Relation Between Oil-Film-Formation and Vibration-Acceleration in Spur Gears

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To certify the effect of the dynamic load on the oil-film-formation under partial elastohydrodynamic condition in spur gears, the cross-correlation function $R_\text{m}(r)$ was measured between the insulating voltage of oil-film and the vibration-acceleration in circumferential direction of the gear. The measured cross-correlation functions show clearly that the breakdown of oil-film is likely to occur at the maximum of vibration-acceleration. Under a light tangential load, the coefficients of the correlation $R_\text{m}(0)$ were minus and their absolute values were large corresponding to large fluctuations of dynamic load, compared with the case of a heavy tangential load. In the case of a pair of hobbed gears, $R_\text{m}(0)$ had a higher absolute value than in the case of ground gears. However, after the oil-film was almost completely formed by running-in, or when some pitting occurred at the tooth-faces, the cross-correlation functions were distorted and the absolute values of $R_\text{m}(0)$ became small.

Key Words: Gear, Lubrication, Oil-Film-Formation, Dynamic Load, Gear Vibration Cross-correlation Function

1. Introduction

The dynamic load acting on the tooth surfaces in gears would inevitably fluctuate due to the transition of meshing teeth from one to another. The fluctuation of load may have a favorable effect as a squeeze action on the oil-film formation, compared with the case where the maximum load acts steadily. On the other hand, under a partially elastohydrodynamically lubricated condition the local collapse of oil-film is likely to occur at a specific contact region corresponding to the peaks of the dynamic load.

As a result of another testing of spur gears, the authors confirmed that the positions where pits occurred coincided with the positions of peaks of the dynamic loads, and the breakdown of oil-film occurred at the peaks of dynamic load$^{[12]}$.

In this study, it has been tried to investigate the qualitative relationship between the oil-film-breakdown and the dynamic behavior, i.e., the cross-correlation between vibration-acceleration in circumferential direction (which relates to the dynamic load) and the insulating voltage of oil-film.

2. Experimental Method

2.1 Apparatus and test gears

The testing machine was a power circulating gear testing apparatus (maximum power 150 kW). Test gears were ordinary spur gears having dimensions given in Table 1. The configurations of test gears were the same as those of the previous report$^4$.

Two kinds of test gears were used: one was made of Chromium-Molybdenum steel (SOM 41SH according to JIS), and finished by tooth grinding to JIS precision grade 0 after carburizing and quenching (Brinell hardness on tooth surface $H_B=800$), and the other was made of 0.45% carbon steel (JIS S45C, $H_S=250$), which was cut by hobbing (JIS precision grade 3-4). The ground gears were subjected to a tip-relieving about 30 μm at the tip and also a side-

<table>
<thead>
<tr>
<th>Table 1 Specification of test gears</th>
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<tbody>
<tr>
<td>Gear ratio</td>
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<tr>
<td>Number of teeth</td>
</tr>
<tr>
<td>Module</td>
</tr>
<tr>
<td>Pressure angle</td>
</tr>
<tr>
<td>Face width mm</td>
</tr>
<tr>
<td>Center distance mm</td>
</tr>
<tr>
<td>Contact ratio</td>
</tr>
</tbody>
</table>

1):Driver 11):Follower
Relieving to give an effective face-width of 5 mm. Figure 1 shows typical examples of tooth profiles.

2.2 Test conditions
Experimental conditions, i.e., combinations of gear materials, tooth finishing, rotational speed, tangential load and so on, are given in Table 2. As the lubricant, turbine oil without EP additives (viscosity 7.0 x 10^{-7} m^{3}/s, at 313 K, 9.2 x 10^{-8} m^{3}/s, at 288 K, specific gravity 0.873 at 288 K) was supplied at a rate of 700 mL/min on the entrance side of the meshing through a nozzle and its temperature was 318 K.

2.3 Method of measurement
The state of oil-film formation was monitored by an electrical resistance method of which measuring circuit is shown in Figure 2. The dynamic root strain was detected using 4 resistance-wire strain guages, each of which was mounted on the compression side of the root of every other tooth of the driving gear. The vibration-acceleration in circumferential direction was detected by a piezo electric accelerometer, which was installed at a position of 45 mm distance from the center of the driven gear shaft.

The cross-correlation function \( C_{xy}(r) \) and the coefficient of cross-correlation \( R_{xy}(r) \) between two signals \( x(t) \) and \( y(t) \) can be expressed as follows:

\[
C_{xy}(r) = \sqrt{C_{xx}(0) \cdot C_{yy}(0) \cdot R_{xy}(r)}
\]

\[
= \lim_{t \to \infty} \frac{1}{T} \int_{t-r}^{t} [x(t) - \bar{x}] [y(t + r) - \bar{y}] \, dt
\]

where \( \bar{x} \) and \( \bar{y} \) are the averages and \( C_{xx}(0) \), \( C_{yy}(0) \) are the variances of \( x \) and \( y \), respectively. In this study, the signal is the vibration-acceleration in circumferential direction and the signal \( y \) is the insulating voltage of oil-film between meshing teeth. The cross-correlation function \( C_{xy}(r) \) was measured directly with the aid of a digital signal processor under the following conditions: sampling period 30 \( \mu \)s, exponential-weight-averaging of spectra 50 times.

3. Test Results and Discussion
The dynamic load should become maximum in coincidence with the maximum circumferential acceleration in the driven gear.

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### Table 2 Details of gear tests

<table>
<thead>
<tr>
<th>No. of Exp.</th>
<th>Combination</th>
<th>Finish</th>
<th>Rotational speed rpm</th>
<th>Tangential load kN/m</th>
<th>Hertzian pressure MPa</th>
<th>EHD film thickness ( \mu )m</th>
<th>( R_{max} )</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SCA415H</td>
<td>G.</td>
<td>1530</td>
<td>1100</td>
<td>1.76</td>
<td>0.69</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>S1/S2</td>
<td>G/H.</td>
<td>894</td>
<td>1100</td>
<td>1.76</td>
<td>0.47</td>
<td>2.4</td>
<td>2.0</td>
</tr>
<tr>
<td>3</td>
<td>S45C</td>
<td>H.</td>
<td>1530</td>
<td>150</td>
<td>0.54</td>
<td>0.97</td>
<td>8.0</td>
<td>5.0</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>894</td>
<td>100</td>
<td>0.54</td>
<td>0.65</td>
<td>6.7</td>
<td>5.0</td>
</tr>
</tbody>
</table>


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(a) Ground gear/Ground gear (Exp. 1)

(b) Ground gear/Hobbed gear (Exp. 3)

(c) Hobbed gear/Hobbed gear (Exp. 5)

[\( \Theta \) is defined as the distance from geometrical starting point of meshing along the line of action divided by normal pitch. \( P \) denotes the pitch point. \( AB \) denotes the single contact region.]

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Fig. 1 Change in tooth profile
Therefore, if it is true that the probability of oil-film-breakdown becomes maximum corresponding to the maximum dynamic load, the coefficient of cross-correlation between the circumferential acceleration and the insulating voltage should become minimum at time difference $\tau=0$, or at least $R_{xy}(0)$ must be negative.

The results of all experiments in this report were $R_{xy}(0)<0$, excepting the initial stages of running where oil-film was hardly formed or the case after states of oil-film formation were altered by the occurrence of pitting. However, it was observed in a few experiments that the time difference which
gave the minimum of $R_{xy}(\tau)$ had a trend to shift in the direction of $\tau>0$, although the value remained in the neighbourhood of $\tau=0$. This means that there is a tendency that the insulating voltage becomes minimum with a certain delay from the maximum circumferential acceleration. In the following paragraphs, the authors will explain the experimental results with regard to the absolute value of the cross-correlation $R_{xy}(0)$ and the time lag $\tau_0$ where $R_{xy}(\tau)$ becomes minimum.

Fig. 2 Measuring circuit of oil-film formation

Fig. 3 Relation between recorded voltage $E_{ab}$ and tangential load (Marks: the same as in Table 2 )

(a-1) Tangential load: 50 kN/m

(b-1) Tangential load: 100 kN/m

[ Exp. (6) : S45C/S45C , 894 rpm ]

Fig. 4 Comparison among dynamic load, oil-film formation and coefficient of cross-correlation, when tooth separation due to gear vibration occurs and when not.
3.1 Cases where tangential load was increased step by step

Since the initial roughness of tooth surfaces is much greater than the theoretical film-thickness according to elasto-hydrodynamic theory, the lubricated condition of test gears would be partial elasto-hydrodynamic until running-in proceeds sufficiently. Figure 3 shows the averaged voltage $E_{av}$ measured by a pen-writing oscillograph. When the tangential load was increased step by step within comparatively short time while running-in hardly occurred, in hobbed gears with large initial roughness the voltage $E_{av}$ fell to 0 mV and oil-film-breakdown became continuous at the tangential load 100 kN/m. On the other hand, in ground gears with small initial roughness the voltage $E_{av}$ decreased more slowly. The voltages $E_{av}$ at low speed (894 rpm; shown by ⊗ in Fig.3) were lower than those at high speed (1530 rpm; shown by ○ in Fig.3) in both cases of hobbed and ground gears, as were expected by the EHL theory. Under a light load, the tooth separation occurred due to gear vibration and the fluctuation of tooth load was large, as shown in Fig. 4 (a-b). However, increasing the tangential load, the tooth separation ceased to occur and the fluctuation became small. The voltages between tooth surfaces can not distinguish an EHL oil-film-formation from an isolation on account of the tooth separation. Therefore, when tooth separation occurred, the coefficients of cross-correlation showed a periodical feature and became minimum at $r=0$. It is notable that $|R_{xx}(0)|=0.55/0.6$ when tooth separations occur. Even under a tangential load where tooth separation did not occur, the smaller the tangential load or the faster the rotational speed, $|R_{xx}(0)|$ became the larger corresponding to a larger fluctuation of tooth load. Under the condition that a large load fluctuation occurred but without tooth separation, $|R_{xx}(0)|$ became approximately 0.3, as shown in Fig. 5. It may be considered that this value is fairly large for the cross-correlation between two phenomena which have very different characteristics of frequency.

3.2 Effect of running-in at constant load

Under a condition of partial EHL, the state of oil-film-formation is improved due to the progress of running-in in long time operation at constant load. In each experiment under the conditions given in Table 2, the recorded voltage $E_{av}$ which indicates the mean state of oil-film formation increased with lapse of the running time, as shown in Fig. 6. In such a case, the coefficients of cross-correlation $R_{xx}(0)$ were minus except in the special cases such as pitting occurred, and their absolute value $|R_{xx}(0)|$ changed as shown in Fig. 7. In experiments (1),(3) where the tangential loads were considerably high and in experiments (2),(6) where the rotational speed was low (894 rpm), the values of $|R_{xx}(0)|$ were comparatively small, being about 0.15.

![Fig. 5 Relation between the absolute value of coefficient of cross-correlation $|R_{xx}(0)|$ and tangential load](image)

![Fig. 6 Change in recorded voltage $E_{av}$ (average state of oil-film-formation)](image)
In the case of ground gears, the fluctuation of tooth load became smaller owing to tip-relief. However, under a heavy tangential load, the contact of the edges of tooth tips and the occurrence of oil-film-breakdown owing to tip contacts made the time lag $\tau_0$ where $R_{xy}(\tau)$ is minimum, widely deviate from $0$, as seen in Fig. 8. In experiments, it is observed that the values of $\tau_0$ became positive, being $0.06$ to $0.15$ ms.

In the experiments (4) and (5) where hobbed gears were tested under relatively high rotational speed, the values of $|R_{xy}(0)|$ were relatively high, being $0.4$ and $0.2$ to $0.3$, until $(35$ to $50)\times 10^4$, and time lag $\tau_0$ became nearly $0$, as shown in Fig. 9 (a). After more repetition cycles, however, $|R_{xy}(0)|$ decreased while the time lag $\tau_0$ remained nearly $0$, because of a significant improvement of oil-film-formation, as shown in Fig. 7 (d). In contrast to this, in experiment (5) the wave of $R_{xy}(\tau)$ was disturbed owing to the occurrence of pitting, as shown in Fig. 9 (b). Therefore, $|R_{xy}(0)|$ approached $0$ rapidly and finally it was changed to a positive value as marked by asterisk in Fig. 7 (e). In experiment (6) where the rotational speed was low, $|R_{xy}(0)|$ was small and differed from $0$ except at the initial stage of running. In this experiment, severe pitting was observed after the running. Now, the relation of the time lag $\tau_0$ with squeeze effect for hydrodynamic oil-film-formation
is of interest. In this investigation, the time lag caused by squeeze effect could not be detected, since \( r_s \) was smaller than a sampling period in many cases; for example, even in experiment (4) where both the fluctuation of load and the value of \( |R_m(0)| \) were large, \( r_s \) was nearly 0. Therefore, it is presumed that the oil-film-breakdown in this study is related to the interactions of asperities of which the radius of curvature is extremely small, not related to the squeeze effect between tooth surfaces with theoretical radius of curvature. When pitting occurred, the coefficients of cross-correlation \( R_{xy}(\tau) \) between the insulating voltage and the vibration-acceleration were disturbed. These disturbances of \( R_{xy}(\tau) \) may have a relation with the spectrum fluctuation of the gear noise, as noted in a prognosis of gear failure by Umezawa et al.\(^{15} \)

4. Conclusions

In order to investigate the cross-correlation between the circumferential acceleration and the insulating voltage which corresponds to the state of oil-film-formation, running tests of spur gears were carried out. As the result, it is recognized that the cross-correlation \( R_{xy}(0) \) is minus; namely, the oil-film-breakdown occurs corresponding to the peaks of dynamic load. The absolute value \( |R_m(0)| \) of the correlation was approximately 0.6, when tooth separation due to gear vibration occurred. Even in the case where vibrational tooth separation did not occur, \( |R_m(0)| \) was nearly 0.3. This value is considered to be large for the correlation between two signal having quite different characteristics of frequency. Thus, it is confirmed by means of cross-correlation function that the dynamic load localizes the oil-film-breakdown under the partial EHL condition, especially in the case where dynamic load fluctuates largely due to gear vibration. It is considered that the effect of dynamic load is a very important factor for oil-film-breakdown in partial elastohydrodynamic lubrication.

Acknowledgements

This investigation was partly supported by the Grant of Takeda Science Foundation, to which the authors wish to express their thanks. The authors also wish to acknowledge the assistance of Mr. Nakayama, T., Nippon Steel Corporation.

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