Engine Oil Condition Monitoring Using High Temperature Integrated Ultrasonic Transducers

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ABSTRACT

The present work contains two parts. In the first part, high temperature integrated ultrasonic transducers (IUTs) made of thick piezoelectric composite films, were coated directly onto lubricant oil supply and sump lines of a modified CF700 turbojet engine. These piezoelectric films were fabricated using a sol-gel spray technology. By operating these IUTs in transmission mode, the amplitude and velocity of transmitted ultrasonic waves across the flow channel of the lubricant oil in supply and sump lines were measured during engine operation. Results have shown that the amplitude of the ultrasonic waves is sensitive to the presence of air bubbles in the oil and that the ultrasound velocity is linearly dependent on oil temperature. In the second part of the work, the sensitivity of ultrasound to engine lubricant oil degradation was investigated by using an ultrasonically equipped and thermally-controlled laboratory test cell and lubricant oils of different grades. The results have shown that at a given temperature, ultrasound velocity decreases with a decrease in oil viscosity. Based on the results obtained in both parts of the study, ultrasound velocity measurement is proposed for monitoring oil degradation and transient oil temperature variation, whereas ultrasound amplitude measurement is proposed for monitoring air bubble content.

1. INTRODUCTION

Engine oil condition includes oil viscosity, oil cleanliness, air bubble content, and oil temperature. Being able to monitor these parameters will not only safeguard engine operation under an oil condition it was designed for, but will also provide a means to assess the health of the entire engine system since any deviation from the nominal state of these parameters could be linked to one or more faulty components. Among oil condition monitoring systems presently used in aircraft engines, inductive oil debris monitor sensor offered by GasTOPS can be fitted to oil lube line and is capable of counting and sizing ferrous and non-ferrous particles above minimum size; Quantitative Debris Monitor (QDM®) technology offered by Eaton Aerospace captures ferrous wear debris and counts ferromagnetic particles exceeding a pre-set mass threshold; Zapper® pulsed electric chip detector system, also offered by Eaton Aerospace, captures ferrous debris and issues a warning signal to prompt for an action when debris buildup bridges the gap between two electrodes. Ultrasound, when applied judiciously and under favorable conditions, has the capability to sense all the aforementioned oil condition parameters. Although methods employing piezoelectric ultrasonic transducers (UTs) have been widely used for real-time, in-situ or off-line non-destructive evaluation (NDE) of large metallic structures including airplanes, automobiles, ships, pressure vessels, pipelines, etc., owing to their subsurface inspection capability, fast inspection speed, simplicity and cost-effectiveness (Gandhi et al., 1992; Ihn et al., 2004; Birks et al., 1991), applications of piezoelectric UTs to engine condition monitoring are relatively few due to difficulties in implementing UTs at elevated engine operating temperatures. In the present work, integrated UT (IUT) and associated wiring assembly designed for engine condition monitoring were fabricated directly onto the lubricant oil supply and sump lines of a modified CF700 turbojet engine. The applicability of the IUT assemblies to real-time engine condition monitoring was then investigated. The engine conditions of interest were air bubble content in the oil supply line, oil viscosity degradation and temperature. In order to assess the capability of ultrasound for oil viscosity degradation monitoring, four lubricant oils were tested in a temperature range of 50 °C to 130 °C by using an ultrasonically equipped test cell.

In the present paper, actual engine and laboratory tests setups and results are presented. Based on the results, ultrasonic approaches for real-time monitoring of air bubble content in oil, oil viscosity degradation, and oil temperature are proposed. Some implementation details and advantages associated with the proposed approaches are discussed.

2. ENGINE OIL CONDITION MONITORING EXPERIMENT

A modified CF700 turbojet engine (with fan module removed), shown in Figure 1, was used as representative of typical vibration, temperature and oil environments, as well as component materials and surface finishes. This engine platform offered the opportunity to assess oil flow in typical fully developed supply line flows and substantially aerated sump return line flows.

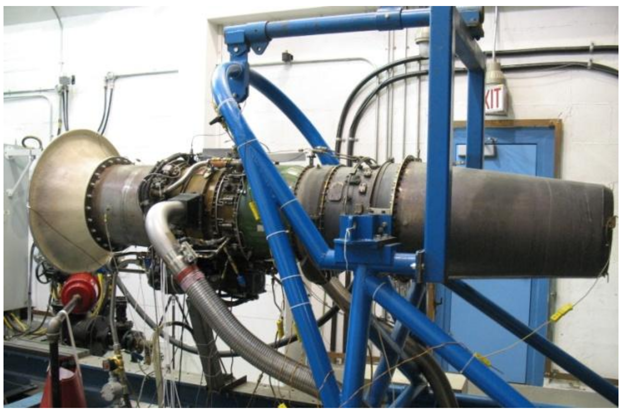
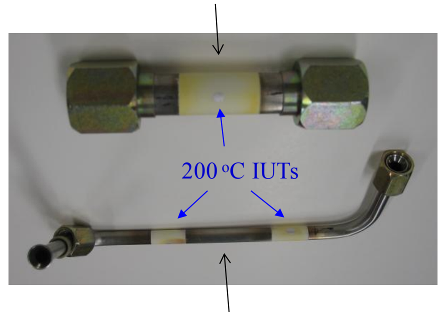


Figure 1. A modified CF700 turbojet engine.

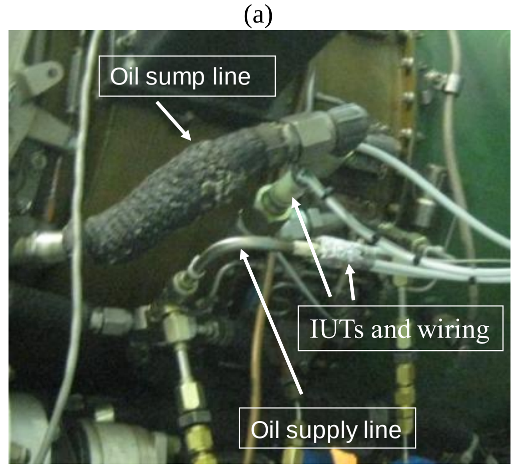
The fabrication of IUTs involves a sol-gel based sensor fabrication process (Kobayashi et al., 2004, 2009) consisting of six main steps: (1) preparation of high dielectric constant lead-zirconate-titanate (PZT) solution, (2) ball milling of piezoelectric bismuth titanate (BIT) or PZT powders to submicron size, (3) sensor spraying using slurries from steps (1) and (2) to form a thin UT film, (4) heat treating to produce a thin solid BIT composite (BIT-c) or PZT composite (PZT-c) film, (5) Corona poling to obtain piezoelectricity, and (6) electrode painting for electrical connectivity. Steps (3) and (4) are repeated multiple times to produce optimal film thickness for specified ultrasonic operating frequency and performance. Silver or platinum paste was used to fabricate top electrodes. BIT-c film is to be used for higher temperature applications (e.g. temperature endurance of 500 °C) (Kobayashi et al., 2004, 2009); whereas PZT-c film is to be used when higher piezoelectricity than BIT-c film is required and when temperature is lower than 200 °C. A series of aging and thermal shock resistance tests have been conducted on sprayed-on films. In one test, a PZT-c film was subjected to 375 thermal cycles between 22 °C and 150 °C. In one aging test, a PZT-c film was heated in a furnace at 200 °C for over 300 days. In another aging test, a PZT-c film was excited with a 125 Volt pulse at 1 kHz pulse repetition rate for 1500 hours. The films performed well in all the tests.

Sump Line Pipe
(O.D. = 15.60 mm, wall thickness = 0.80 mm)



Supply Line Pipe
(O.D. = 7.92 mm, wall thickness = 1.09 mm)

(a)



(b)

Figure 2. PZT-c film IUTs (200°C) coated onto the sump and supply lines pipes before installation on the engine (a) and installation of ultrasonically instrumented oil sump and supply lines (b).

The present work aimed at performing monitoring during an actual engine test. PZT-c film IUTs were first coated on metal tubing of sump and supply lines (Figure 2(a)) and then these tubes were reinstalled in the engine as shown in Figure 2(b). The cables used could sustain temperatures of up to 200°C. The center frequencies of these PZT-c film IUTs were in the range of 10 to 12 MHz. The IUTs were operated in transmission mode whereby one IUT was used as a transmitter and another on the opposite side of the tube as a receiver. Two ultrasonic systems were used to monitor simultaneously oil in the supply and sump lines. Ultrasonic diagnostic signals were generated at a pulse repetition rate of 10 Hz, and digitized at a sampling rate of 100 MHz. The digitized signals were sent to a remote computer via a 40 meter-range USB communication adaptor for processing. In the meantime, oil temperatures in the sump and supply lines as well as engine speed, together with other engine operation related parameters were measured and recorded with a separate data acquisition system (DAS). The oil used was grade BPTO 2380 by Air BP USA.

Table 1 describes a test schedule developed as representative of transient and steady state operations. Data recording by DAS was controlled manually. Both steady state (SS) and transient (TR) recordings of engine data were conducted at every 50 milliseconds (20 Hz) when the engine speed was changed, after stabilization of two minutes, and after engine shutdown. The points and transitions selected are representative of basic performance tests in a test cell. The maximum speed is limited to 80% because of the matching of the engine and test cell airflow capabilities.

Sequence	**Case**	**Notes**	**Status to record (SS: steady state TR: transient state)**
1	Start-up	Take point before startup and during transient to idle	SS, TR
2	Idle	5 min @ idle, 50%, take points @ 2 min and 5 min	SS,SS
3	Slow accel.	30 second acceleration to 65%, hold for 2 min	TR, SS
4	Slow accel.	30 second acceleration to 80%	TR
5	Hold @ 80%	5 min hold @ 80%	SS
6	Slow decel.	30 second deceleration to 65%, hold, take points @ 2 min	TR, SS
7	Slow decel.	30 second deceleration to idle, hold, take points @ 5 min	TR, SS
8	Slow accel.	30 second acceleration to 65%, hold for 2 min	TR, SS
9	Slow accel.	30 second acceleration to 80%	TR
10	Hold @ 80%	5 min hold @ 80%	SS
11	Slow decel.	30 second deceleration to 65%, hold, take points @ 2 min	TR, SS
12	Slow decel.	30 second deceleration to idle, hold, take points @ 2 min	TR, SS
13	Shut-down	shut down, take SS after engine has stopped	TR, SS

Table 1 Schedule of an engine test

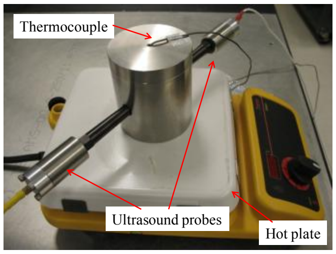
3. STATIC ULTRASONIC MEASUREMENT

A test cell shown in Figure 3 was used for studying the sensitivity of ultrasound to oil viscosity. The data will be presented in the Results and Discussion section. The ultrasound probes were composed of a stainless steel rod and a PZT-c film deposed on one end of the rod. The probes were intrusively mounted in the test cell with the inside end being in touch with the oil sample. One probe was used as transmitter and the other as receiver. A thermocouple was used for oil temperature measurement. Two oil samples of grade BPTO 2380 and two samples of a generic car motor oil with viscosity rating of SAE 5W20 were tested. Of the two BPTO 2380 samples, one was fresh and the other was degraded due to long term storage. These two samples can be easily differentiated from their colors as shown in Figure 4. For the two generic car motor oil samples, one was in fresh condition, and the other was used. Their difference could also be seen from their color difference. During the testing, the test cell was wrapped with a piece of thermal insulation fabric and was heated up to a pre-set temperature (130 °C). After the test cell reached thermal equilibrium, the heater was turned off and then data acquisition was carried out when the test cell was cooled naturally in a 23 °C room temperature setting. The cooling rates were about 1.3 °C/minute and 0.3 °C/minute when the oil temperatures were at 112 °C and 40 °C, respectively. We estimated that these cooling rates were slow enough to ensure a uniform temperature distribution in the probed section. The distance between the probing ends of the ultrasound probes was determined at room temperature by using water as sound wave propagation medium in the test cell and by measuring the transit time, t, for ultrasonic waves to travel the distance between probes ends. This distance was measured to be $d=c\times t$=9.59 mm, where c is the sound speed in water at 23 °C.

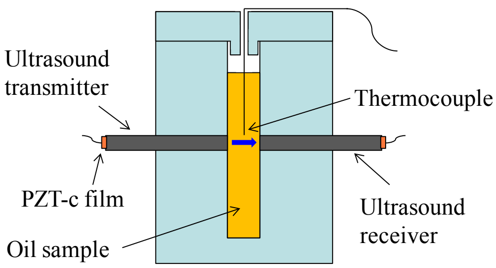
In a parallel experiment, the viscosities of the four oil samples were measured using a constant stress rotational rheometer, SR-200, presented in Figure 5. The strain response as a function of time under a constant stress load was monitored in a Couette type testing environment, at room temperature. The measured oil viscosities, resulting from the step stress (creep) measurements, are listed in Table 2.

BPTO 2380		**Generic 5W20**	
Fresh	0.0448	Fresh	0.1041
Old	0.0406	Used	0.0841

Table 2 Oil viscosity at 22 °C (Pa·s)



(a)



(b)

Figure 3. Ultrasonically instrumented testing cell used in the study. (a) picture of the setup; (b) schematic of a section view.

Figure 4. Fresh (left) and degraded (right) BPTO 2380 oil samples.

Figure 5. Rotational rheometer (Rheometrics SR-200) used for oil viscosity measurement.

4. RESULTS AND DISCUSSION

Figure 6 displays the variation of engine speed during the test described in Table 1. The asterisks represent the average of 20 samples acquired within a one-second period when the engine stabilized whereas the solid lines represent the speed when the engine was in a transient state.

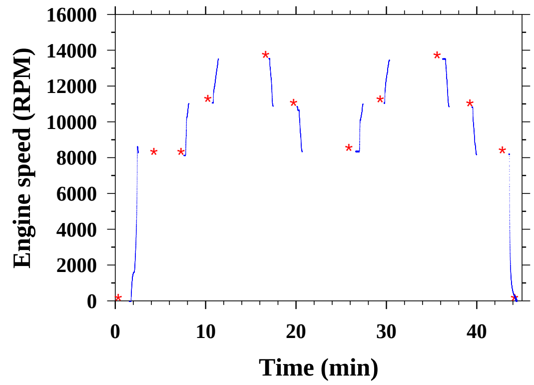


Figure 6. Variation of engine speed during the test scheduled in Table 1. The asterisks represent the steady state recording and the solid lines represent the transit state recording.

Figure 7 illustrates variation of oil temperature, measured with a T-type thermocouple, during the same engine test. By comparing Figures 6 and 7 one can see that oil temperature increased with increase of engine speed. The oil in the supply line was at higher temperatures than that in the sump line.

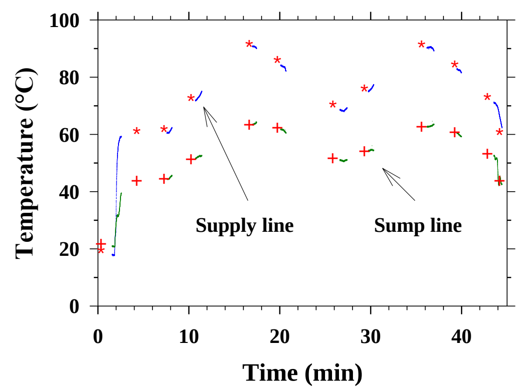
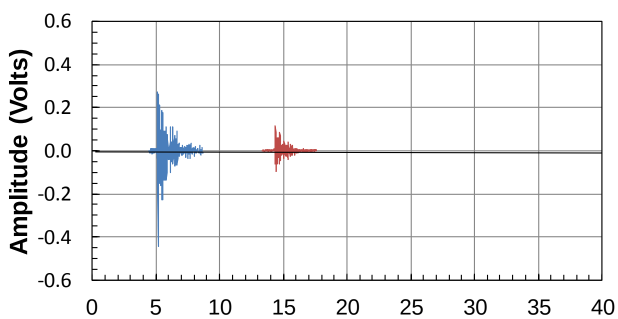


Figure 7. Variations of engine oil temperatures in the supply and sump lines. The asterisks represent the steady state recording and the solid lines represent the transit state recording.

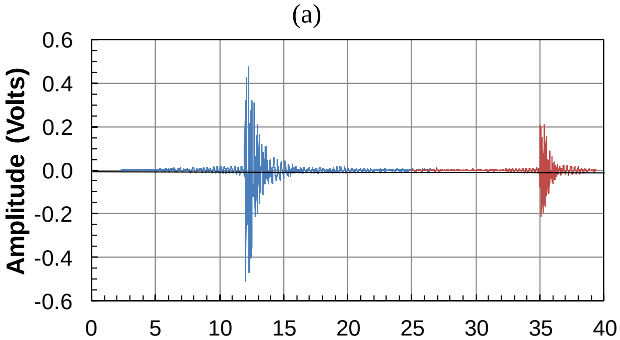
Figure 8 displays one ultrasonic signal acquired in the supply line (a) and one in the sump line (b). In these recordings, not only the first transmitted signal (1st arrival), but also the second arrival resulting from one round-trip reflection of the first transmitted signal inside the oil flow channel are seen clearly. Since the sump line tube has a larger inner diameter, the ultrasonic signals across it arrive later than those in the supply line. Knowing the inner diameter of a pipe, d, and time delay between the 1st and 2nd signal arrivals, τ, the sound velocity in the oil can be obtained as $V=2d/\tau$.

Figure 9 displays the variation of the signal-to-noise ratio (SNR) of the 2nd arrival of the transmitted signals shown in

Figure 8. The signal-to-noise is defined as 20log10(Asig/Anoise) with Asig and Anoise being respectively the peak-to-peak amplitude of the signal and the peak-to-peak amplitude of the noise measured just before the signal arrival. The display covers about 40 minutes of process time with each data point being the SNR of one acquired signal. Since ultrasound signals were generated at a pulse repetition rate of 10 Hz, about 24,000 data points are displayed for each test result. A large signal-to-noise ratio means a strong transmitted signal. While the SNR of signals measured in the supply line remains high and quasi constant, the SNR of signals measured in the sump line fluctuates significantly. For two reasons the signal quality fluctuation in the sump line is believed to be caused by the presence of air bubbles in the oil. First, the high sensitivity of ultrasound amplitude to air bubbles has been proven by extensive experimental and theoretical work (Leighton T., 1996). Second, air bubbles do get trapped in the oil circuit. The air was forced into the oil mainly by the high speed rotation of the bearing (and the parts in it like the balls and cage). The foamy oil left the bearing, passed into a sump and was drawn through the sump line to an oil/air separator. The recovered oil was then sent back through the supply line to the oil circulating system. The variation of SNR indicates that the quantity of air in the oil varied during the test. At the beginning of the test, the oil in the sump line had few bubbles. This translates into strong signals (high SNR).



(a)



(b)

Figure 8. A trace of ultrasound signal recorded with supply line IUTs (a) and sump line IUTs (b).

On comparing Figures 6 and 9, overall, a higher engine speed with higher oil flow rate and temperature appears to lead to larger counts of low SNR. The signal quality in the supply line was stable because the oil was pumped and filtered before being sent to the ultrasonically probed section of the supply line. The sensitivity of ultrasound to air bubbles indicates that ultrasound can be used to evaluate the quantity of air bubbles in the engine oil supply system. Thus condition monitoring assessments might be made of the oil system integrity and oil condition. A preliminary study on using this technique for detection of metal particles was carried out previously (Kobayashi et al., 2007). Further studies with injected debris are underway to assess if the approach may also be used to detect the presence of metal debris in the oil circuit.

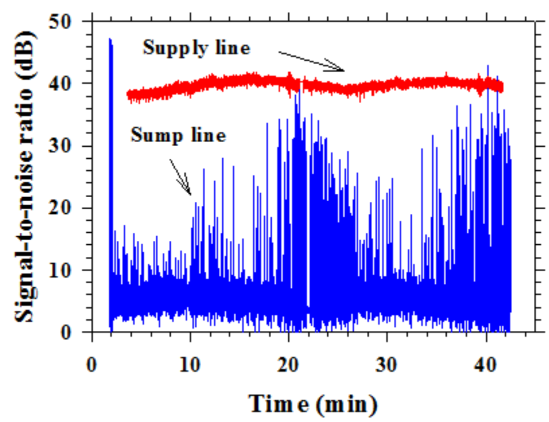


Figure 9. Variation of the signal-to-noise ratio of the 2nd arrival of transmitted signals in the supply (upper curve) and sump (lower curve) lines.

Figure 10 illustrates the variation of ultrasound velocity in the engine oil in the supply line (solid line). The circled cross hairs represent the ultrasonic measurement data recorded at the same times the steady state recordings, shown in Figures 6 and 7, were taken by the DAS. Figure 11 shows the variation of ultrasound velocity versus temperature using the steady state recorded data. Also shown in the figure is a linear regression fit of the sound velocity versus oil temperature data, illustrating the linear dependence of ultrasound velocity on engine oil temperature.

The measured viscosities of the oil samples (BPTO 2380 and generic 5W20) are listed in Table 2. Figure 12 presents the relationship between ultrasound velocity and temperature for the four oil samples measured with the test cell illustrated in Figure 3. Significant difference is observed between oil families BPTO 2380 and generic 5W20. In order to better assess the sensitivity of ultrasound velocity to the freshness state of the oil, closer views are provided in Figures 13 and 14. For each oil sample, several tests were performed to evaluate the consistency of the results. For each oil family, the fresh sample, which possesses a higher viscosity, has a higher ultrasound velocity. This indicates that oil viscosity degradation can be assessed by monitoring the decrease in ultrasound velocity. However, the ultrasound velocity is quite sensitive to oil temperature. The ultrasound velocity difference between the fresh and the used (or degraded) oil samples can be easily offset by a temperature variation of merely 0.7 °C. This makes in-flight ultrasonic oil viscosity monitoring more challenging since the oil temperature has to be accurately monitored to compensate for ultrasound velocity change by temperature. This difficulty could be overcome if the following conditions are observed: (1) The thermocouple used for oil temperature measurement performs consistently over time; (2) a fairly large number (e.g. 100) of ultrasound velocity and oil temperature readings are taken in a short period of time during which the oil temperature change is considered negligible. Then the averages of these readings (which are much less affected by random noise in ultrasound and temperature signals) can be used to represent the physical state of the oil. Practically speaking, today's thermocouples can be made to be inexpensive and robust. Not only does this mean that long term reliability and consistency of thermocouples are generally guaranteed, but it also means that more than one thermocouple could be implemented economically to cross-check oil temperature, thus significantly reducing the chance of having erroneous readings. The second requirement can also be fulfilled easily given that today's data acquisition systems can deliver hundreds of readings per second with ease and that stable oil temperature is achievable after the engine enters a steady state. Although technically achievable, the necessity of precise oil temperature measurement, usually through an intrusive temperature sensor, would negate the benefit of non-invasive ultrasonic viscosity measurement. A pure acoustic viscosity measurement solution is highly desirable and will be the subject of a follow-up research.

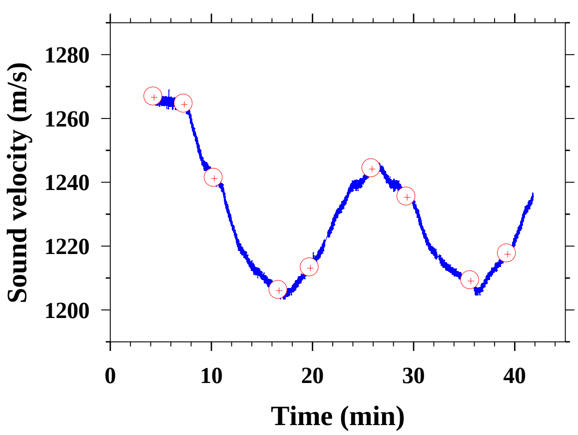


Figure 10. Variation of ultrasound velocity in the engine oil in the supply line (solid line). The circled cross hairs represent the ultrasonic measurement data recorded at the same times the steady state recordings were taken by DAS.

It is observed in Figures 13 and 14 that the sound velocity variation induced by a change in oil viscosity would not exceed that caused by 1 ºC of oil temperature change. This indicates that ultrasound velocity can be used for oil temperature sensing with guaranteed uncertainty smaller than 1 ºC regardless of oil freshness state. Compared with conventional thermocouples, ultrasonic temperature measurement has the advantages of having instant response, providing average temperature over the entire monitored section instead of a limited area at the sensing tip of a thermocouple, and not being affected by the temperature of the oil tube on which the ultrasound transducers are mounted. These beneficial features may make ultrasonic temperature measurement particularly attractive for capturing abnormally fast oil temperature surges which may come as an early sign of a deficient engine component.

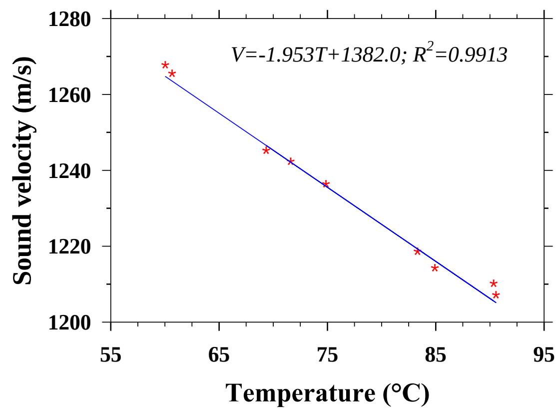


Figure 11. Variation of ultrasound velocity versus the temperature of engine oil in the supply line. The asterisks represent the steady state recording and the solid line represents a linear regression fitting.

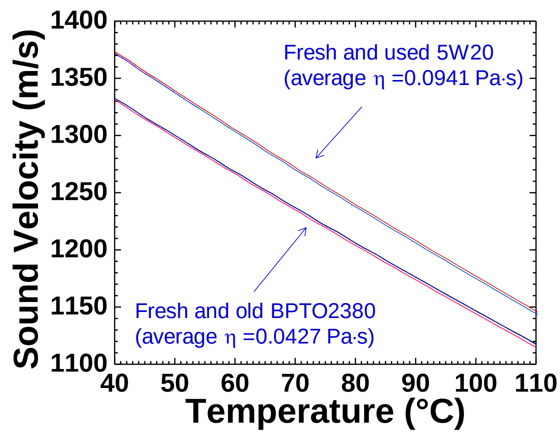


Figure 12. Ultrasound velocity versus temperature relationship for four oil samples measured with the testing cell shown in Figure 3.

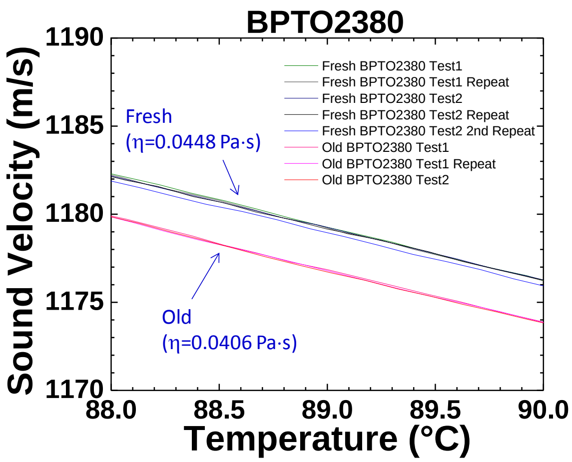


Figure 13. Ultrasound velocity versus temperature relationship for BPTO 2380 oils.

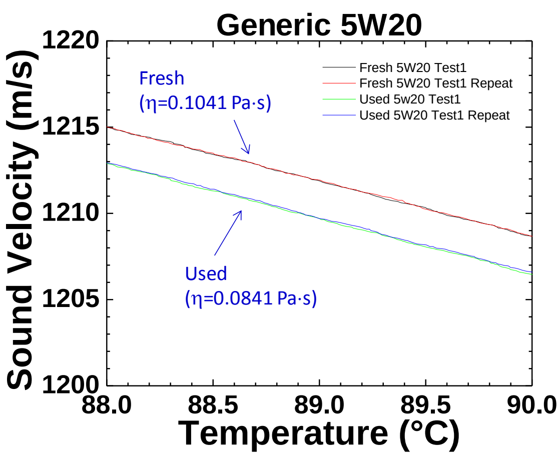


Figure 14. Ultrasound velocity versus temperature relationship for the generic 5W20 oils.

5. CONCLUSIONS

High temperature integrated ultrasound transducers made of thick piezoelectric composite films have been coated onto the lubricant oil supply and sump lines of a modified CF700 turbojet engine. These transducers have been used during an actual engine test cell operation to evaluate their potential usefulness in engine oil condition monitoring. Furthermore, a study on the sensitivity of ultrasound to engine lubricant oil viscosity degradation has been carried out using a thermally-controlled laboratory test cell and lubricant oils of different grades. The actual engine tests results and laboratory tests results have shown that the presented ultrasound technique can provide an effective non-intrusive means for detection of air bubbles in the oil supply line (oil system component degradation/failure) and for instantaneous oil temperature measurement. The capability of the technique for oil viscosity measurement is compromised by the necessity of simultaneous oil temperature measurement. The applicability of the technique to absolute temperature measurement and to the detection of metal debris in oil needs to be further investigated in the future.

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