Development of a New Lubricant Degradation Monitoring Technique Using Terahertz Electromagnetic Waves †

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Abstract: Condition monitoring of lubricating oil is an effective method for early detection of abnormalities in rotating machinery in plants. In this research, a new monitoring technique for lubricant degradation using terahertz waves, which are electromagnetic waves located in the boundary region between light and radio waves, is developed based on the correlation between lubricant degradation and the transmission characteristics of terahertz waves. It is found that there is a correlation between the transmission characteristics of terahertz waves, such as transmittance and refractive index, and typical lubricant degradation, such as base oil degradation, water contamination, and metallic wear debris contamination. The results suggest that a new lubricant degradation monitoring technique using terahertz waves is possible by using these transmission characteristics.

Keywords: terahertz electromagnetic waves; lubricating oil; degradation monitoring

1. Introduction

Terahertz (THz) waves are electromagnetic waves in the frequency range of 0.1 to 10 THz, which is the boundary region between light and radio waves. THz waves have characteristics such as penetrating through polymeric materials and ceramics, being harmless to the human body, and having absorption characteristics unique to materials. THz waves are expected to enable nondestructive and non-contact inspection and measurement of objects [1]. In this research, an experimental study was conducted to develop a new degradation monitoring technique using THz waves for lubricating oil used in rotating equipment in plants. Lubricating oil is essential for the smooth operation of machinery, but it gradually deteriorates with changes in appearance and performance due to oxygen, heat generated in sliding parts, and contamination by foreign substances such as water and wear debris [2]. In this research, THz time-domain spectroscopy (THz-TDS) was used to investigate the possibility of detecting oxidative degradation and contamination of water and metal wear debris, which are typical forms of degradation of lubricants.

2. Materials and Methods

2.1. Measurement Method

THz time-domain spectroscopy (THz-TDS) used in this research is a spectroscopy method in which pulsed THz waves are irradiated to targets and changes in the electric field intensity of the transmitted or reflected THz waves are measured as time waveforms. The amplitude and phase of each frequency are then obtained by Fourier transforming time waveforms. In the experiment, THz-TDS transmission measurements were conducted with lubricating oil in plastic cells that are highly transparent in the THz band.
2.2. Measurement Samples

Artificially degraded lubricating oil was used as a sample. Samples shown in Tables 1 and 2 are oxidative degradation lubricants. Samples were prepared by heating two types of lubricants, one consisting of mineral oil and the other of synthetic oil based on alkyl-diphenyl-ether. The oxidation level of the samples was controlled by changing the heating time. After heating, the kinematic viscosity of the lubricant was measured and used as an indicator of the oxidation level. Samples shown in Table 3 are mineral oil-based lubricants containing iron powder with a particle size of 50 µm to simulate the contamination of wear debris. Furthermore, the samples shown in Table 4 are mineral oil-based lubricants containing water added to simulate the condition of water mixed in the lubricant.

Table 1. Oxidative samples (mineral oil).

<table>
<thead>
<tr>
<th>Degradation Level</th>
<th>Kinematic Viscosity at 40 °C (mm²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No degradation</td>
<td>132</td>
</tr>
<tr>
<td>Oxidative 1</td>
<td>143</td>
</tr>
<tr>
<td>Oxidative 2</td>
<td>145</td>
</tr>
</tbody>
</table>

Table 2. Oxidative samples (synthetic oil).

<table>
<thead>
<tr>
<th>Degradation Level</th>
<th>Kinematic Viscosity at 40 °C (mm²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No degradation</td>
<td>320</td>
</tr>
<tr>
<td>Oxidative 1</td>
<td>325</td>
</tr>
<tr>
<td>Oxidative 2</td>
<td>526</td>
</tr>
<tr>
<td>Oxidative 3</td>
<td>514</td>
</tr>
</tbody>
</table>

Table 3. Iron powder contamination samples.

<table>
<thead>
<tr>
<th>Degradation Level</th>
<th>Iron Powder Concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No degradation</td>
<td>0</td>
</tr>
<tr>
<td>Iron powder 1</td>
<td>100</td>
</tr>
<tr>
<td>Iron powder 2</td>
<td>500</td>
</tr>
<tr>
<td>Iron powder 3</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 4. Water contamination samples.

<table>
<thead>
<tr>
<th>Degradation Level</th>
<th>Water Concentration (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No degradation</td>
<td>0</td>
</tr>
<tr>
<td>Water 1</td>
<td>0.05</td>
</tr>
<tr>
<td>Water 2</td>
<td>0.1</td>
</tr>
<tr>
<td>Water 3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

2.3. Investigation of Relationship between Degradation Level and Transmission Characteristics

In the experiment, two THz-TDS measurements were performed for each sample, one with the cell empty (reference measurement) and one with the cell filled with lubricant (sample measurement). Using time waveforms obtained in measurements and the frequency waveforms obtained by the Fourier transform of time waveforms, the following transmission characteristics of samples were obtained and compared with the degradation level of the samples.

1. Transmittance
Figure 1 shows the time waveforms obtained by THz-TDS measurements. As shown in Figure 1, the peak intensity value was extracted from the time waveform, and the transmittance $T$ of the sample was determined by Equation (1).

$$T = \frac{I_{\text{sam}}}{I_{\text{ref}}}$$

where $I_{\text{sam}}$ is the average peak intensity of the sample time waveform and $I_{\text{ref}}$ is the average peak intensity of the reference time waveform.

2. Peak time difference

As shown in Figure 1, the intensity peak of the sample time waveform, appears later than the intensity peak of the reference time waveform due to the refractive index of lubricants. The peak time difference $\Delta t$ was determined by Equation (2) and used as the characteristic value corresponding to the refractive index.

$$\Delta t = t_{\text{sam}} - t_{\text{ref}}$$

where $t_{\text{sam}}$ is the average peak time of the sample time waveform and $t_{\text{ref}}$ is the average peak time of the reference time waveform.

3. Standard deviation ratio of peak intensities

To evaluate the variation of transmitted wave intensities, the standard deviation ratio $r$ was determined by Equation (3).

$$r = \frac{s_{\text{sam}}}{s_{\text{ref}}}$$

where $s_{\text{sam}}$ is the standard deviation of peak intensities of sample time waveforms and $s_{\text{ref}}$ is the standard deviation of peak intensities of reference time waveforms.

4. Attenuation

The attenuation of the transmitted wave was determined by Equations (4) and (5).

$$T(\omega) = \frac{E_{\text{sam}}(\omega)}{E_{\text{ref}}(\omega)}$$

$$A(\omega) = \log_{10}(T_{\text{sam}}(\omega)/T_0(\omega))$$

where $E_{\text{sam}}(\omega)$ is the average amplitude of sample frequency waveforms, $E_{\text{ref}}(\omega)$ is the average amplitude of reference frequency waveforms, $T_{\text{sam}}(\omega)$ is the transmittance for the degraded sample, and $T_0(\omega)$ is the transmittance for the non-degraded sample.

3. Results and Discussion

3.1. Measurement Results of Oxidative Degradation Lubricants

Figure 2 shows the transmission characteristics of oxidative degradation samples. For synthetic oils, as the kinematic viscosity increases due to oxidation, the transmittance decreases and the attenuation increases. In addition, the peak time difference corresponding
to the refractive index increases. It is suggested that THz-wave transmission characteristics were affected by changes in molecular structure due to polycondensation by oxidation and the formation of insoluble substances such as varnish and sludge. On the other hand, the mineral oil sample was hardly oxidized, so no change in transmission characteristics could be observed in this experiment.

![Figure 2. Measurement results of oxidative lubricants: (a) Transmittance measurement result; (b) peak time difference measurement result; (c) attenuation measurement result.](image)

3.2. Measurement Results of Lubricants Containing Iron Powder

Figure 3 shows the transmission characteristics of iron powder-containing samples. As shown in Figure 3b, the attenuation increases with increasing iron powder concentration in the frequency range above about 0.5 THz. Since the particle size (50 μm) of the iron powder is sufficiently smaller than the wavelength (0.3–1.5 mm) of the THz-TDS system used in this study, Rayleigh scattering may occur, and the higher frequency components may be more scattered. In addition, as shown in Figure 3a, the standard deviation ratio increases as the iron powder concentration increases. It is thought that the intensity of the transmitted wave varies depending on the measurement position and timing because iron powders are not dispersed in a completely uniform state in lubricants.

![Figure 3. Measurement results of lubricants containing iron powder: (a) Standard deviation ratio of peak intensity measurement result; (b) attenuation measurement result.](image)

3.3. Measurement Results of Lubricants Containing Water

Figure 4 shows the transmission characteristics of water-containing samples. As the water concentration increases, the transmittance decreases and the attenuation increases. Since THz waves are well absorbed by water, it is considered that THz waves were absorbed by water particles dispersed in oil.

![Figure 4. Measurement results of water-containing samples: (a) Transmittance measurement result; (b) peak time difference measurement result; (c) attenuation measurement result.](image)
4. Conclusions

To develop a new monitoring technique for lubricant degradation using THz waves, the transmission characteristics of lubricants in the THz band were experimentally investigated. It is found that the transmission characteristics of lubricants vary depending on the degree of oxidation of the oil and the amount of iron powder and water mixed in the oil. THz-wave measurement is expected to make it possible to determine the degradation factors and the degree of progress of the degradation of lubricants.


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References

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