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ENGINE OIL CONDITION MONITORING USING HIGH TEMPERATURE INTEGRATED ULTRASONIC TRANSDUCERS

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ABSTRACT

High temperature integrated ultrasonic transducers (IUTs) made of thick piezoelectric composite films have been coated directly onto the lubricant oil supply and sump lines of a modified CF700 turbojet engine. These thick piezoelectric films are fabricated using a sol-gel spray technology. The center frequencies of these IUTs are in the range of 10 to 12 MHz. The top electrodes, electrical wires, conducting adhesive bond, connectors and cables have been tested successfully for temperatures of up to 500°C. By operating these IUT 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. The results have shown that the strength 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. Based on the sensitivity of ultrasound velocity to oil temperature, a method for real-time monitoring of engine oil degradation is proposed.

INTRODUCTION

The increasing demand to improve the performance, reduce downtime, increase reliability and extend the life of engines requires the use of sensors for continuous engine condition monitoring during development and service. 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. because of their subsurface inspection capability, fast inspection speed, simplicity and cost-effectiveness [1-3], applications of piezoelectric UTs to engine condition monitoring are relatively few due to

difficulties in implementing UTs at elevated engine operation temperatures. In the present work, integrated UT (IUT) and associated wiring assembly designed for engine condition monitoring were fabricated and tested for temperatures of up to 500°C. The wiring assembly include top electrodes, electrical wires, conducting adhesive bond, connectors and cables. Then the applicability of the IUT assemblies to real-time engine condition monitoring was investigated. The engine conditions of interest were air bubbles and metal or other debris in the engine oil supply line and engine oil viscosity condition.

**INTEGRATED ULTRASONIC TRANSDUCER
FABRICATION AND TESTING**

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

The fabrication of IUTs involves a sol-gel based sensor fabrication process [4-6]. Such process consists of six main steps: (1) preparing 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 because of its high temperature (500°C) endurance [5, 6]. PZT-c film is to be used when higher piezoelectricity than BIT-c film is required and when temperature permits (up to 200°C).

Figure 1 A modified CF700 turbojet engine.

For illustration purpose, Figure 2(a) shows a BIT-c film IUT coated onto an engine bleed line access cover, together with high temperature silver paste top electrode, electrical conducting bonding, and electrical conducting wire. The same wiring technique was used for PZT-c film IUTs coated on the oil supply and sump lines. (This instrumented access cover was used in a separate study in which the feasibility of using ultrasound for engine body temperature measurement was investigated.) Figure 2(b) shows the installation of this access cover on the engine body.

In order to test the fabricated BIT-c film IUTs and silver paste top electrodes, electrical connectors, and conductive adhesive, a 25.4 mm diameter 150 mm long steel rod, simulating the engine component, has been used for the deposition of IUTs (Figure 3(a)). The center frequencies of these IUTs were about 10 MHz at room temperature. Such an assembly was placed into a furnace (Figure 3(b)) and thermally cycled from room temperature to 500°C. The results of two thermal cycles are shown in Figure 4. The upper and middle traces indicate the ultrasonic signal with a high signal-to-noise ratio (SNR) which traveled a distance of 300 mm. The middle trace is a zoomed view of the upper trace. The lower trace in Figure 4 indicates the temperature profile in the oven during thermal cycles. To the right of the middle trace is the attenuation number (Attn) indicating the total loss of IUT, electrical connections and ultrasonic attenuation propagating via a round trip of the 150 mm long steel rod. At 500°C this attenuation was only 6 dB.

EXPERIMENTAL FOR ENGINE OIL CONDITION MONITORING

In a previous study, ultrasonic monitoring of lubricant quality and metal debris was simulated [9]. The present work aimed at performing such monitoring during an actual engine test. PZT-c film IUTs were first coated on metal tubing of sump and supply lines shown in Fig. 5(a) and then these tubes were reinstalled in the sump and supply lines as shown in Fig. 5(b). The cables used can 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 an ultrasound transmitter and another IUT on the opposite side of the tube as a receiver. Two SIMI ultrasonic systems supplied by PACE Simulations Inc. 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 (T type thermocouple) in the sump and supply lines as well as engine speed, together with many other engine operation related parameters were measured and recorded with a separate data acquisition system (DAS). The engine oil used was grade BPTO 2380 by Air BP USA.

(a)

(b)

Figure 2 An engine bleed port access cover (a) illustrating wiring connection of a BIT-c film IUT (500°C) and its installation on the engine body (b).

Figure 3 (a) One IUT made of BIT-c films on top of a steel rod (delay line) together with top electrode, wire connection, conducting adhesive bond, electrical connector and cable; (b) 500°C thermal cycle test chamber.

Figure 4. Thermal cycle tests of 500°C BIT-c film IUT directly coated on top of a 150 mm long steel rod including top electrode, conducting bond, wire, connector and cable.

Table 1 describes an engine 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 (20 Hz) of engine data were made when the engine speed was changed.

RESULTS AND DISCUSSIONS

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

Figure 5. Ultrasonically instrumented oil sump and supply lines (a) and PZT-c film IUTs (200°C) coated onto the sump and supply lines pipes before installation on the engine (b).

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.

Table 1. Schedule of an engine test

Sequence	Case	Notes	Status to record
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 acceleration	30 second accel to 65%, hold for 2 min	TR, SS
4	Slow acceleration	30 second accel to 80%	TR
5	Hold @ 80%	5 min hold @ 80%	SS
6	Slow deceleration	30 second decel to 65%, hold, take points @ 2 min	TR, SS
7	Slow deceleration	30 second decel to idle, hold, take points @ 5 min	TR, SS
8	Slow acceleration	30 second accel to 65%, hold for 2 min	TR, SS
9	Slow acceleration	30 second accel to 80%	TR
10	Hold @ 80%	5 min hold @ 80%	SS
11	Slow deceleration	30 second decel to 65%, hold, take points @ 2 min	TR, SS
12	Slow deceleration	30 second decel to idle, hold, take points @ 2 min	TR, SS
13	Shut-down	shut down, take SS after engine has stopped	TR, SS

Figure 7 displays variations of oil temperatures during the same engine test. As can be seen in the figure, in the present test, the oil temperature increases with increasing engine speed. The oil in the supply line has higher temperatures than that in the sump line.

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 case of 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 readily obtained as $V=2\tau/d$.

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

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

Figure 9. Variation of ultrasound velocity in the engine oil in the supply line. The circled x-hairs represent the samples recorded at the same times the steady state recordings were taken by DAS.

Figure 10. 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 fit.

Figure 9 displays the variation of ultrasound velocity in the engine oil in the supply line. The circled x-hairs represent the samples recorded at the same times the steady state recordings were taken by DAS. By comparing Figure 9 and 7 one can see that the ultrasound velocity follows a density or viscosity trend - an opposite trend as compared to that of temperature. Figure 10 displays the variation of ultrasound velocity versus temperature by using the steady state recording data. Also shown in the figure is a linear regression fit of the sound velocity versus oil temperature data. Clearly the ultrasound velocity in the engine oil depends linearly on oil temperature. Since the viscosity of an engine oil decreases with increasing temperature (and vice versa), the high sensitivity of ultrasound velocity to oil temperature change implies high sensitivity of ultrasound velocity to oil viscosity. For real-time oil condition (i.e., oil degradation) monitoring, one can combine ultrasound velocity and oil temperature measurements and

compare the measured ultrasound velocity versus oil temperature relationship with the one established previously when the engine oil was fresh. A deviation of the measured relationship from the pre-established one would mean a change (or degradation) in oil condition.

Figure 11. 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 11 displays the variation of the signal-to-noise ratio (SNR) of the 2nd arrival of transmitted signals shown in Figure 8. A large signal-to-noise ratio means a strong transmitted signal. While the quality of this signal remains high and quasi constant for the supply line, that measured in the sump line fluctuates significantly. The signal quality fluctuation in the sump line was caused by the presence of air bubbles in the oil. 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 of quantity of air in the oil varied during the test. At the beginning of the test, the oil in the sump line had few air bubbles. This translates into strong signals (high SNR). Overall, a higher engine speed with higher flows and temperatures appears to lead to higher 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. Further studies with injected debris are planned to study if the approach may also be used to detect the presence of metal debris.

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 operations to evaluate their potential usefulness in engine oil condition monitoring. The results suggest that by combining ultrasound velocity and oil temperature measurements, the engine oil condition could be monitored to provide improved maintenance decisions. The results have also shown that the signal-to-noise ratio of ultrasonic signals through the lubricant oil is sensitive to the presence and the quantity of air bubbles in the oil. This information is also attractive for maintenance decision support. Further work is planned to integrate these oil condition assessments to the detection of metal debris in the engine oil.

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