Abstract
This report discusses relationship between a handle rotational feeling in reel and a gear pair vibration. The vibration occurs when a handle of the reel rotates. When the vibration is large, an angler feels uncomfortable. To measure the gear pair vibration, an evaluation method using a bone conduction speaker was proposed. In this method, the bone conduction speaker is attached onto the handle knob of the reel, and the slight vibration is measured. The measured data was analyzed by spectrogram and FFT (Fast Fourier Transform) analysis, and characteristic data for the forecast of handle rotational feeling in reel were extracted from the result of the FFT analysis. A total of five sample reels were prepared for evaluation. The evaluation points were made into a ranking, and the handle rotational feeling in these sample reels was judged through human judgment. The best estimate for the forecast was defined to be the average of rankings. In the evaluation for the relationship between handle rotational feeling in reel and the measured data, the MT-system of robust engineering was used. In this analysis, a forecast value was calculated based on these characteristic values. As a result, although the vibration was quite small, it was confirmed that there is a strong relationship between the two. Thereby, it becomes possible to make quantitative judgment. During the judgment, an inspector can hear the vibration sound amplified from the speaker, similar to that of the rotational feeling conducted from the handle. Consequently, the judgment becomes easier, and the judgment accuracy improves dramatically.

Key words: Face gear, Transmission error, Fishing reel, Bone conduction speaker, Gear vibration, Spectrogram

1. Introduction

Generally, fishing spinning reels (Fig.1) utilize a face gear and a pinion gear. Fig.2 shows the face gear pair, and Fig.3 shows internal structure of the reel. The face gear system is commonly utilized in fishing reels because it offers good handle rotational feeling in reel (Rotational feeling). However, it is very weak against alignment errors. If the reel has an alignment error, vibration due to the gear pair engagement occurs in this gear system when a handle of the reel rotates. The vibration is transmitted to a tip of a finger of the angler via the handle. When this vibration is large, the angler feels uncomfortable, and information from fish or water cannot be accurately transmitted to the tip of the finger.
via the fishing line. Therefore, such vibration results in considerable devaluation of a reel. In order to solve this problem regarding alignment errors, a new method of tooth design was proposed (Inoue and Kurokawa, 2012). It was reported that when the tooth flank of the face gear is shaped according to a transmission error (TE) controlled curve (Inoue and Kurokawa, 2013a), the reel has robustness against influence of alignment errors.

On the other hand, it is known that there is a nonlinear relationship between tactile sensibility of a finger and frequencies of vibration (Gescheider, et al, 2001) (Beceren, et al, 2013) etc. According to a previous report (Shimojou, et al, 2014), the frequency around 200Hz results in the highest sensibility in terms of human feeling. Moreover, according to the reference (Shimojou, et al, 2014), it was indicated that there is a pachinian corpuscle under the skin of human. The pachinian corpuscle is sensitive against vibration, and it acts as the part of the acceleration sensor. It has been confirmed that the rotational feeling changes when the rotational speed of the handle changes. The result shows that there is a possibility that the rotational feeling can be improved by controlling a mesh frequency without changing tooth flank accuracy. In other previous reports, it was confirmed that the rotational feeling depends on the mesh frequency (Inoue and Kurokawa, 2013b). Furthermore, the vibration can be divided into two categories based on the peak frequency at which tactile sensibility is at the maximum, namely those like a drum vibration in low frequency band, and those like a string vibration in high frequency band (Inoue and Kurokawa, 2014a) (Inoue and Kurokawa, 2014b). Base on this result, a possibility was discovered where the rotational feeling may be improved if the mesh frequency gets higher than the peak frequency.

In order to improve the rotational feeling, it was required that the rotational feeling needs to be measured in high accuracy. In the mass production, the rotational feeling is conventionally evaluated by expert inspectors. However, such evaluation is carried out based on human judgment; therefore, it is vague, inefficient, and not quantitative. In the case of the acoustic sensibility of a human, there are reports on a relationship between the acoustic sensibility and the sounds which a gear pair emits (Brecher et al, 2010) (Faventi et al, 2014). The sound was classified into for types, namely, loudness, sharpness, roughness, and fluctuation strength. In addition, the relationship of excited gear noise based on the tooth flank form and sound level is also reported (Mohamad et al, 2010). Moreover, there are many researches for a tactile sensibility of a human finger as affective engineering, for example the research of sensitivity of a finger and a temperature (Brecher et al, 2010), and the research of sensitivity of a finger and texture (Aizawa et al, 2015). However, there is no report on a relationship between the tactile sensibility of a human finger and the vibration which a gear pair generates. In previous reports, a quantitative method for evaluating rotational feeling was reported using a face gear pair via a TE measurement system (Inoue and Kurokawa, 2013b). In this report, in order to convert rotational feeling into numerical values, characteristic values were extracted from TE curves and were used to calculate for forecast in Maharanobis-Taguchi system (MT-system) of robust engineering. As a result of calculation, it was confirmed that there was a high correlation between forecast ranking and actual ranking; thereby the quantitative method has been established. However, the method cannot evaluate rotational feeling in a situation where the gear pair has been assembled in the reel.

This report discusses how rotational feeling is evaluated and judged based on gear pair vibration in a situation where the gear pair has been assembled in the reel. In order to measure the gear pair vibration, an evaluation method using a bone conduction speaker was proposed. The handle vibration was measured in a situation where the bone conduction speaker was attached onto the handle nob of the reel. The measured vibration was converted to the sound data, and the data was recorded in the voice recorder. And the recorded sound data were analyzed by spectrogram and FFT analysis. In this report, at first, sufficient validity of the system is investigated using spectrogram analysis. At the end, the rotational feeling was forecasted by MT-system of robust engineering in high correlation using the FFT analyzed data.
2. Measurement of slight vibration on the handle knob of reel

Fig. 4 shows the system configuration of the vibration measurement system. This system consists of a bone conduction speaker, an amplifier, and a voice recorder. Here, the bone conduction speaker (NEC tokin VS-BV201) uses a piezoelectric type sensor, and the size of the sensor is 5mm wide, the thickness is 1mm. In this method, the bone conduction speaker is attached onto the handle knob of the reel. The slight vibration is measured and converted to sound data, and the data was recorded in the voice recorder (Panasonic RR-S500).

A total of five sample reels were prepared for evaluation. The difference in rotational feeling between these sample reels was slight. The evaluation points were made into a ranking, and the rotational feeling of these samples was judged through human judgment by seven evaluators, three times each. These evaluators were selected from twenty one evaluators in the previous report (Inoue and Kurokawa, 2013b). In the experiment, the reel body is held with the right hand, and the handle is rotated in 80min⁻¹ with the left hand. The sound data are recorded for 20 seconds each, and then a metronome was used so that the handle rotates at a substantially uniform rotational frequency. These sound data are used for the verification of the system and the quantitation of the rotational feeling. In this evaluation, an evaluator judges the handle rotational feeling of a feel based on the gear pair vibration when the reel rotates. It is important that “small vibration” does not always equal to “good feeling”. This is a comprehensive evaluation includes comfortable feeling and uncomfortable feeling.

3. Ranking of rotational feeling of the sample reels

Table 1 shows the rating result of human judgment by the seven evaluators, three times each. The lowercase alphabets of “a” to “e” in Table 1 represent sample names. The numbers in Table 1 represent ranking of each sample. It was defined that ranking No.1 corresponds to one point and ranking No.5 corresponds to five points. Namely, a ranking point of small number indicates good feeling, and a ranking point of large number indicates bad feeling. At the time of evaluation, an evaluator cannot distinguish the sample number.

Fig. 5 shows the graph which was calculated based on the result of Table 1 as the ranking of rotational feeling. This graph shows the relationship between sample names and ranking points. In this case, it is found that samples D and E have a difference of over 1.2 point. Namely, it is shown that the two samples have a large difference in terms of the rotational feeling. Conversely, it is found that samples E and C have only a difference of under 0.7 point. Namely, it is shown that the two samples do not have large difference in terms of the rotational feeling. The X axis represents sample name. These samples are arranged, in order, such that the left side represents good feeling samples. The Y axis represents ranking point. The best estimate for this calculation was defined as the average of rankings from twenty one data (7 evaluators x 3 times).

Each evaluator’s evaluation capability is given a weight which is regarded as odds rate during calculation. When the weight of evaluator Mr. A is set as \( \eta_A \), it is calculated by the following equation (1). And the average data is calculated in consideration of this weight. In this equation, \( R \) represents a correlation coefficient (i.e. Pearson product-moment correlation coefficient) between an average ranking of seven persons and an average ranking of each evaluator. \( i \) represents each person and \( i \) is an alphabet from A to G in this case.

\[ R = \frac{\sum_{i=A}^{G} \sum_{k=1}^{7} i_k - \bar{i} \sum_{k=1}^{7} k}{\sqrt{\left( \sum_{i=A}^{G} \sum_{k=1}^{7} (i_k - \bar{i})^2 \right) \left( \sum_{k=1}^{7} k^2 - \frac{(\sum_{k=1}^{7} k)^2}{7} \right)}} \]
\[ \eta_i = \frac{R_i^2}{1 - R_i^2} \quad (i=A,B,C\ldots G) \quad (1) \]

The thick blue line in Fig. 5 represents the average ranking. Each of the fine lines shows the individual ranking. If the individual result and the average result were the same, it suggests that the person has a good sensing level with respect to judgment of rotational feeling. Evaluator Mr. D shows the result of the best evaluator, and its square of correlation coefficient is 99.9%. Actually, Mr. D is an inspector. Based on this result, it is confirmed that the inspector has a high sensing level. Evaluator Mr. F shows the result of the worst evaluator, and its square of correlation coefficient is 75%. However, sensing level of Mr. F is still high enough. From this result, it is found that judgment ability differs for each evaluator. This is the reason that the weight was applied to the calculation of ranking, thereby giving priority to the result from high performance evaluators. This average ranking is set to represent the best estimate for the verification of the system and the quantitation of the rotational feeling.

### Table 1  Result of rating among 7 evaluators, 3 times each.

<table>
<thead>
<tr>
<th>Evaluator</th>
<th>Number of judgment</th>
<th>Sample number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mr. A</td>
<td>1</td>
<td>a, b, c, d, e</td>
</tr>
<tr>
<td>Mr. B</td>
<td>1</td>
<td>a, b, c, d, e</td>
</tr>
<tr>
<td>Mr. C</td>
<td>1</td>
<td>a, b, c, d, e</td>
</tr>
<tr>
<td>Mr. D</td>
<td>1</td>
<td>a, b, c, d, e</td>
</tr>
<tr>
<td>Mr. E</td>
<td>1</td>
<td>a, b, c, d, e</td>
</tr>
<tr>
<td>Mr. F</td>
<td>1</td>
<td>a, b, c, d, e</td>
</tr>
<tr>
<td>Mr. G</td>
<td>1</td>
<td>a, b, c, d, e</td>
</tr>
</tbody>
</table>

![Fig. 5](image)  Ranking of rotational feeling. Blue thick line represents average ranking among 7 evaluators, 3 times each. Thin line represents each evaluator’s result. Sample-a demonstrates good rotational feeling, and sample-b demonstrates bad rotational feeling.

### 4. Verification of the measurement system

The recorded data were analyzed by spectrogram and FFT analysis (KTH WaveSurfer 1.8.8p3). Fig.6 shows five sample results of spectrogram analysis. The X axis represents time, and the graph shows data recorded only for 0.75 second. The time of 0.75 second represents the time for one handle rotation. The Y axis represents frequency of sound. The color in the graph represents a power spectrum obtained by FFT analysis. In this graph, red color suggests large power spectrum according to the color bar. In the five spectrogram graphs, the range slightly differs for each color bar display, but the correlation checking in advance results in that the color which was indicated in each graph can be regarded as approximately the same color.

These graphs are arranged, in order, from small ranking point to large ranking point, namely samples- a, d, e, c and b. As a result, it is found that the graphs of samples- e, c and b have more red-to-yellow-colored regions as compared with the graphs of samples- a and d. In the graph of sample-b, significantly more red-to-yellow-colored regions are found in the high frequency band. This result corresponds to the ranking as shown in Fig. 5. From this result, it was inferred that the system can distinguish slight vibration differences in high sensitivity.
In the evaluation of the relationship between rotational feeling and the sound data, the MT-system of robust engineering was used. In this analysis of MT system, a forecast ranking was calculated based on characteristic data. Each characteristic data is referred to as an “item”. At first, the stabled sound data for only 4 cycles (3.0s) of the rotation were extracted from the data of 20 seconds. Next, these extracted sound data were analyzed by FFT analysis. Fig.7 shows the result of the FFT analysis. The X axis represents frequency, and the Y axis represents power spectrum. The X axis is indicated with log scale. In the graph, each solid curve represents sample data, and the dotted curve represents the average data. It was confirmed that there are 3 types of characteristics at 3 different frequency bands, namely, 100-500Hz, 600-1200Hz, and 2000-4800Hz. In these frequency bands, it is found that the curves of high ranking point are above the average curve, and the curves of low ranking point are below the average curve. From the result of the analysis, it is inferred that there is a relationship between the result of FFT and ranking point.

In order to define items for evaluation, Fig.7 was converted to the graph as shown in Fig.8. In the graph, power spectrum of zero represents the average power spectrum of five samples. Namely, this graph shows the fluctuation of the FFT power spectrum from the average. The X axis represents frequency, and the Y axis represents power spectrum fluctuation from the average. The X axis is not indicated with log scale. A total of twelve items for the forecast of ranking point were extracted based on the result of the FFT power spectrum data. If a rotational feeling is calculated based on these items, a quantitative evaluation will be possible without human judgment. The frequency range from 0 to 6kHz was used, and the average data were calculated every 500Hz. The average data of each of the respective frequency bands was calculated as an item. Table 2 shows data of the calculated items.

5. Definition of characteristic value

Fig.6 Result of handle vibration by spectrogram analysis. The time of 0.75 second represents the time for one handle rotation. These graphs are arranged, in order, from small ranking point to large ranking point, namely samples-a, d, e, c and b.
6. Analysis by MT system

The data analysis was carried out by a method of a pattern recognition called T-method (Taguchi-system) in MT-system of robust engineering (Tatebayashi, et al., 2008). MT-system is a synthesis measurement method of creating one scale from the measurement value of many dimensions. Basically, MT-system is included in the robust engineering (i.e. Taguchi-Method). And the method is applied to pattern recognition, judgment, clarification, forecast, and estimation. Moreover, MT-system has a many type of method, namely, MTA-method, TS-system, T-method, and RT-method. T-method is included in the MT-system. Regarding the T-method, a scale is created using a calculated weight by S/N ratio of each measurement value. Here, S/N ratio represents a ratio where the size of the desirable factor effect (i.e. Signal) and the size of the undesirable factor effect (i.e. Noise). And, sensitivity represents a ratio where the input and the output, namely it means the constant of proportionality.

When a forecast ranking is set as \( \hat{E} \), it is calculated by the following equation (2) (Tatebayashi, et al., 2008). In this equation, \( X \) represents item, \( \eta \) represents S/N ratio of each ranking, \( \beta \) represents sensitivity, \( R \) represents correlation coefficient, \( M \) represents ranking point, \( j \) represents a sample number and \( k \) represents an item number. And \( j \) is a lower case alphabet from “a” to “e” and \( k \) is an integer from 1 to 12 in this case.

\[
\hat{E}_j = \frac{\eta_1 X_{1j} + \eta_2 X_{2j} + \cdots + \eta_k X_{kj}}{\eta_1 + \eta_2 + \cdots + \eta_k} \\
(j=a,b,c,d,e) (2)
\]

\[
\eta_k = \frac{R_k^2}{1 - R_k^2} \\
\beta_k = \frac{M_1 X_{1k} + M_2 X_{2k} + \cdots + M_j X_{jk}}{M_1^2 + M_2^2 + \cdots + M_j^2} \\
(k=1,2,3\cdots12)
\]
Fig. 9 shows the result of the calculated forecast rankings. In this graph, the X axis represents the best estimate and the Y axis represents a forecast ranking. As a result, although the vibration was quite small, it was confirmed that there is a high correlation between best estimate and forecast ranking. The square of a correlation coefficient is 0.99.

In order to confirm accuracy of this equation, the square of correlation coefficient was calculated in situations where one data is removed. The graph of Fig. 9 represents the result of forecast in which five data were used. The graph of Fig. 10 show the results of forecast in which only four data were used. And the red markers in these graphs represent target data, namely samples- A, B, C, D, and E which were removed in the respective calculations. If the equation is inaccurate, the red marker would not fall on near the approximate curve which was indicated in the graph, and also the square of correlation coefficient would be low. However, every square of correlation coefficient was over 0.95. In particular, the square of correlation coefficient is 0.99 without data of sample-a, 0.95 without data of sample-B, 0.97 without data of sample-C, 0.99 without data of sample-D, 0.99 and without data of sample-E. From this result, it was confirmed that the ranking could be forecasted in high accuracy, and it is possible to judge rotational feeling quantitatively in a situation where the gear pair has been assembled in the reel.

![Graph showing correlation between best estimate and forecast ranking.](image)

Fig. 9  Result of calculated forecast ranking. Although the vibration was quite small, it was confirmed that there is a high correlation between best estimate and forecast ranking. The square of a correlation coefficient is 0.99. In this calculation, five sample data were used for forecast

![Graphs showing forecast rankings with different data removed.](image)

(a) Without data of sample-a  (b) Without data of sample-b  (c) Without data of sample-c  (d) Without data of sample-d  (e) Without data of sample-e

Fig. 10  Result of calculated forecast ranking by the Jackknife method. Although one data was removed from the calculation, it was confirmed that there is a high correlation between best estimate and forecast ranking. In this calculation, only four sample data were used for forecast.
7. Discussion

Fig. 11 shows result of item diagnosis. The graph indicates which frequency band is relevant for forecast of ranking point. The X axis represents frequency band, and the Y axis represents the square of correlation coefficient. In this result, high correlation is found at 0 to 499Hz and at 2500 to 4999Hz, namely at items -1, 6, 7, 8, 9, and 10. However, a square of correlation coefficient of 0.89 is only found at 0 to 499Hz, namely at item-1. From this result, there are still some doubts, namely, whether evaluators feel a vibration at high frequency bands or not.

According to the previous reports, it was confirmed that evaluator cannot recognize a frequency over 1000Hz by a tip of a finger, (Inoue and Kurokawa, 2014a) (Inoue and Kurokawa, 2014b). Thereby, the following hypothesis is inferred. At first, low frequency noise is converted into vibration, and evaluator can judge rotational feeling by a tip of a finger. And next, high frequency noise is converted into sound, and evaluator can judge rotational feeling by ears. Consequently, a new possibility was found where rotational feeling may be judged by sound or spectrogram evaluation. Evaluator can recognize a frequency at 2500~5000Hz by a sound or via the graph of spectrogram.

![Figure 11: Result of item diagnosis. High correlation is found at 0 to 499Hz and at 2500 to 4999Hz, namely at items -1, 6, 7, 8, 9, and 10.](image)

8. Conclusion

According to the result of previous research, a quantitative method for evaluating rotational feeling was reported using a face gear pair via a TE measurement system (Inoue and Kurokawa, 2013b). However, the method cannot evaluate rotational feeling in a situation where the gear pair has been assembled in the reel. In order to measure the gear pair vibration in that situation, an evaluation method using a bone conduction speaker was proposed. Thereby, it becomes possible to make quantitative judgment using a reel product. Consequently, the judgment becomes easier, and the judgment accuracy improves dramatically. The results obtained from this research are as follows.

1. In order to measure a handle rotational feeling in a reel, an evaluation method using a bone conduction speaker was proposed and developed as the vibration measurement system.
2. The handle vibration was measured in a situation where the bone conduction speaker was attached onto the handle nob of the reel. And the measured sound data were analyzed by spectrogram and FFT analysis.
3. Sufficient validity of the vibration measurement system was investigated using a spectrogram analysis. As a result, it was confirmed that the system can distinguish slight vibration differences at high sensitivity.
4. The rotational feeling was evaluated and forecasted in high accuracy by T-method of MT-system. As a result, it was possible to judge rotational feeling quantitatively using a reel product.
5. During the judgment, an inspector can hear the vibration sound amplified from the speaker, similar to that of the rotational feeling conducted from the handle. Consequently, the judgment becomes easier, and the judgment accuracy improves dramatically.
References


