In this paper, a novel mesh condition monitoring method for spur gears is presented which utilizes a nonlinear vibro-acoustic effect on a piezoelectric element integrated on the end face of the drive gear. In the presented technique, the piezoelectric element is driven by a sinusoidal voltage source with an ultrasonic frequency to excite a certain vibration mode of the drive gear. The meshing motion of the gears yields a time-varying boundary condition at the contacting point between the drive and driven gears, which leads to a fluctuation of the scattering conditions for the ultrasonic elastic wave radiated from the piezoelectric layer. This nonlinear effect of vibro-acoustic interaction appears as a modulation of the coupled electromechanical admittance of the piezoelectric element, which can be observed as an amplitude and phase modulation of the current response of the piezoelectric element. In this preliminary study, a test rig consisting of a motor-driven pair of meshing spur gears with an electromagnetic powder brake for loading is developed, and the current responses of the piezoelectric element are investigated with low speed rotation under various loading levels.

Keywords: condition monitoring, gear, vibro-acoustic modulation, piezoelectric sensor

1. Introduction

Early detection of gear faults is one of the most critical building blocks in the development of condition-based maintenance systems for rotating machinery. Most of the existing approaches to this problem are vibration-based because of the ease of measurement, which utilize the vibration signal emitted from the gears that is received on the exterior of the gearbox casing. The earliest studies were done in 1970s [1, 2], and since then, various kinds of signal processing techniques have been proposed [3, 4, 5, 6, 7]. The underlying common idea is to detect the variation of the meshing vibration due to the local tooth defects [8, 9], which can be observed as amplitude and phase modulation in the time domain, sidebands around the mesh frequency or its harmonics in the frequency domain, or augmentation of specific components in the time-frequency domain.

Despite utilizing the vibration signal originated from the contact area of the gear teeth which is expected to be sensitive to the early defect, all of those vibration-based approaches have the same limitation; the vibration at the contact area is not directly measurable, but only the vibration response on the exterior of the gearbox can be measured where a vibration transducer (usually an accelerometer) is mounted. The
major difficulties stem from this limitation are twofolds: one is that the vibration from the gear of interest is contaminated by various vibration components from other gears, bearings, and other mechanical components connected to the input/output shafts of the gearbox. This can be mitigated by introducing time synchronous averaging [10]. It is, however, still a challenge to extract the meshing vibration from the target gear in the case the rotation is slow because the signal-to-noise ratio can become quite low. The other is that the acquired signal is considerably distorted by the transfer functions between the contact area and the transducer, including the dynamical characteristics of the gears, shafts, bearings, and the gearbox casing. Because these transfer functions are hardly identified in practical situations, removing their effects is not simple [11, 12, 13].

In this study, a completely different approach to the gear fault detection is proposed based on the concept of smart structures. In this approach, the gear itself plays a role of the transducer by introducing a piezoelectric material (PZT) layer attached on its end face. Since the piezoelectric material allows the host structure electromechanically coupled with an electric circuit, the concept of the nonlinear piezoelectric impedance modulation (NPIM) [14] can be applied, in which the electromechanical coupled admittance of the piezoelectric element is measured at an ultrasonic frequency range to evaluate the meshing condition more directly. This paper first presents the concept of the piezoelectric impedance modulation particularly applied to the condition monitoring of mechanical components. Because this is the first attempt to apply this technique to the gear fault detection, preliminary experiments are conducted using a test rig in which a pair of spur gears with the same dimensions rotate in 30 rpm to see how the piezoelectric element induces ultrasonic vibration in the rotating gears, and how it is fluctuated by the meshing motion.

2. Concept of NPIM-based condition monitoring system

Figure 1 shows a conceptual drawing of the NPIM-based condition monitoring system for mechanical components. In this drawing, a part of the mechanical component of interest is expressed as an elastic body B1 which is engaged with another elastic body B2 with intimately contacted rough surfaces $\Gamma_1$ and $\Gamma_2$. In the case of rotating gears, B1 is the gear of interest while B2 is the gear engaging with it. The system has a single piezoelectric element PE bonded on the surface of B1 driven by a high-frequency constant-amplitude sinusoidal voltage source (probe). The driver circuit has a current detector to measure the current flowing through the piezoelectric element.

When the mechanical component works, the contact surfaces $\Gamma_1$ and $\Gamma_2$ undergo relative motion such as rolling and sliding. The contact pressure between $\Gamma_1$ and $\Gamma_2$ fluctuates with a specific pattern because...
of the relative motion. This fluctuation of the contact pressure induces a vibration originated in the contact area, which also affects the scatter characteristics of the high-frequency probe wave in the area. Because of this vibro-acoustic interaction, the driving-point impedance at the location of the piezoelectric element may change temporally in synchronization with the contact vibration. Since the piezoelectric element is electromechanically coupled with the host structure, the admittance of the piezoelectric element may also become time-varying, so that the current response flowing through the piezoelectric element is modulated both in amplitude and in phase, in synchronization with the contact vibration.

When the contact surfaces incur surface defects due to rolling contact fatigue or abnormal wear, the contact pressure variation will be altered from the normal pattern. Because the modulation of the probe current directly reflects the fluctuation of the contact pressure, the demodulated amplitude and phase of the probe current is expected to be a sensitive indicator of the defects in the contact surfaces.

3. Experiments

3.1 Specimen and test rig

Two steel spur gears with the same dimensions listed in Table 1 were used in this study. On the end face of the drive gear, a piezoelectric element (Fuji Ceramics Inc., C6 PZT, 20 mm × 30 mm × 0.5 mm) was bonded with epoxy adhesive on the location shown in Fig. 2 (a). It should be noted that only the intact gears were tested in this study to obtain a basic understanding how the piezoelectric element on the gear could induce ultrasonic vibration in the meshing gears.

The specimen gears are installed in a test rig shown in Fig. 2 (b), in which the drive shaft is driven by a 200 W AC motor with a 1/30 reduction gearbox (Mitsubishi GM-SHY-RL-0.2KW-4P-1/30) controlled by

<table>
<thead>
<tr>
<th>Gear parameter</th>
<th>Drive &amp; driven gears</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooth number</td>
<td>50</td>
</tr>
<tr>
<td>Module</td>
<td>2 mm</td>
</tr>
<tr>
<td>Pitch diameter</td>
<td>100 mm</td>
</tr>
<tr>
<td>Pressure angle</td>
<td>20°</td>
</tr>
<tr>
<td>Tooth width</td>
<td>20 mm</td>
</tr>
<tr>
<td>Shaft diameter</td>
<td>20 mm</td>
</tr>
</tbody>
</table>

Figure 2: Specimen and test rig.

Table 1: Gear parameters.
an inverter controller (Mitsubishi FR-D720-0.2K). The driven shaft is terminated by an electromagnetic powder brake (Mitsubishi ZKB-2.5HBN) so that the load torque is controlled by adjusting the current applied to the brake. The load torque at the driven shaft is measured by a torque meter (Unipulse UTM II-20Nm). The lead wires from the piezoelectric element are pulled out of the test rig via a slip ring (Tokyo Tuushin Kizai TSR201-00-01B) installed at the end of the drive shaft.

### 3.2 Experimental procedure

Preparatory to conducting the experiment, vibration modes of the gear available for the test were specified. Considering the configuration of the piezoelectric element attached on the end face, it was expected that the bending vibration modes would be predominant. In order to verify the prediction, the piezoelectric impedance method [15] was applied, in which the peaks in the real part of the admittance of the piezoelectric element indicated the natural frequencies of the vibration modes that showed strong electromechanical coupling. Among several vibration modes obtained, the vibration mode which had the natural frequency around 53.3 kHz was chosen. The actual measurement of this mode using a laser Doppler vibrometer and the FEM analysis indicated that it was a bending mode with three radial nodal lines which was similar to the (3,0) mode of a circular disk. Further analyses revealed that, if meshed with the driven gear, this mode would separate into two modes with close natural frequencies: one, which is shown in Fig. 3 (a), was the mode in which one of the nodal line passed through the meshing tooth; the other one had its nodal lines rotated by 30° as shown in Fig. 3 (b), which corresponded to the half of the angle between nodal lines.

Then, the experiments were conducted as follows: the AC motor was driven at the constant speed of 0.5 s⁻¹ (30 rpm), while the load torque was set at several levels by controlling the brake current. At the same time, the piezoelectric element was driven by a 50 Vp-p sinusoidal voltage at the frequencies range from 53.2 kHz to 53.6 kHz by a 25 Hz increment. The current response of the piezoelectric element at each frequency was obtained by measuring the voltage drop at the shunt resistance of 1 Ω. The waveforms of the voltage source and the current response for two seconds were acquired by a data recorder with the sampling frequency of 1 MHz. All the data collected were processed offline using MATLAB.

### 4. Results and discussions

Figure 4 shows the typical examples of the current waveforms measured in the test under 20.3 Nm load. The plot in Fig. 4 (b) is at the frequency 50 Hz higher than that of the plot in Fig. 4 (a).
both plots, one can see that the current responses are significantly modulated in amplitude. It seems that there are two kinds of modulations superposed: a periodic modulation three times a second, and another modulation with much shorter period, 25 times per second. Considering the rotation speed and tooth number, it can be reasonably explained that the former modulation was due to the influence of the nodal lines, while the latter was due to the gear meshing.

The amplitude modulation in the current response at each probe frequency was demodulated by using Hilbert transform, then the absolute value of the instantaneous admittance was calculated by dividing the demodulated current amplitude by the probe voltage amplitude, and aligned with respect to the probe frequency and the rotation angle for four levels of load torque of 0, 0.99, 5.90 and 20.3 Nm. The results were shown in Fig. 5, in which the absolute value of the instantaneous admittance is displayed in 2D color maps.

When the load torque is zero, no considerable fluctuation is found along the rotation angle axis, which means the admittance of the piezoelectric element remained constant for each probe frequency because the induced vibration mode rotated together with the gear rotation, and the interaction between the drive and driven gears was negligibly small. In contrast, as the load increased, the dynamical interaction between the gears increased significantly, which made the modulation due to the meshing clearly observable. Furthermore, the modulation due to the nodal lines of the induced mode shape was also pronouncedly manifested, the phase of which was shifted for unknown reason depending on the probe frequency. This phase shift is also observed in Fig. 4. The measurement of the operational deflection shapes (ODS) by the laser Doppler vibrometer suggested that the behavior of the induced mode shape differed depending on the load magnitude and the probe frequency; it rotated with the gear when the load was small, but stayed spatially referring to the meshing tooth when the load was sufficiently large. Further understanding of this behavior of the induced mode shape is necessary to find a way to separate and eliminate the influence of the specific mode shape from the instantaneous admittance signals.

5. Conclusions

In this preliminary study, a novel approach to the gear fault detection has been proposed based on the concept of the nonlinear piezoelectric impedance modulation, which utilizes a nonlinear vibro-acoustic effect of a piezoelectric element attached on the end face of the drive gear in the ultrasonic frequency range. A test rig consisting of a motor-driven pair of meshing spur gears with an electromagnetic powder brake has been developed, and the current responses of the piezoelectric sensor have been investigated with low speed rotation with various levels of loading. Significant modulation in amplitude has been
observed, which has been related to the shape of the induced vibration mode and the gear meshing. Further understanding about the dynamic behavior of the induced modes is necessary to find the way to isolate the modulation due to gear meshing. Also, the evaluation of the proposed approach in terms of the sensitivity to the tooth defect must be addressed in the future study.

REFERENCES


