48, 49]. The integration of organic transistors and rubber pressure sensors can provide an ideal solution to realize a practical artificial skin.

Successful attempts to attain the same have been made in the past by Someya *et al*. But the authors reported that the minimum bending diameter reported so far is only 30mm [50] as the use of inorganic materials still continues in many previous transistors for some components such as gate insulators (SiO2, Al2O3) and base films (glass, silicon). Also, the highest mobility reported so far for plastic transistors has been around 0.1 cm2/Vs [44], much lower than the best values around 2–5 cm2/Vs obtained with hard substrates [52]. These are the major hurdles to the application of organic transistors to large-area flexible electronics.

Razian and Pepper [53] developed a tri-axial pressure transducer (Fig. 7(a)) with 10×10 mm and 500-μm thick elements of PVDF-TrFE (Trifluoroethylene) sandwiched between three 0.7-mm thick double-sided PCB transducer boards and ultralow-noise tricoax-cable imbedded in a central groove in the lower PCBs. The linearity was better than1%, and the hysteresis was less than 2% in all cases. The designations indicated in the Fig. 7(b) are V = vertical, M-L = medio-lateral, and A-P=anterior-posterior forces at the monitored sites between the sole of the foot and the shoe.

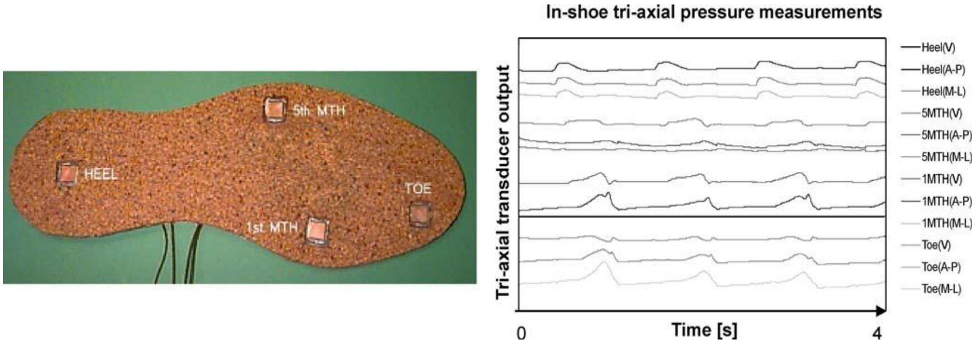

Fig. 7. (a) Insole with four embedded triaxial force measurement transducers; (b) Typical force-time diagram showing measurements for three steps, adapted from [53]

Tactile sensors for monitoring human skin were developed by several groups in Japan. Jiang et al [54] made a soft tribo-sensor made up of aluminium pipe covered with concentric layers of sponge rubber, a 28-μm thick film of PVDF and a protective layer of cellophane tape to simulate a human finger. Three data analysis techniques were devised and a wavelet transform method was found to be the most satisfactory.

Tanaka *et al.* [55, 56] developed a "haptic finger" consisting of a copper plate with a layer of vulcanized rubber on top of which was an electroded PVDF film with a protective surface layer. A strain gauge was used to measure force applied on the haptic finger and the signals from PVDF film was recorded by a digital oscilloscope. The index of surface roughness and dispersion of the power spectrum density in the frequency domain were used to characterize the hardness of various fabrics and human skins with various disorders. Good agreement was obtained between the results measured on the skin and obtained after clinical analysis.

Tanaka *et al*. also developed an active palpation sensor for the detection of prostate cancer and hypertrophy [57] comprising of a PVDF film placed on the surface of a sponge rubber layer that was mounted on a linear translation bar.

It is important for a surgeon to be able to feel the tissue during endoscopic manipulation. Dargahi [58, 59] developed an endoscopic grasper where in the magnitude of the applied force could be found from the magnitude of the output of the PVDF. The position of application of the load was found from the slope of the output. It comprises of a tooth-like structure formed of silicon with 25 μm PVDF film with four electrodes sandwiched between the silicon and a Plexiglass substrate. Kim *et al*. presented the design, fabrication, and calibration of a piezoelectric polymer sensor based micro-gripper [60] that can provide force feedback to the operator assist in damage free assembly of parts.

2.7. PVDF as an Energy Harvesting EEL

Taylor *et al*. [61] developed a structure using piezoelectric polymers for converting the mechanical flow energy available in oceans and rivers, to electrical power. It used the trail of travelling vortices behind a bluff body to strain the piezoelectric elements. The undulation of the polymer resembled that of a natural eel swimming and hence named as 'Energy harvesting eel'. Based on the results shown in Fig. 8, the tail generates less power and with more harmonics, possibly due to a whipping action at the free boundary. It was found that the maximum power transfer occurred when the flapping frequency matched the vortex shedding frequency.

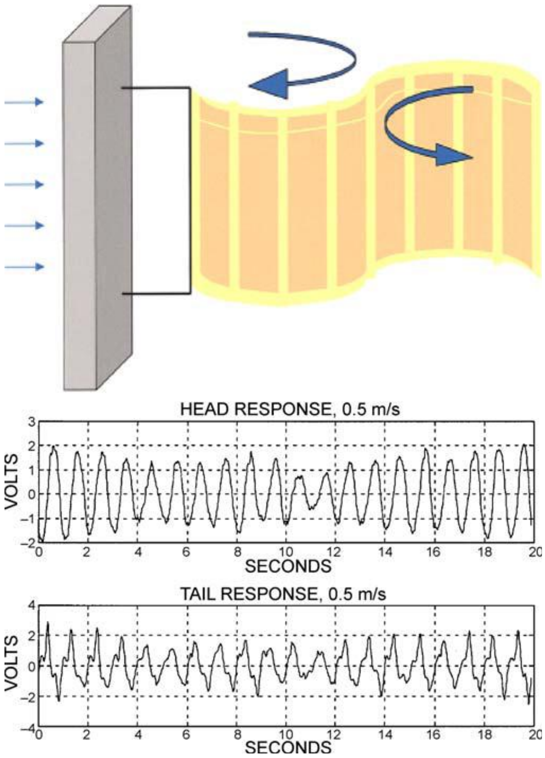

Fig. 8. Upper: Eel movement behind bluff body. Lower: Open-circuit Eel measurements as functions of time, adapted from [61]

2.8. PVDF for Comet Dust Flux Monitor

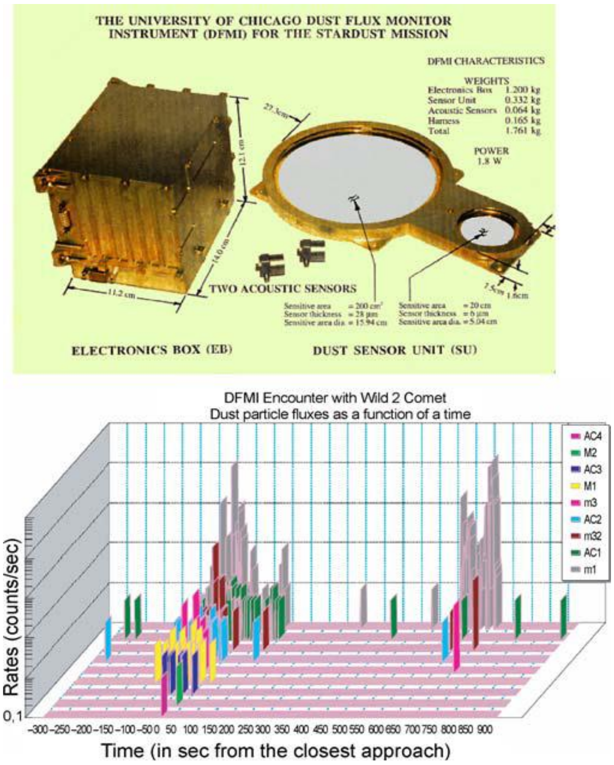

Fig. 9. Upper: Dust flux monitor instrument (from [62]). Lower: Total number of counts measured during encounter with comet, adapted from [67]

The Dust flux monitor instrument [62, 63] comprises of two PVDF sensors, one with a sensitive area of 200 cm2 and a thickness of 28μm and the other with an area of 20 cm2 and a thickness of 6μm. The instrument provides real-time data on variations in the particle flux and mass distribution in the coma of the comet as well as measurements of dust in interplanetary space. The PVDF detectors were designed to detect particles of masses between 10−11 and 10−4 g and at counting rates up to 104 per second. An impacting dust particle on the PVDF detectors produced a rapid local destruction of the dipoles (either a crater or a penetration hole) and created a sharp output pulse which was detected by the electronics. The technology used in the design of the DMFI (Dust Flux Monitor Instrument) (Fig. 9) had been previously used in the study of the dust in the coma of Halley's Comet in 1986 [64-66].

2.9. Porous PVDF Membranes as Transport Electrolyte

PVDF-based gel electrolytes is widely used in Li-ion polymer batteries with many companies from Japan and the United States already marketing PVDF-based devices for applications in computers and portable phones and for near future applications in electric vehicles [68]. These electrolyte compounds are multi-component systems, in which PVDF uptakes large amounts of non-aqueous liquid electrolyte, thus reaching liquid like conductivities at room temperature, as well as exhibiting good mechanical properties.

Phase separation can be used to prepare PVDF films with ability to retain large amounts of liquid electrolyte [69-71]. When this technique is performed via immersion precipitation, it is possible to prepare PVDF membranes with different porosities and morphologies, ranging from "sponge" like to "finger" like, simply by modulating experimental parameters such as the nature and the ratio of the solvents and non-solvents, the concentration, and the crystallinity of the polymer [72]. Solid polymer electrolytes are generally based on polyvinylidene fluoride (PVDF), silver triflate (AgCF3SO3), and x wt% of aluminium oxide (Al2O3) nanopowders, (where x = 1, 3, 5, and 10, respectively) [73].

Quartarone et al. [74] reported some preliminary results about the conductivity of PVDF membranes with different morphologies and porosities ranging from 55 and 85%, activated by the solution EC/DEC/LiPF6 (Lithium Hexafluorophosphate in ethylene carbonate and diethyl carbonate)1.0 M, pure and with the addition of TEGDME (Tetraethylene glycol dimethyl ether) as a third component. They showed that nearly all of the pore structure is accessible to the liquid and that it is possible to separate the swelling contribution from the total electrolyte uptake. High porosity and low porosity membrane preparation had been outlined [72, 75] with the liquid uptake.

The bulk of the electrolyte solution is absorbed by filling of the pores, whereas a fraction ranging from 5 to 15 vol%, depending on the residual amorphous polymer phase, results from swelling. The conduction mechanism may be rationalized as a percolation process through a Bethe lattice.

2.10. Surface Pressure Mapping Using PVDF as Pressure Sensors

Aircraft performance is generally limited by the inability of the wings to produce lift at high angles of attack due to flow separation. Boundary layer separation leads to aircraft stall thereby inflicting severe aerodynamic performance penalties. Hence, there is a need for a technique that detects and controls flow separation even before it occurs. The concept of using smart sensors for benefits of aircraft performance enhancement like flow separation control, lift enhancement, drag reduction and other related applications is gaining considerable interest. The unsteady pressures from the wind tunnel measurements are a prerequisite for the prediction of dynamic loads and vibrations during the development and design of new fighter aircraft structures. "Smart" control of flow separation involves array of sensors which gives the crucial information on the state of the boundary layer (attached/separated), used as a signature of flow separation. This signature can be used in a closed loop control system to activate the flow control device to achieve the "smart" separation control.

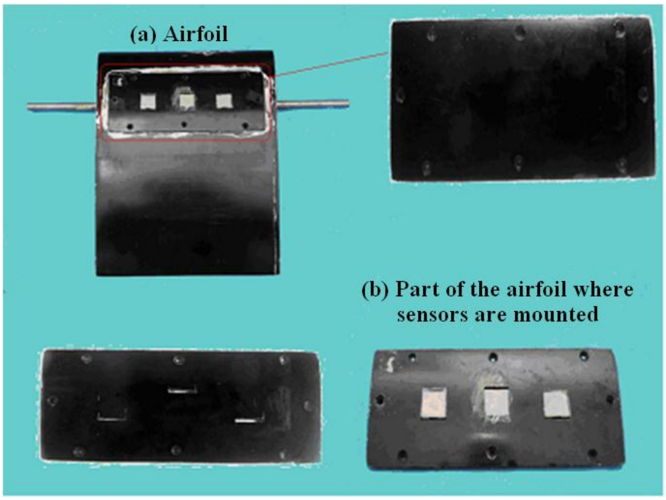

Fig. 10. (a) Airfoil; (b) Inset part of the airfoil where sensors are mounted

The application of the PVDF foil Smart Sensor & Signal Processing Technology as a promising technique for the measurement of unsteady pressures has been proposed by a few authors [76-79]. The experiments on this application can be found in the form of an experimental investigation carried out by the EADS-MAS (European Aeronautic Defence and Space Company-Military Air System) on military aircraft wind tunnel models [79]. The EADS-MAS team, in their attempt to combine a Trainer and a Light Combat Aircraft (LCA) together had to meet the requirements of a pure fighter aircraft i.e. the structure should be designed to withstand all the buffet excitation and as a LCA should fly a very long time with more flight hours, have proposed a similar system [79].

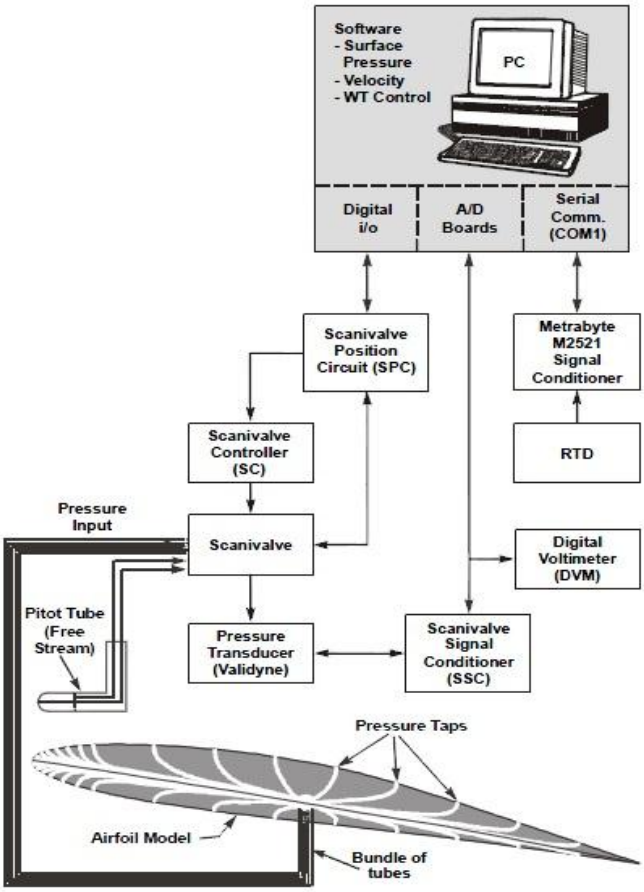

Fig. 11. Schematic of the data acquisition system [81]

This exploratory experiment is also being initiated at National Aerospace Laboratories (NAL), Bangalore after successful feasibility tests for the wind velocity range of 5 to 15 m/s. Surface pressure mapping using pressure orifice has been carried out already at NAL [80]

The PVDF sensors have been checked for surface pressure by bonding it on an airfoil (Fig. 10(a)). The NACA (National Advisory Committee for Aeronautics) 4415 airfoil with sensors was subjected to tests inside wind tunnel at various speeds and angle of attacks. The basic application of sensor is to detect the change in the flow patterns (from laminar to turbulent state), and aid the studies on unsteady aerodynamics. The part of the airfoil where the sensor has to be bonded is shown in Fig. 10 (b).

When the air/fluid flows over the PVDF film, it exerts a pressure or force on the film. The piezoelectric material undergoes deformation and generates a corresponding electric signal. PVDF based sensors can be digitized to desired shape and size permitting pressure detection at an extremely localized point. This would help in improving the resolution of study and would eliminate the error in spatial data due to the pressure measurement averaged over a wide area. This signal can be calibrated for determining the surface pressure at a localized point. The PVDF film can detect a change in force as minute as few micro-Newtons. A predominantly capacitive mode of response renders PVDF extremely suitable for high speed data acquisition. A typical circuit involving pressure orifice for surface pressure mapping would be similar to the circuit shown in Fig. 11 [81].

2.11. PVDF as a of Piezo-Actuator for Flapping Wing Micro Air Vehicles

DARPA (Defense Advanced Research Project Agency) [82] defines Micro Aerial Vehicles (MAVs) as "six-degree-of-freedom aerial robots, whose mobility can deploy a useful micro payload to a remote or otherwise hazardous location where it may perform any of a variety of missions, including reconnaissance and surveillance, targeting, tagging and bio-chemical sensing". DARPA denotes a size-limitation and performance requirements of air vehicles to be termed as an MAV [83]. The total wingspan of a MAV is expected to be less than 15 cm, the highest velocity is about 48 km/h, the range of the flight mission is about 10 km, and the flight endurance is about 20–120 min. An up-to-date historic overview of flapping MAVs can be found in [84].

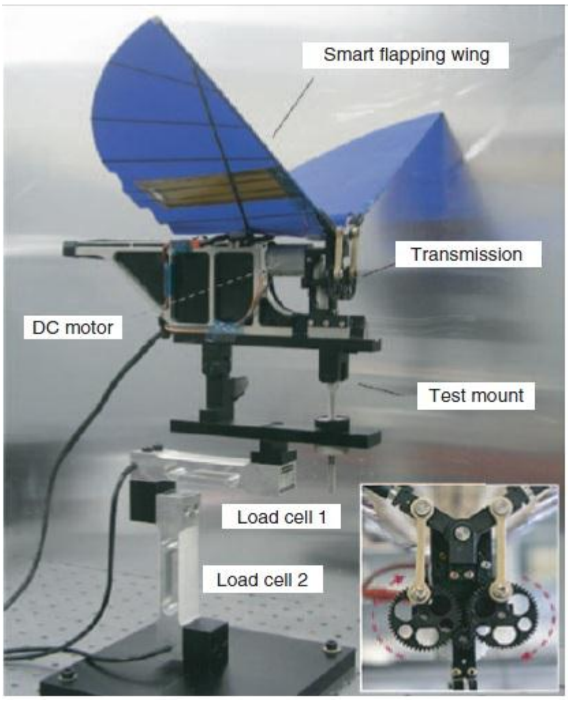

Fig. 12. Configuration of flapping system and test stand. The inset is the front view of the transmission [85]

The use of PVDF as an actuator for flapping wing MAV is a proposed exploratory application tested at the National Aerospace Laboratories (NAL), Bangalore. PVDF films obtained after qualitative and quantitative measurements were mounted on the Mylar wings as patches. The thickness of PVDF and Mylar wing are coupled variables which are critical to achieve the desired flapping action of the wings. Hence, these ought to be optimized to match resonant frequency between PVDF and Mylar. PVDF as well as its variants (copolymer, composites) are being evaluated for actuation, without tampering with the inherent properties of the polymer. Hence developed actuator, will subsequently undergo rigorous trials on test rigs and MAV. The PVDF can also be employed in dual mode (as an actuator and sensor as well) to facilitate adaptive control of wing aerodynamics as well as flapping action. Subsequently, the feasibility study will be carried out, to achieve textured wings actuated by PVDF and its composites. The test stand consisting of a driving part, a test mount, and a measurement 0part would look similar to the Fig. 12 [85].

3. Remarks

PVDF is a promising new age material with applications across varied sectors. The applications of PVDF is only limited in areas where very high piezoelectric constants or applications where pulse echo mode is employed. A lot of work remains to be done on exploring alternate dopants with PVDF for specific applications.

The applications enlisted above do not form an exhaustive list but enlists only certain typical applications of PVDF. Apart from the above applications, PVDF is used as a pressure sensor, acoustic sensor, strain measurement sensor, low cost accelerometer, vibration damping system, hydrophones, shock sensor, medical ultrasound, microphones and loudspeakers, to name a few.

Work on development of PVDF films had been already going on in NAL since 2009 [4, 86-90]. Film synthesis and development facilities cannot be found easily in India. In addition, the tailor made PVDF films for a specific application, are expensive and not easy to procure from within the country or abroad. The film development facility is available with NAL. The film's process parameters have been optimized in the past for certain applications [88, 89].

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