Integrated Ultrasonic Piezoelectric-based Transducers for Structural Health Monitoring

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Integrated Ultrasonic Transducers Made by Sol-Gel Spray Technique For Structural Health Monitoring

M. Kobayashi[1], C.-K. Jen[1,*], J.-F. Moisan[1], N. Mrad[2] and S.B. Nguyen[3]

1. Industrial Materials Institute, National Research Council of Canada, Boucherville, Quebec, Canada J4B 6Y4.
2. Department of National Defence, Defence R&D Canada, Air Vehicles Research Section, National Defence Headquarters, Ottawa, Ontario, Canada K1A 0K2
3. Department of Electrical and Computer Engineering, McGill University, Montreal, Quebec, Canada H3A 2A7

*Tel: (450) 641-5085, Fax: (450) 641-5106, E-mail: cheng-kuei.jen@cnrc-nrc.gc.ca

Abstract

Integrated piezoelectric-based ultrasonic transducers (UTs) have been developed for potential structural health monitoring. Fabrication techniques and performance evaluation of these transducers at selected monitoring sites are presented. Our novel transducer fabrication approach focuses on the use of handheld and readily accessible equipment to perform sol-gel spray coating including the use of a heat gun or a torch, to carry out drying and firing, poling and electrode-fabrication. The application of these integrated UTs for thickness measurement of graphite/epoxy composites, thickness monitoring of ice build up on aluminum plates at low temperatures, viscosity measurement of a cooling oil flow at temperatures up to 160°C and monitoring metal debris in cooling oil engines, are demonstrated.

1. INTRODUCTION

The increasing demand to improve the performance, reduce downtime, increase reliability and extend the life of transportation vehicles, structures such as nuclear power plants, and engineering systems such as molding and casting devices, requires the use of smart or adaptive materials and structures [1-5]. These can be defined as systems that have integrated capabilities with built-in sensors that perceive and process in-service information and take actions to accomplish desired operations and tasks. It is established that ultrasonic methods employing piezoelectric ultrasonic transducers (UTs) are widely used for real-time, in-situ or off-line nondestructive testing (NDT) and evaluation of large metallic and polymeric composite structures including airplanes, automobiles, ships, pressure vessels, pipelines. Because of their subsurface inspection capability, fast inspection speed, simplicity and cost-effectiveness [3-9], there has been considerable interest in the use of piezoelectric materials. Some of these can be integrated with metals or polymer composites for structural health monitoring (SHM) purposes [3,4,10,11] subjected to high temperature environments [3-5,12,13]. Common limitations of the current UTs are (1) the requirement of couplant; (2) lack of suitability for use on curved surfaces; (3) the difficulty for use in pulse-echo mode; and (4) the difficulty for use in temperature higher than 60°C. In this investigation, some of these limitations will be addressed and will focus on lowering process temperatures of sol-gel sprayed lead-zirconate-titanate (PZT)/PZT composite UT films, of thickness greater than 40 μm, reported in [3,4]. To integrate these PZT based films onto flat and/or curved metallic or graphite/epoxy substrates, handheld equipment was used. The process temperature achieved using a handheld heat gun should not affect the performance of graphite/epoxy (Gr/Ep) composites or metal components. These UTs can be fabricated as arrays and at desired sensor locations with ease. The application of these integrated UTs targets thickness measurement of Gr/Ep composites, thickness monitoring of ice buildup on aluminum substrates, viscosity measurement of cooling oil flow, at elevated temperatures, and engine oil metal debris monitoring.

2. TRANSDUCER FABRICATION AND CHARACTERIZATION

Sol-gel fabricated thick piezoelectric films were initially reported by Queen's University [14]. The aim of the development was not for high temperature NDT applications and the fabrication techniques used did not consider the integrated sensor approach at specified monitoring sites. Taking this into consideration, transducer material and processing techniques were properly selected for this development. In this investigation, piezoelectric PZT powders were purchased with a particle size distribution of 1 to 3 μm. The powders were dispersed into PZT sol-gel solution by a ball milling method to achieve desired transducer characteristics. The final PZT mixture (paint) was estimated to be of sub-micron size. An airbrush was then used to spray the PZT/PZT sol-gel composite directly onto selected substrates, such as graphite/epoxy, aluminum and steel. With the sol-gel spray technique, the PZT/PZT films can be produced with specified thickness at desired locations using a paper shadow mask. After spraying the coating, thermal treatments such as drying, firing and annealing were carried out using a heat gun or a gas torch. Multiple layers were made in order to reach desired transducer thickness. The film was then electrically poled using the corona discharging technique [15]. For corona poling, the temperature of the stainless steel substrate was around 120°C. A high positive voltage was supplied from a 28 kV DC power supply. This was fed into a thin and sharp needle located several centimeters above the PZT/PZT film coating on the top of the metal substrate. The substrate served as the ground electrode for corona poling. The distance, from the film surface, and the voltage were optimized for different PZT/PZT film thicknesses and geometries. The poling time was about 10 minutes. The corona poling method was chosen because it could pole the piezoelectric film over a large area with complex geometries. Finally, silver paste painting was used to form the top electrode at room temperature. This convenient approach makes the selection of electrode size and sensor size simple. The silver paste has been tested and its operating temperature could reach 200°C. The flow chart of the fabrication process is shown in Figure 1. The novelty in this study is that the thermal treatment is carried out by a heat-gun or torch in lieu of a furnace as used in a previous study [3]. In addition, here aluminum substrates are used instead of steel substrates. Because of the low temperature used the firing and annealing of the PZT/PZT film would not be complete, the piezoelectric strength will then be lower than those completely fired and annealed films reported in [3].

It is noted that PZT sol-gel solution acted as bonding agent between the PZT powder and the substrates. The dielectric constant of the PZT/PZT films was 60 measured by a Hewlett Packard 4192A LF Impedance Analyzer at 1 kHz. The measured piezoelectric coupling constant k_t using the standard method described in [16] was 25%.

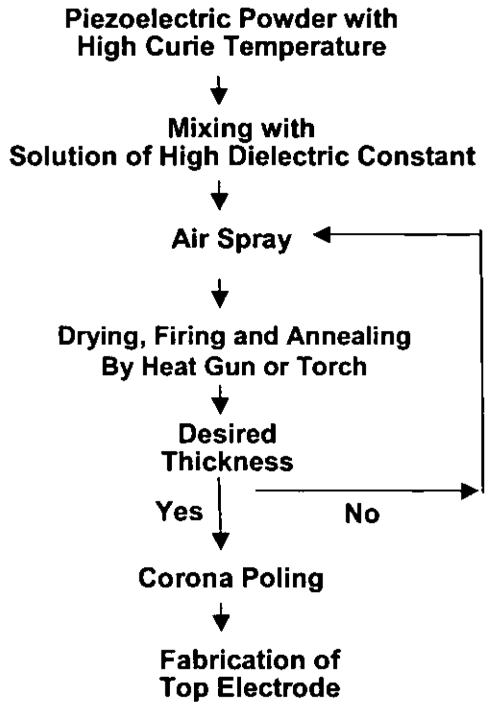

Figure 1. Flow chart of the fabrication process for piezoelectric thick film UT

3. PERFORMANCE OF UT FOR POTENTIAL ULTRASONIC SHM

3.1 Integrated UT on graphite/epoxy composites for thickness measurement

The fabrication of the Gr/Ep composite follows the manufacturer's recommended cure cycle shown in Figure 2 for Gr/Ep. In the curing stage the highest temperature was 176°C and the duration was 120 minutes. During the PZT/PZT composite film fabrication, thermal treatment such as drying, firing and heating for corona poling was carried out using a heat-gun producing gentle heat. The torch used in study [4] proved to be difficult in controlling the heating speed and temperature. In order to not affect the performance of the graphite/epoxy composite a thermocouple contacting the surface of the graphite/epoxy composite was used to ensure that each heating would not exceed 176°C. It is the intention of this study to evaluate the performance of the novel PZT/PZT film sensor for thickness measurement under such low temperature thermal treatments. A 70 μm thick PZT/PZT film UT deposited on the 13.1 mm thick unidirectional Gr/Ep composite shown in Figure 3. The 70 μm film thickness was achieved through applying the process shown in Figure 1 eight times where each layer of coating proceeded for 150 seconds. The Gr/Ep composite has sufficient conductivity to serve as the bottom electrode for the produced piezoelectric film based UT.

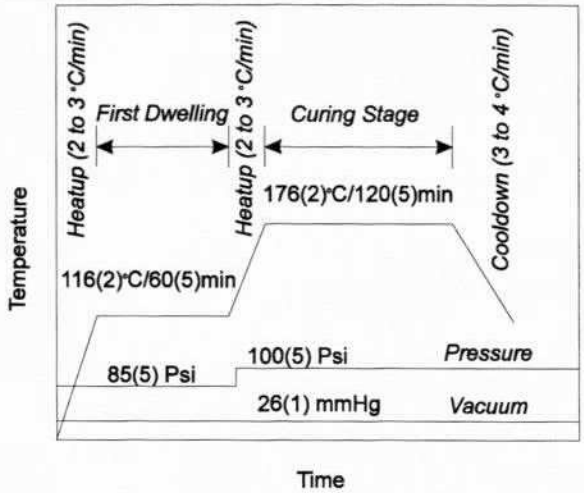

Figure 2. Manufacturer recommended cure cycle for Gr/Ep composite.

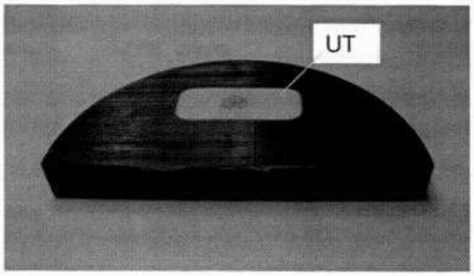

Figure 3. Integrated PZT/PZT composite film UT on a 13.1 mm thick Gr/Ep composite.

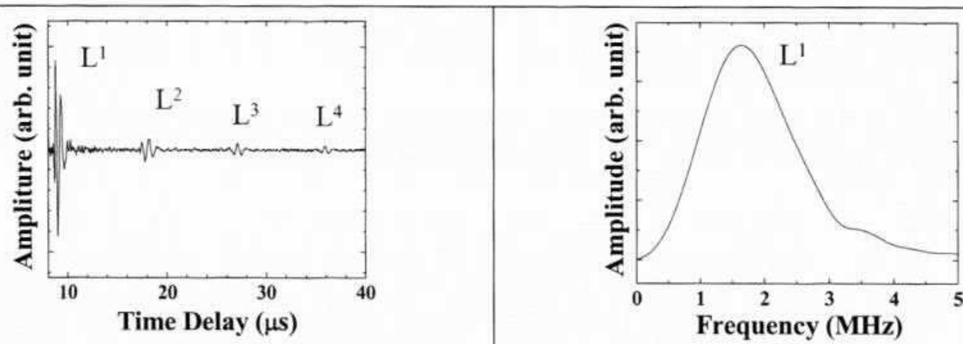

Figure 4. Ultrasonic performance of 70 μm thick PZT/PZT UT film deposited on the 13.1 mm thick Gr/Ep sample shown in Figure 3 in (a) time and (b) frequency domain at room temperature.

Figures 4a and 4b show a typical ultrasonic performance of the integrated UT shown in Figure 3 operated in pulse-echo mode at room temperature. In Figure 4a the measured signal-to-noise ratio (SNR) of the ultrasonic signal L^1 is about 15 dB. L^1, L^2, L^3 and L^4 are respectively the 1[st], 2[nd], 3[rd] and 4[th] round-trip reflected echoes through the thickness of the Gr/Ep composite. The SNR is defined as the ratio of the amplitude of the first echo, L^1, traveled one round trip in the through thickness direction over that of the signals, which are undesired, between the echoes traversing back and forth in the sample. The measured center frequency and 6 dB bandwidth of L^1 is 1.6 MHz and 1.5 MHz, respectively. The low center frequency and bandwidth were caused by the high ultrasonic attenuation within the 13.1 mm thick composite. In principle, the ultrasonic attenuation is proportional to the operation frequency squared. The higher frequency components suffer significant ultrasonic attenuation. It is expected that improved SNR of L^1 can be obtained if the thickness of the PZT/PZT film increases and the center frequency of the integrated UT decreases. This is the first time that piezoelectric UT can be directly deposited onto the Gr/Ep composite to carry out the thickness measurement provided that the ultrasonic velocity in Gr/Ep composite is known. For such a Gr/Ep composite, the thickness would be 2.96 mm per μs time delay in ultrasound for one-way travel along the thickness direction at 22°C.

3.2 Integrated UT on aluminum substrates for thickness measurement

Aluminum alloys are common materials for aircraft structures and other transportation systems, such as automobiles. Typically, the melting temperature of these alloys is around 580°C. For the Al. specimen under consideration, all the fabrication procedures of UT are identical to those reported in the previous section except that the firing and annealing for the PZT/PZT composite film were carried out using a gas torch which provides higher temperature than that of heat gun. During the corona poling a heat gun was still used though. Figure 5 shows that two areas of PZT/PZT composite film were deposited onto a 25.4 mm thick Al. plate. Since the Al. substrate serves as the bottom electrode, the size and shape of the top electrode determines that of the UT. If multiple top electrodes are made, then a UT array is achieved. For this study only one top electrode of 10 mm diameter (not shown) was made. Figures 6a and 6b show the measured ultrasonic signals in the pulse-echo mode at 150°C. L^1, L^2, L^3 and L^4 are respectively the 1st, 2nd, 3rd and 4th round-trip reflected echoes through the thickness of the Al. The measured SNR, center frequency and 6 dB bandwidth of L^1 in Figure 6a are 29 dB, 3.4 MHz and 3.3 MHz, respectively. For this Al. plate the thickness would be 6.30 mm per μs time delay in ultrasound for one-way travel along the thickness direction at 22°C.

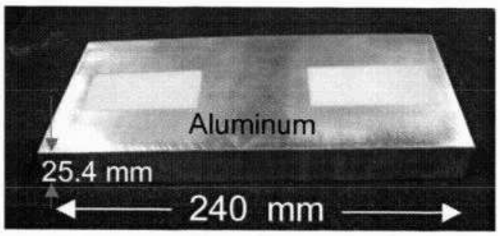

Figure 5. Integrated PZT/PZT composite film UTs on a 25.4 mm thick aluminum plate

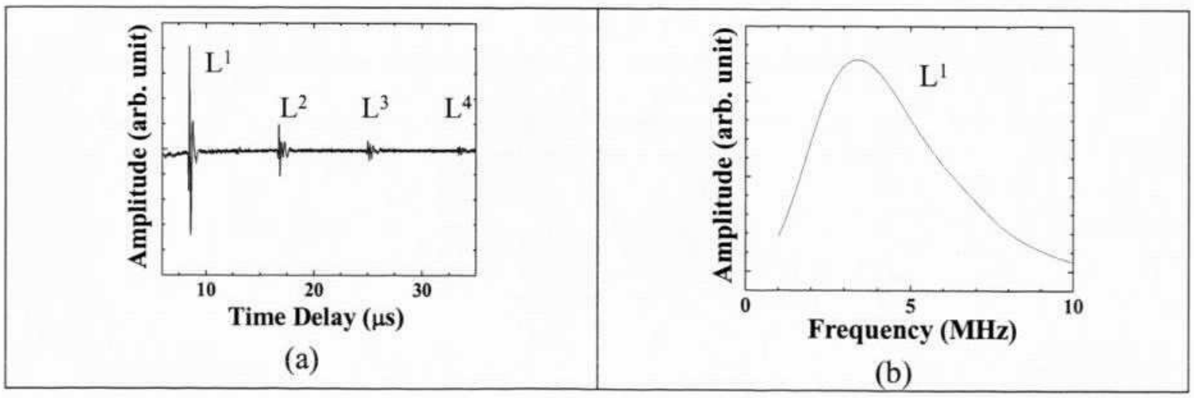

Figure 6. Ultrasonic performance of 100 μm thick PZT/PZT film deposited on an aluminum plate shown in Figure 5 in (a) time and (b) frequency domain at 150°C.

3.3 Integrated UT for ice buildup thickness measurement

The accumulation of ice on wings of aircrafts poses a serious safety concern for all aircraft operators. It may happen during taxiing and waiting for takeoffs in winter and/or during flight at high altitudes. Here an UT sensor was directly fabricated onto a 9.9 mm thick Al. plate, analogous to the previous section, and used to monitor the thickness of ice building on the Al. plate. Water droplets on the opposite side of the plate were cooled by liquid nitrogen, as illustrated in Figure 7. The time delay of echo L_{ICE}, reflected from the ice-air interface, increased in the traces from top to bottom in Figure 8 indicating growth of the ice thickness. L^1 and L^2 echoes are the 1st and 2nd round trip echoes, respectively, through the thickness of the 9.9 mm Al. plate. The thickness (h) of the ice can be estimated using the time delay difference (Δt) between L_{ICE} and L^1 echoes and ultrasonic velocity (V=3230m/s) in the ice using $h = V \times \Delta t / 2$. The ice thickness was calculated to be 3.2mm and 4.0mm for top and bottom traces, respectively. Additional experiments not reported here also supported the high performance of the sensors at operating temperatures below –100°C.

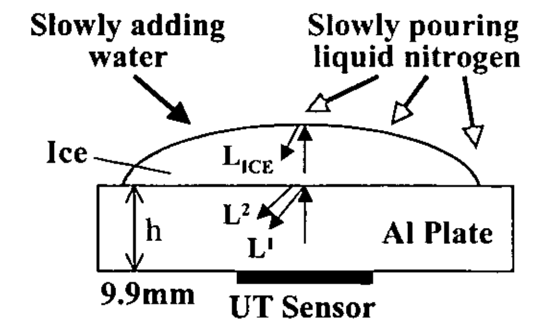

Figure 7. Schematic for thickness monitoring of ice growing on an aluminum plate using UT.

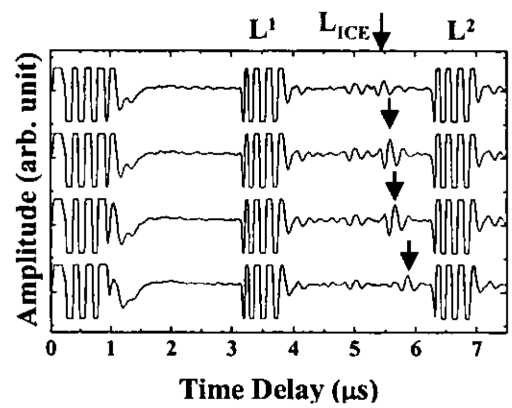

Figure 8. Ultrasonic echoes, L_{ICE}, observed as ice growing on an aluminum plate of Figure 7.

3.4 Integrated UT at elevated (100°C) temperature for thickness measurement

It is also of interest to know that when a structure or system, such as cooling pipes in nuclear reactors, operates at elevated temperatures whether the developed sensor can still be integrated and respond to its designed performance requirement. To simulate such a situation a steel block with a dimension 56 mm x 75 mm x 61 mm was first heated on a hot plate to 100°C and remained at this temperature. The 100°C was chosen because it is the temperature when the cooling water becomes vapor. All transducer fabrication processes described in Section 2 were carried out for this configuration. Figure 9 shows the integrated UTs on this steel block and Figures 10a and 10b show the ultrasonic performance of the integrated UT operated in pulse-echo mode at 100°C. The measured, SNR, center frequency and 6 dB bandwidth of L^1 is 20 dB, 2.1 MHz and 3.1 MHz, respectively. It is shown that although the SNR is not high, it is sufficient enough for thickness measurement of this steel block at 100°C. For such a steel block, the thickness would be 5.54 mm per μs delay in ultrasound for one-way travel along the thickness direction.

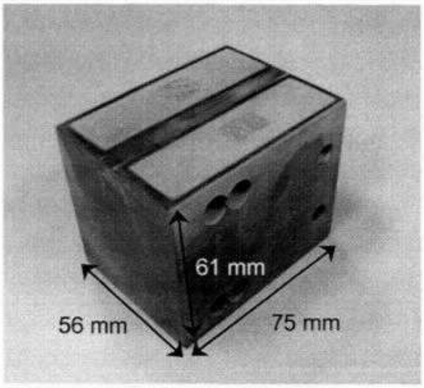

Figure 9. Integrated PZT/PZT composite film UTs deposited onto a 56 mm x 75 mm x 61 mm steel block heated at 100°C.

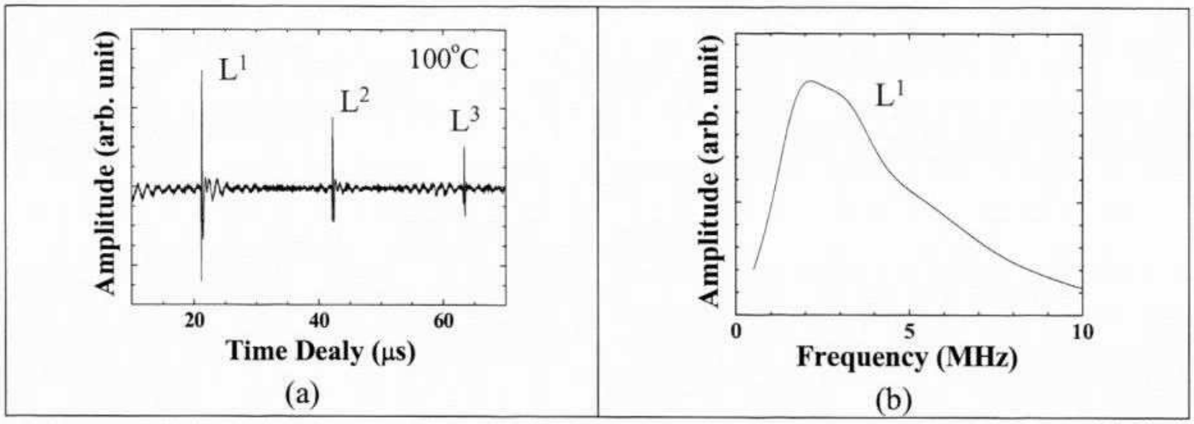

Figure 10. Ultrasonic performance of one 100 μm thick PZT/PZT film deposited on the steel block heated at 100°C as shown in Figure 9 in (a) time and (b) frequency domain.

3.5 Integrated UT for viscosity measurement and oil debris monitoring

When engines, in particular, in aerospace vehicles are running, not only for the cost but also for safety reasons, it is crucial to know engine health condition. While in operation engines are hot and cooling oil is often used to lower temperature. In addition, if the engines do not operate properly, gears may be damaged and metallic debris will be produced and carried by the flowing oil in cooling channels. Thus, it is of significant importance to have a viscosity and metal debris monitoring system operable at elevated temperatures.

Although the integrated UT made of bismuth titanium/PZT composite films can operate at 400°C and higher [3,4], in this investigation only the performance of PZT/PZT film operated up to 160°C is presented. Figures 11 and 12 show, respectively, the schematic and actual set-up of a simulated oil viscosity measurement and debris monitoring system. The V shape probes, shown in Figure 12, were used to measure the flow speed of the flowing oil [17]. Two pairs of integrated Uts, coated on the top and bottom sides of the pipe, were made at both sides of the V shapes probes. They can operate in pulse-echo or transmission mode. The pipe is of square shape. The outer dimension is 12.7 mm by 12.7 mm and inner dimension is 9.53 mm by 9.53 mm. The size of the sensor, decided by the top silver paste electrode, was 5 mm diameter located at the center of the pipe surface. It is well known that the viscosity of the oil is temperature dependent. For our experiment a Thermocast™ heater machine, used in connection with polymer and metal processing machines, provided flow of Thermia-C oil (Shell), which simulates the engine oil. The temperature of the flowing oil has been changed from 22°C to 160°C at increments of 10°C. The measured ultrasonic velocity in this oil via the transmission mode as a function of the temperature of the oil is given in Figure 13. In practice, the ultrasonic velocities in oil vary according to their viscosity. If the ultrasonic velocity of oil, at constant temperature, is lower than a set threshold that determines a must change operation of oil, the integrated UT and acoustic electronics indicator will be able to issue commands to key operators.

Figure 14 shows the reduction of the transmitted ultrasonic signal due to steel bearing balls of 1.59, 2.38 and 4.76 mm in diameter flowing in water and pass one pair of the integrated UTs sensing zone along the pipe shown in Figure 12. The pipe shown in Figure 12 was placed vertically and the balls are freely dropped from the top open end and flow through the sensor site in water. These steel bearing balls simulate metal debris of different dimensions carried by flowing oil in cooling channels. The results indicate that the larger the ball diameter, the higher the signal reduction. In addition, Figure 15 shows the reduction of the ultrasonic signal due to the presence of one metal ball of 1.59 mm diameter flowing in the water but for four times. It indicates that the repeatability is quite acceptable and the ball is clearly identifiable. In Figure 16 copper powders of 100-500 μm diameters with a total weight of 0.05 g and 0.1 g were also freely dropped and flow through the sensor site. The signal strength reduction also was experienced and was clearly recognizable, but the shapes were different from those of the single ball. Such reduction of signal strength can be used to identify the count and size of the metal debris in the cooling oil analogous to our previous work [18]. Thus, it is our conclusion that although the shape and the size of metal debris may vary much, the signal reduction pattern as a function of time may still be used effectively to assess the health condition of the engine. The integrated UT system can be used both as a viscosity and metal debris diagnostic tool.

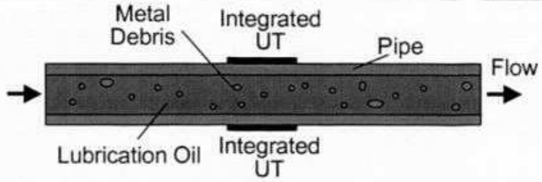

Figure 11. Schematic of oil viscosity measurement and debris monitoring.

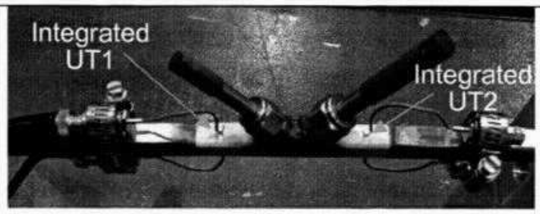

Figure 12.Integrated UT set-up for oil viscosity and debris monitoring.

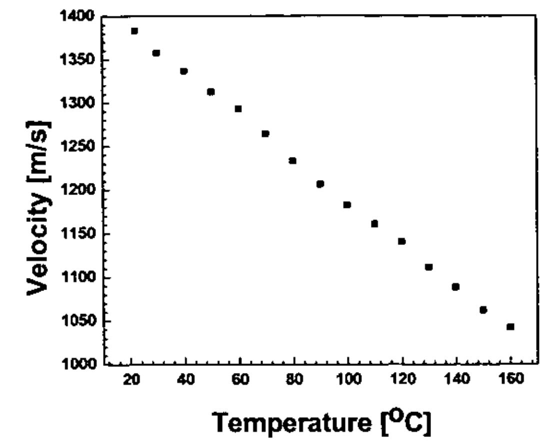

Figure 13. Relation between ultrasonic velocity in oil and temperature.

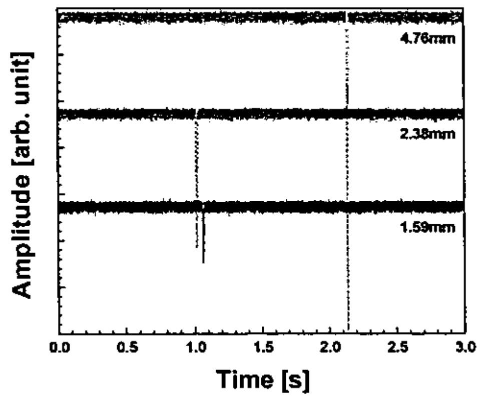

Figure 14. The reduction of the ultrasonic signal due to the presence of one metal ball of 1.59, 2.38 and 4.76 mm diameter flowing in the water.

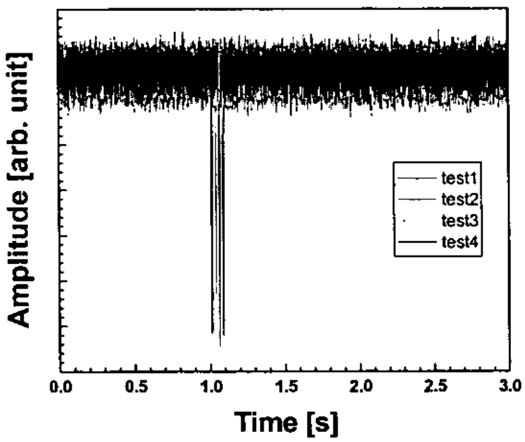

Figure 15. The reduction of the ultrasonic signal due to the presence of one metal ball of 1.59 mm diameter flowing in the water repeated four times.

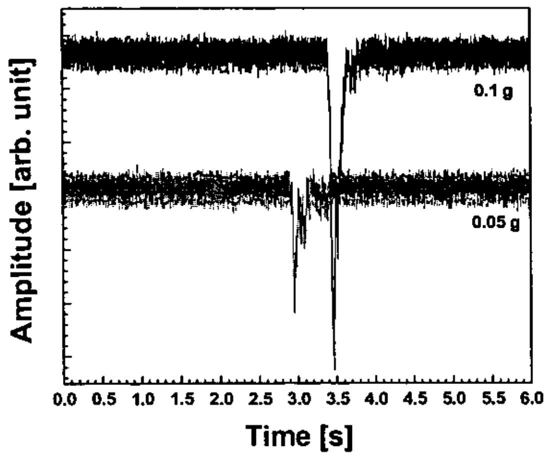

Figure 16. The reduction of the ultrasonic signal due to the presence of copper powders of average size of 100-500μm diameter with a total weight of 0.05 g and 0.1 g flowing in the water.

4. CONCLUSIONS

Integrated piezoelectric-based ultrasonic transducers (UTs) have been developed for potential structural health monitoring and integration into prognostics health management systems. Fabrication techniques focused on the use of handheld and readily accessible equipment to perform sol-gel spray coating using a heat gun and torch to achieve drying and firing, poling and electrode-fabrication in the manufacture of these transducers. These UTs can be fabricated at desired NDT sites. In this investigation, the PZT powders were dispersed into PZT solution as the piezoelectric composite material for spraying at room temperature. The merits of these integrated UTs are (1) no need for couplant, (2) applicable to complicated and complex surfaces, (3) operable in the pulse-echo and transmission mode and (4) efficient to be used for temperature up to 400°C [3,4]. For the first time these UTs have been successfully integrated onto graphite/epoxy composites for ultrasonic thickness measurement. The ultrasonic performance of integrated UT on aluminum plates for thickness monitoring at 150°C and for the monitoring of the ice accumulation on aluminum plate was demonstrated. This simulated the accumulation of ice on wings of airplanes, which always poses a serious safety concern for operators. In addition, the integrated PZT/PZT UT can sustain 100°C operation temperature. Integrated UTs were also deposited onto metal pipes for real-time viscosity measurement of a simulated cooling oil flow at temperatures up to 160°C. Metal ball bearings, of 1.59, 2.38 and 4.76 mm in diameter, and copper powders, of 100-500 μm diameters in a total weight of 0.05 and 0.1 g, in flowing liquid simulating metal debris in cooling oil engines were clearly identified by monitoring the reduction of transmitted signals through a metal pipe. Thus, the integrated UT system can be used as well for both viscosity and metal debris diagnostics.

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