REMOTE THICKNESS MEASUREMENT OF OIL SLICKS ON WATER BY LASER-ULTRASONICS

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ABSTRACT: At the National Research Council of Canada Industrial Materials Institute, research is in progress on the application of laser-ultrasonics to remote measurement of the thickness of oil on water. Laser-ultrasonics is a novel technique developed for the nondestructive inspection of materials. It uses a short pulse laser for the generation of ultrasonic waves in the oil layer and a second laser, coupled to an optical interferometer, for the remote detection of the ultrasonic surface motion. Direct measurement of the time of flight of the ultrasonic wave provides the value of the thickness of the oil layer. Application of this technique to thickness measurement of oil on water has been studied in small and large scale laboratory tests. Small scale tests demonstrate the direct and unambiguous determination of the oil layer thickness. Accuracy is essentially limited by the knowledge of the acoustic properties of the oil. Large scale tests show that a distance of almost 37 meters does not severely impede the method, so airborne application appears possible. Surface motion such as that caused by sea waves does not reduce the accuracy of the thickness determination but does limit the measurement rate. Preliminary airborne tests with a single laser probe confirm that laser-ultrasonics monitoring of the thickness of an oil spill is feasible.

Remote sensing is an important tool in oil spill management. Cleanup personnel have recognized that remote sensing can increase the effectiveness of countermeasures. Remote sensing can also provide a better understanding of the physical behavior of an oil slick. Presently numerous systems are available commercially that can identify the presence and position of oil on water. However, no absolute method is available for the remote measurement of the thickness of oil on water. Laser-ultrasonics, a novel technique developed for nondestructive evaluation of materials at the National Research Council of Canada Industrial Materials Institute (IMI), seems to be a promising avenue for such a remote measurement. This technique combines the precision and unambiguity of thickness determination by ultrasonics with the remote sensing capability of optics.

The principle of thickness measurement by ultrasonics is rather simple. Let us assume that a high frequency ultrasonic pulse has been launched through a sample by a suitable transducer. When it reaches the back surface, or the interface in the case of liquids, it is partially transmitted and partially reflected back toward the surface. After a delay proportional to the thickness of the sample, this reflected acoustic pulse reaches the surface causing a displacement that can be monitored by the launching ultrasonic transducer. This echo of the initial pulse is reflected back toward the bottom of the sample. The ultrasonic pulse travels, therefore, back and forth partially losing its energy by attenuation in the sample itself and partially by transmission through the interfaces. It produces a periodic surface displacement. If the acoustic velocity in the sample is known, measurement of the time delay between the arrival at the surface of two consecutive echoes yields an accurate measurement of the sample thickness. This thickness measurement technique requires access to only one surface of the sample. It requires, however, that the acoustic impedance of the sample and of the backing medium are sufficiently different so that a sizable fraction of the acoustic energy is reflected back towards the surface. Generally, the delay is determined by cross-correlation of two consecutive echoes. If the medium is not dispersive, that is, if the acoustic velocity is not a function of frequency, the error in the estimate of the delay is inversely proportional to the bandwidth of the acoustic pulse and to the signal-to-noise ratio. This provides a high precision of the delay estimate, and hence, a high precision of the thickness measurement.

Conventional ultrasonics requires contact between the sample and the transducer, which is not always possible. For example, in steel mill applications, the temperature of the sample is sometimes too high to be sustained by the transducer. In these cases, a noncontact probing system is needed. Laser-ultrasonics, which uses a high power pulse laser to generate the ultrasonic pulse and a second probe laser to monitor the surface displacement resulting from the ultrasonic echoes, eliminates these difficulties. In laser-ultrasonics, the absorption of the high power laser pump pulse produces a thermal pulse in the sample. The thermal pulse generates a rapid thermal expansion of the sample near the surface where the laser beam was absorbed. The resulting pressure wave produces a step-like rise of the sample surface as well as an acoustic pulse of high frequency and large bandwidth, typically about 15 MHz in the case of oil. After a delay determined by the thickness and the acoustic velocity of the sample, the acoustic pulse returns to the surface.
and produces a slight surface displacement. Figure 1 shows the surface displacement, as function of time, of a 2 mm oil layer on water generated by a 100 mJ laser pulse with a 100 ns rise time. (Physical properties of oil and water used for this calculation are given in Table 1.) Notice the sharp initial step displacement, which is followed by the echoes.

To measure the surface displacement, a second laser beam, the probe beam, is directed onto the surface of the sample. The surface motion produces a phase shift or frequency shift (Doppler effect) upon the reflected probe beam. The ultrasonic surface displacement is therefore encoded as a frequency or phase modulation of the probe beam. To perform the demodulation, IMI has developed a technique based on a confocal Fabry-Pérot laser interferometer. The Fabry-Pérot acts essentially as a very narrow optical filter which directly permits clear observation of the second echo, which is barely visible on the displacement curve. This technique is very insensitive to low frequency motions, such as those generated by vibrations, and highly sensitive to high frequency surface displacements generated by the ultrasonic pulse. Additional low frequency filtering is usually added to reduce the noise level further. Figure 1 also shows a typical signal provided by the confocal Fabry-Pérot interferometer scheme, sensitivity is essentially determined by the light intensity received by the detector. Fortunately, oil is a very good specular reflector at 1.06 µm, the probe beam wavelength used. The probe beam is totally reflected, with the exception of the ripples of capillary waves at the oil-water interface. The main loss affecting the probe beam intensity is caused by the low optical reflection coefficient of oil, about 4.5 percent at the probe beam wavelength. This loss is not a severe problem since the probe laser has a very high intensity.

The accuracy of the oil thickness measurement by laser-ultrasonics is determined by both the precision in the determination of the time delay between echoes and by the accuracy of the value of the acoustic velocity of oil. In this case, it turns out that the larger error lies with the value of the acoustic velocity of oil. Published data show that the acoustic velocity of crude oil varies as a function of the concentration of its different constituents and with temperature. In a remote sensing application, it will not be possible to determine either oil concentration or temperature. However, several experiments performed at IMI show that the temperature variation of the acoustic velocity is weak, less than 3 percent for a temperature variation from 5°C to 15°C. The impact of the composition of oil is more difficult to assess. Published data show that the velocity variation can be as high as 25 percent.

We have performed several experiments in the laboratory to evaluate the use of laser-ultrasonics for remote measurement of the thickness of oil on water. A typical experiment is described below. A 5 mm thick layer of Norman Wells North-West Territories crude oil was spread on tap water in an 8 cm diameter beaker. The oil was weathered for at least 16 hours before the measurement. A 4 cm depth of water was used to prevent any interference echo from reflection by the bottom of the beaker. The temperature of the oil-water bath was about 22°C.

The CO2 generation laser used was a Laser Science (10.6 µm wavelength) TEA pulse laser with a pulse width of approximately 100 ns and a pulse energy of 200 mJ. The beam was spatially filtered to provide a single mode Gaussian distribution at the surface of the sample. The beam diameter on the sample was 4 mm giving a 399 µJ/cm2 energy density at the oil layer surface. The probe beam was a long pulse YAG laser (1.06 µm wavelength, approximately 50 µs pulse width) previ-
The probe beam was focused by a single lens onto the sample to a spot size approximately equal to that of the CO₂ laser. No optics were used to focus the CO₂ pump beam. A Ge beam mixer was used to superimpose colinearly the probe and pump beams. Both beams were directed to the center of the beaker to prevent any interfering effect by surface waves reflected by the beaker walls. The reflected probe beam was collected by a 5 inch diameter lens and focused onto an optical fiber, which transmits the reflected probe beam light to the confocal Fabry-Pérot. The sample was located about 2 meters from the 5 inch diameter lens of the optical system.

Data acquisition was performed with a LeCroy TR8828C digitizer at a sampling rate of 25 MHz. The signal was filtered to eliminate low frequency noise. Data acquisition was controlled with a personal computer using UDASP, a software program developed by IMI and Ultra-Optec Inc. Each signal was 1024 sampling points long, that is, recorded over a 40.96 µs time window. Thirty consecutive data acquisitions were averaged to eliminate spurious fluctuations of the intensity of the probe beam, which affect the signal. A diagram of the complete experimental setup is shown in Figure 2.

Figure 3 shows the laser-ultrasonic signal recorded for this oil-water sample. We can clearly observe the surface signal and the echoes. Notice that the surface signal just barely saturates the detector. Also notice that the surface signal has a shape quite different from the echoes, as expected. The inversion of the second echo with respect to the first echo follows from the higher acoustic impedance of water compared to oil, which gives a noninverting reflection (there is inversion at the oil-air interface). The amplitude of the echoes shows a rapid drop, to about 12 percent (18 db). This is in reasonable agreement with the expected 14 percent (17 db) estimated previously. The attenuation of the acoustic pulse in the oil layer is mainly due to the transmission loss into water. The shapes of the echoes are consistent with each other; therefore, a direct cross-correlation estimate of the delay is possible. A low frequency oscillation seen at times greater than 30 µs is caused by intensity fluctuations of the probe beam, which are not completely eliminated by averaging.

Direct measurement of the oil thickness gives a value of 5 mm ± 2.5 mm. The large error in determining the thickness accurately is due to the capillary properties of oil. The laser-ultrasonics thickness measurement of the oil sample is calculated using an acoustic velocity of 1410 m/s with an error of 1 percent, as determined experimentally at IMI for this type of oil using conventional ultrasonics. With the cross-correlation between the two consecutive echoes of Figure 3 and the known acoustic velocity, we deduce an oil thickness of 6.23 mm with an accuracy of 1 percent, limited by the accuracy of the acoustic velocity.

As can be seen in Figure 3, the amplitude of the second echo is relatively weak. In most cases, especially in actual remote sensing, the signal-to-noise ratio will not be sufficient for the observation of this second echo. Cross-correlation delay estimates can only be performed by using the surface signal and the first echo. However, the shapes of these two signals are not identical. This will introduce an error in the estimation of the thickness. The cross-correlation estimate of thickness obtained by using the surface signal and the first echo is 6.26 mm. This is only different by 0.5 percent from the value deduced by the cross-correlation of the consecutive echoes. Theoretical simulations show that this error is a function of the Fabry-Pérot configuration and of the pump beam pulse energy (which produces nonlinear effects at detection). Generally it is less than 1 percent, and is therefore much smaller than the error resulting from the uncertainty associated with the acoustic velocity.

Our small scale experiments have demonstrated that laser-ultrasonics can be used for the noncontact thickness measurement of oil on water. Due to the relative acoustic properties of oil, weathered oil, and water, the estimate of the oil thickness will be performed by cross-
correlation of the surface signal with the first echo. The accuracy of the measurement is limited by the accuracy of the value of the acoustic velocity of the oil. The next step to assess the feasibility of using the technique in remote sensing conditions is to increase the probing distance much farther.

Large scale test

The main problem of any remote sensing technique is one of sensitivity. In the case of laser-ultrasonic remote sensing, the sensitivity depends upon the generation efficiency and the minimum displacement that can be detected. Generation efficiency is primarily determined by the concentration of pump beam energy that can be achieved at a large distance. The minimum detectable displacement is determined by the amount of light that can be collected by the optical system at that distance. A test facility was set up in the large scale laboratory of IMT to access the feasibility of remote sensing measurement of oil thickness on water.

A pool, 3 meters in diameter and 60 cm deep, was used to hold the oil-water sample. Oil layers from 250 µm up to 35 mm were studied. Two mirrors suspended from the ceiling and two lying on the floor were used to fold the laser beams' path to obtain an equivalent laser system-to-sample height of approximately 37 meters. The folding mirrors were cheap off-the-shelf, aluminum-coated glass and had appreciable losses. The total round-trip transmission of the four mirrors at the distance much farther.

The triggering scheme was used during these tests, leading to laser firing and data acquisition only when the surface had the proper tilt. Figure 5 shows a typical signal recorded in these conditions which shows clearly the surface feature and the echo, allowing adequate thickness measurement. The signal-to-noise ratio observed in the case of the rippled surface is generally less than in the static case (compare Figure 5 and Figure 4). This is explained by the fact that the surface is no longer a perfectly flat optical reflector but is given a slight curvature by the presence of waves. The reflected probe beam is, therefore, more diverging and, hence, less light is actually received by the collecting optics. This in turn results in a lower signal-to-noise ratio. This effect is more severe with capillary waves of short wavelength which lead to higher surface slopes. Fortunately these waves are highly damped by oil, especially crude oil.

During these tests, two levels of wave generation were used. As we increased the intensity of the ripples, the acquisition rate was found to
From a rate of 1 acquisition per second for light ripples, the rate fell to a level of 1 acquisition per 3 seconds for strong ripples. Note that no precise measurements of the amplitude of the ripples were made. Extrapolation to actual sea conditions is difficult on the basis of these data. It should be noted that, in actual remote sensing from an airplane, the pitch and roll of the airplane would have decreased rapidly. From a rate of 1 acquisition per second for light ripples. Note that no precise measurements of the amplitude of the ripples, the rate fell to a level of 1 acquisition per 3 seconds for strong ripples. The signal-to-noise ratio was found to be significant during our large scale laboratory tests, even though the acceptance angle was half that of the large scale tests. This confirms our previous suggestion that the motion of the plane increases the probability of finding a probed area over the sea surface with a suitable orientation.

Our results also show that the rate of acquisition is strongly dependent upon airplane height above sea level. We observed an average rate of 1 Hz at 91 meters down to 0.2 Hz at 150 meters. Trials were made at 210 meters but no triggering was observed, probably because of improper adjustment of the optical system for this height. As plane altitudes increase, the acceptance limit of the probed area becomes smaller, and hence the probability of finding such an area is reduced. Notice that these are only average values. Data show that delays between consecutive triggers as short as 0.3 s (the minimum delay given the acquisition program) and as long 10 s can be observed for both altitudes, although longer delays are more frequent at 150 meters.

In conclusion, these airborne tests demonstrate an adequate rate of data acquisition in real field conditions. We suggest that this rate can be increased by a scanning-type light collecting system that would actively search for optimum conditions.

**Conclusions**

We have demonstrated that laser-ultrasonics is a promising technique for measuring the thickness of an oil slick by remote sensing. As demonstrated by small scale laboratory experiments as well as large scale tests, laser-ultrasonics provides a direct way to determine the thickness. If the ultrasonic echo from the oil-water interface is observed, then the thickness can be calculated. The accuracy of the determination is essentially limited by the uncertainty associated with the value of the acoustic velocity of the oil in the spill. Large scale laboratory tests have demonstrated that the technique can be applied at considerable distance and have shown that the data acquisition rate is limited by the surface motion. Preliminary airborne tests have shown that, in actual field conditions, this rate is sufficient for adequate thickness mapping of an oil slick. Preliminary airborne tests have shown that, in actual field conditions, this rate is sufficient for adequate thickness mapping of an oil slick. Field tests with a complete laser-ultrasonic system are to be conducted in the fall of 1992.

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References


