104 齒車単体の振動個性の抽出
（同期平均処理と回転次数比解析の適用）

Extraction of Vibration Characteristics of an Individual Gear
-Utilization of Synchronous Averaging Method and Shaft Order Analysis-

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Synchronous averaging method is applied to extract the signal attributed from driving and/or driven gear from each other. Some concepts about signal processing used in synchronous averaging method are discussed here.

From the results, it is recommended that the length of each block of the signal that will be averaged should be selected to fit with the period of driving or driven shaft revolution. In this case, rectangular window is used instead of the other window functions. Shaft order analysis is applied for extraction vibration components at each shaft order from the vibration waveform. With these processes, the more precision in amplitude and frequency of vibration results are obtained. The effect of the number of averaging is also discussed.

齒車の振動は駆動側および被動側両方の影響を受けて発生している。異常診断や性能検査の見地から振動計測結果を用いて各歯車単体の寄与を特定するのに同期平均処理が有効である。本研究では同期平均した波形を1回転分切り出してフーリエ解析することが有効であることを示す。

Key Words: Gear, Vibration, Synchronous averaging, Diagnosis, Shaft order analysis, Length of data block, Window function

1. Introduction

It is difficult to detect an error gear or a noise source gear from a gear system having many stages and many gears because of complicated signals mixed from various gears in the system. Moreover, these signals frequently not only compose of mesh components but they also compose of non-integer orders of mesh components called ghost noises.

Not like mesh components that vibration source can be detected easily by considering gear rotational speed and number of teeth of the gear pair, because ghost frequency does not relate with any dimension of meshing gears, the noise source cannot be detected.

Synchronous averaging method is an effective method used for extraction vibration signals attributed from each gear from each other. Each block of signal that will be averaged is started to measure synchronously with rotational speed of an interested gear. After enough averaging, the signals attributed from other gears on the other shafts and signals from other components are eliminated, leaving only signal attributed from the interested gear and mesh components that are the common signals attributed from both gears in a meshing pair, so vibration characteristics of an individual gear can be detected.

With this advantage, synchronous averaging method is often used for detection of failure in the gear system, and it is also possible to apply this technique for tooth surface inspection.

In this research, some matters about utilization of synchronous averaging together with frequency analysis or shaft order analysis of a gear system are discussed. The appropriate analytical method is also recommended.

2. Experiment

The experimental set is shown in fig.1. Driving gear has 30 teeth and driven gear has 53 teeth. Driven gear was driven by a variable speed motor and run at rotational speed 1800 rpm. Absorbed torque was set as 245 Nm. Both experimental gears were finished by indexed generation method. Another parameters of test gear are shown in tab.1.

The vibration of gears was measured by two-acceleration

<table>
<thead>
<tr>
<th>Table 1 Gear parameters</th>
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<tr>
<td><strong>Driving gear</strong></td>
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<tr>
<td><strong>Module</strong></td>
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<tr>
<td><strong>Number of teeth</strong></td>
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<tr>
<td><strong>Pressure angle</strong> [degree]</td>
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<td><strong>Helix angle</strong> [degree]</td>
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<td><strong>Face width</strong> [mm]</td>
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<td><strong>Center distance</strong> [mm]</td>
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<td><strong>Total contact ratio</strong></td>
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pick-ups attached at the driven gear. Driving and driven trigger signals; one pulse per revolution; were also measured by two magnetic pick-ups. Vibration signal was measured at sampling rate 12800 Hz. The number of samples per block of data was set at 1024 points. With these values, the length of the block of data can be calculated. In this case, it is equal to 80 ms.

3. Sample of experimental results

Two analytical methods of the utilization of synchronous averaging and frequency analysis of a gear pair are discussed here that are method A and method B that is the proposed method.

Figure 2 is the synchronous averaging result received from method A. Each block of the vibration signal was measured and averaged synchronously with driving or driven shaft trigger. Signal measured and averaged synchronously with driving shaft rotation (with driving trigger) shows the characteristics of driving gear; on the other hand signal averaged with driven trigger shows the driven gear characteristics. Averaged signals with driving and driven trigger are shown in fig.2(a). The ordinate is amplitude of vibration. The abscissa is the time axis that is written to fit with the length of the block of data that is equal to 80 ms. In this method, the length of the block of data did not match with neither the period of driving nor driven shaft rotation.

Because the length of each block of signal did not match with the period of shaft rotation, when the signals are processed by frequency analysis, the window function must be applied to reduce the effect of leakage. In this example, hanning window was used. The signals processed by the hanning window are shown in fig.2(b). Figure 2(c) shows the frequency analysis results. The abscissa is the frequency. The resolution in frequency domain can be calculated from sampling frequency and the number of samples per block of signal, in this case is equal to 12.5 Hz that did not match with neither driving nor driven shaft frequency.

The positions of mesh frequency \( f_g \) and its harmonics \( 2f_g \) and \( 3f_g \) are marked by the arrows. The spectra in fig.2(c) show characteristics of an individual gear. Mesh components that are the common characteristics between both gears are remained after averaging with both driving and driven trigger. Their amplitudes appearing in both graphs are the same.

About driving gear signals (signal averaged with driving trigger), there are some peaks of the non-integer order of mesh components at about 500 and 900 Hz and a cluster of peaks between 4000 and 5000 Hz. The cluster of peaks is believed to be caused by the undulation of tooth surface. On the other hand, almost all the peaks of the driven gear signals are the mesh components. Only some small peaks at about 3600 Hz and 4000 Hz are occurred. From the waterfall spectra results (not shown in this paper), it can be diagnosed that these peaks are caused by the effect of resonance.

Although, it is simple to use synchronous averaging together with frequency analysis as the method A discussed above to extract characteristics of individual gear, this method also has some disadvantages.

1. The utilization of window function in this method leads to reduction of the amplitude of the signal at the both sides of the data block, so some information of gears at the both sides of the block are lost, and some errors in the amplitude of vibration must be occurred in the frequency analysis results.

2. Due to the utilization of synchronous averaging, peaks in

![Figure 2 Synchronous averaging result (method A), (a) averaged waveform, (b) averaged waveform processed by window function, (c) frequency analysis result](image-url)
the frequency domain should appear only at the integer order of driving or driven shaft frequency. However in the method A, resolution in frequency domain is fixed by the value of sampling frequency and the number of data per block, in this case it is equal to 12.5 Hz, that does not equal to driving or driven frequency, therefore significant errors in the position and amplitude of peaks are occurred.

From discussion above, it is obvious that selection of the length of data block affects highly to the precision in the frequency domain. In method B that is the proposed method, the length of data block is set to equals to the driving or driven shaft period. With this setting, the point of averaged signal at the beginning of the block match with the point at the end, therefore the discontinuity does not occur. The window function is unnecessary to use in this case, so all averaged data in the block is used to analysis, no averaged data are lost. Moreover, with this setting, the resolution in the frequency domain is equal to the frequency of driving or driven gear, and agrees with the real signal that is remained from the synchronous averaging process, so there are no error in frequency and amplitude of peaks.

Figure 3 shows the results from the method B. The synchronous averaged waveform is received from averaging the data that the length of each data block is set to equal to the period of driving or driven shaft. The points of data are resampled, so the position and the number of data points are matched with the length of data block. The averaged waveform are shown in fig.3(a). The abscissa is the time axis that its length is written to fit with the length of the block of data that is equal to the period of driving shaft or 18.87 ms in the case of driving trigger is used, and equal to the period of driven shaft or 33.33 ms in the case of driven trigger is used. Note that the length of the abscissa in this figure does not equal to the abscissa shown in fig.2(a).

Because the length of the block of data is equal to the period of each shaft rotation, the window function is unnecessary to use in this case. The rectangular window (no window function) is used instead of other window functions. Figure 3(b) shows the result of shaft order analysis; the ordinate is the amplitude of vibration; the abscissa is the order of driving or driven shaft rotation in the range of 0 to 5000 Hz (driving shaft order 0-95th, driven shaft order 0-167th). The resolution in this case is equal to the frequency of shaft rotation, so there are no error in both position and amplitude of peak of vibration.

Comparison results from both methods, it can be seen that the results in general are almost the same. However it also has some noticeable differences between both results. The amplitude of peaks received from method B is slightly higher than the result received from method A, especially at the second order of mesh component (2fz) and the cluster of peaks between 4kHz and 5kHz. The difference of the amplitude of peaks analyzed by method A and method B at some orders of driving shaft rotation are shown in fig.4. The reasons of these amplitude differences are the effect of using window functions and the difference of the position of peak caused by difference of accuracy between both methods. It can noticed that the amplitude of the vibration at the both ends of the block of the averaged waveform with the driving trigger in fig.2(a) are relatively high, but after this waveform is processed by the window function, the amplitude at the both ends of the block are reduced to zeros to make the continuity at both ends, so the shape of the waveform that will be processed by frequency analysis is changed, therefore the amplitudes of peaks in the frequency domain are slightly less than the exact result should be.

![Figure 3 Synchronous averaging result (method B), (a) averaged waveform, (b) shaft order analysis result](image)

![Figure 4 Amplitude of peaks from method A and method B in the case of driving trigger are used](image)
Moreover, the resolution in the frequency domain processed by method A is equal to 12.5 Hz that does not match with the shaft frequencies, so the position of peaks in the result from method A are occurred at the integer times of 12.5 Hz, and does not conform with the position of peaks from the real signal that must occur at the integer times of shaft frequency. With this reason the errors must be occurred when using method A. On the other hand, method B has no error about the position of peaks and no window function is used, therefore the result in this method is more accurate comparing with method A, and so the amplitude of peaks in this method is slightly higher.

4. The effect of the number of averaging to the accuracy of the averaged signal

The number of averaging is one of the important factors affecting the accuracy of the averaged signal. Enough averaging is required for completely extraction of the vibration signals attributed from interested gear from each other. The larger number of averaging brings the higher accuracy, but more the measurement and calculation time must be consumed. The selection of optimum number of averaging will bring the accurate results together with short calculated time.

In this research, the errors from the results using averaged number 8, 16, 32, 64, 128, 256 and 512 are considered. The result received from average number equal to 1024 is assumed to be the precise signal and used as the reference. Normalized mean square error is used as the parameter for consideration. Normalized mean square error can be calculated from eq.(1).

\[
NMSE = \frac{\sum_{N} (S_{nf} - S_{m})^2}{\sum_{N} S_{nf}^2}
\]

\[S_{nf} = \text{Reference signal} \]
\[S_{m} = m \text{ times averaged signal} \]
\[N = \text{Number of data} \]

Figure 5 shows the effect of the number of averaging to the normalized mean square error of the results. Normalized mean square error of waveform is shown in fig.5(a) and normalized mean square error of spectra is shown in fig.5(b). The abscissa is the number of averaging. The ordinate is the values of normalized mean square error calculated from eq.(1). Both axes are written in logarithmic scale.

From the results, it is evident that the more number of averaging used, the more precise signal obtained. Because the error affected from the number of average decreases exponentially when the number of average increase, the error after averaging more than 128 times is almost unaltered. Consider the number of averaging used in the examples in this paper that is 256 times, the result shows that after the signal is averaged, normalized mean square error of the waveform is less than 0.01, and less than 0.003 in the case of spectral. With these accuracies along with short calculated time, 256 times averaging is recommended to use in the practical calculation.

5. Conclusion

This paper discusses about the method of the utilization of the synchronous averaging together with frequency analysis to extract vibration characteristics of an individual gear. Analysis by the method that each data block does not fit with the period of driving or driven gear rotation, the window function is necessary to use. This method brings the significant error in the amplitude of peaks in the frequency domain. It is recommended to select the length of data block, and resample data points to match with the period of driving and driven shaft and use shaft order analysis for more precision in amplitude and frequency of the results. The effect of the number of averaging is also discussed in this paper.

6. References


