

Development of Evaluation Method for Waviness Property on Hypoid Gear Tooth Surface

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ABSTRACT

Measuring and analysis methods have been discovered for quantitative evaluation of tooth surface waviness, which cause high-order sound radiation from hypoid gears. Tooth surface waviness was measured by an optical, non-contact 3D measuring device. Taking this measurement result, images were filtered by applying a 2D Fourier Transform and inverse Fourier Transform to extract the cyclical waviness components impacting gear noise frequencies. The method was used to evaluate tooth waviness of hypoid gear in an actual gearbox unit. The cyclical peak order of the waviness matched the peak order of frequencies of sound radiation from gears. In addition, upon evaluating multiple specimen gears, a quantitative correlation was found between the amplitude of peak order waviness and the pressure level of sound radiation from gears. This has newly made quantitative evaluation of hypoid gears in isolation possible.

1. Introduction

With the spreading popularity of all-wheel drive (AWD) multi-purpose passenger vehicles, typified by the SUV, Honda has developed and commercialized numerous hypoid gears for drivetrains. A hypoid gear is a type of bevel gear that turns the rotational axis at a right angle on the transfer path of rotational power from the engine or motor to the driving wheels. As illustrated with the AWD drivetrain of the Honda vehicle shown in Fig. 1, a common structure is to place gear sets at both the front and rear ends of the propeller shaft. The front end gear set is built into the power transfer unit attached to the transmission, and the rear end gear set is built into a rear drive unit mounted above the rear axle, with each transmitting driving torque.

With the increase in cabin quietness for passenger vehicles in recent years, the quality and performance demands for drivetrain components are higher than ever in terms of noise, vibrations, and harshness, collectively termed NVH. Hypoid gears have posed particular challenges in the development stage for cabin noise due to the high-frequency NVH they emit from meshing. These high-frequency meshing sounds are raspy in the normal driving range on actual vehicles. NVH generated by toothed gears transmitting power is synchronized with the mesh cycle frequency of meshed tooth surfaces of a gear pair -- namely, the driver and driven gears. With the order number being a constant multiple of the mesh cycle frequency, the frequency of high-order gear noises is known

to take on the waviness of tooth surface and be affected by accuracy control in the tooth surface manufacturing process⁽¹⁾. However, there were no conventional indicators or methods capable of quantitatively evaluating the tooth surface waviness causing this high-order gear noise. Thus, with the gears being challenging to evaluate in isolation, these waviness had been evaluated in the mass production manufacturing process using a quality pass/fail judgment based on meshing test results of completed gear sets, followed by production control. This led to increased man-hours for controls and decreased production efficiency. Additionally, much time and effort was spent on gear meshing tests for different manufacturing conditions and for parameter studies on actual unit noise tests to feed preventive measures for gear noise and waviness back into the manufacturing control criteria for individual gears.

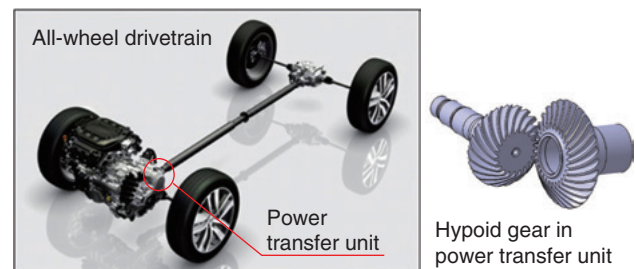


Fig. 1 Drivetrain and hypoid gear of Honda AWD vehicle

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2. Generating Mechanism for High-order Gear Noise

2.1. Relationship between Hypoid Gear Tooth Surface Waviness and High-order Gear Noise

Comparisons in cabin noise for development vehicles were made between vehicles with and without noticeable high-frequency noise near the 3000 Hz to 4000 Hz range. A hypoid gear set as built into the power transfer units of vehicles producing high-frequency noise was loaded into a meshing test machine assembled the same as in the actual unit and tested under equivalent loads to those in the actual units. This test confirmed a transmission error peak in the meshing order corresponding to the frequency of the high-frequency noises being generated in vehicle. Cabin noise data for the vehicles generating high-frequency noise is shown in Fig. 2. Here, the x-axis represents the meshing order number for the frequency of one meshing cycle of hypoid gear, and the y-axis represents vehicle driving speed. The color tones in the contour diagram represent the sound pressure levels. For this paper, one meshing cycle is defined as the time from the moment that two tooth surfaces on a hypoid gear mesh to the moment when they move to their adjacent tooth surfaces and repeat the same movement again. This cycle is the same for both driving and driven gears and is equal to the value of the time required for the gears to make one rotation, divided by the number of teeth. While cabin noise is being measured, the vehicle is test driven according to set mode conditions and at a constant rate of acceleration. Sound pressure data was recorded for all frequency ranges at each measured driving speed, and the sound pressure levels used to analyze the meshing order number for one meshing cycle of hypoid gear were arranged along the x-axis. Next, the data was continuously recorded while moving up the graph y-axis with the vehicle driving speed. From the graph, it was confirmed that the hypoid gear was generating a constant 7.5-order high-frequency noise for each meshing cycle at nearly all speed ranges during measurement. The gear unit meshing transmission error data is given in Fig. 3. For the meshing tester, a Gleason Works 600HTT was used in the measurements. The transmission error data was collected during gear

rotation for a fixed time and then analyzed for frequency using a Fast Fourier Transform (FFT). The meshing order numbers for one meshing cycle of hypoid gear were then graphed on the x-axis with transmission error amplitude on the y-axis. In this graph, 7.5-order transmission error peak that was the same as the high-frequency noise observed in the cabin noise data was confirmed.

This meshing transmission error, a value measured in rads or mm, represents the rotational motion for one meshing cycle as the two gears rotate. It is also equivalent to the position relative to the normal direction as determined from the geometric shape (profile) of both teeth surfaces. This transmission error is known to cyclically generate an angular acceleration on the driven gear that contributes directly to vibratory forces causing NVH^{(2), (3)}. From these results, the high-frequency noises causing issues in prototypes were identified as 7.5-order gear noises radiating from the hypoid gear tooth surface. Additionally, a stripe pattern facing the same direction at regular intervals was observed on the hypoid gear meshing teeth surfaces radiating a gear noise. Tooth surfaces from driving side pinion are illustrated in Fig. 4. Next is Fig. 5, which is a sketch of the meshing points on the tooth surface acting as the load center for power transmission. The tooth surface has a mesh trajectory (denoted as “path of contact” in Fig. 5) connecting the contact points between mesh starting point A1 and mesh ending point A2. Power is transmitted by these contact points moving at a constant speed along the path of contact. There are also two switching points on this line: B1 for the moment when the tooth switches from meshing with

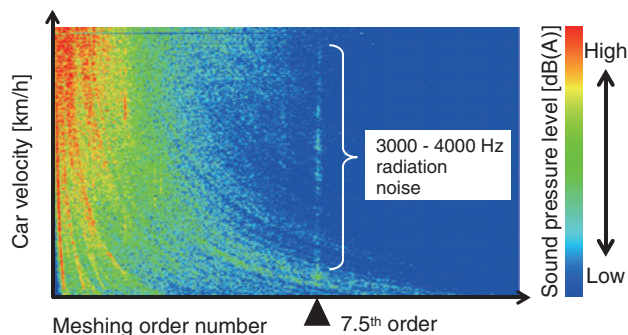


Fig. 2 Sound radiation level inside actual vehicle

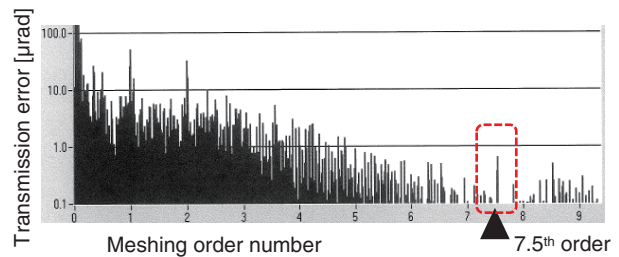


Fig. 3 Transmission error spectrum of hypoid gear

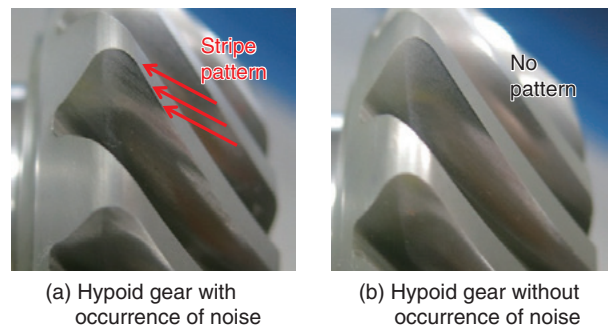


Fig. 4 Stripe pattern on tooth surface of hypoid gear

the previous tooth, and B2 for the moment when the tooth switches to meshing with the next tooth. As the gear rotates for an angle of 2π divided by the number of teeth, the mesh point will move from B1 to B2. Taking this motion as one unit, power is transmitted as this motion is repeated. From these points, it was surmised that the striped pattern found on the tooth surface in Fig. 4 crosses the path of contact at regular intervals. Next is Fig. 6, a motion graph of the transmission error properties over one meshing cycle. Here, the x-axis represents the rotational angle of the driving gear and the y-axis represents the delay amount (transmission error) as the amplitude of rotational fluctuation in the driven gear. Where the transmission error is 0 on the x-axis, the tooth surfaces of the driving and driven gears are contacting at a constant speed and there is no delay in rotation for the driven gear. The intersections on the transmission error curve match up with mesh switching points B1 and B2. This interval is equal to the angle of rotation for one meshing cycle. At points B1 and B2, a first-order cycle rotational delay is generated according to how crowned the tooth profile is at the point. The delays generated are equal to the position relative to the normal direction of the tooth surface. Thus, hypothetically, if there were a constantly cyclical waviness along the path of contact between B1 and B2, a transmission error and rotational fluctuation will be generated over one meshing cycle while rotating with a cycle order multiplied by the value of the distance moved between B1 and B2 divided by the waviness interval pitch length. Existing research has clearly shown that these tooth

surface waviness do impact specific-order transmission error^{(1),(4)}.

2.2. Purpose of Quantitative Evaluation Method for Tooth Surface Waviness

Existing research has shown a method of measuring and evaluating tooth surface waviness two-dimensionally on a measurement line of tooth profile and tooth lead shape by using a gear measuring machine or other profile measuring machine⁽¹⁾. Applying this existing method, the authors used a Klingelnberg AG gear profile measuring machine and dedicated software to measure tooth profiles on the path of contact shown in Fig. 5, then identified the resulting section curve in the normal direction. They also ran an FFT to analyze the cyclicity of the waviness on the curve. For the test gear used for measurement, the cutter alignment was adjusted during gear cutting to intentionally produce tooth surface waviness. The measurement results are given in Fig. 7. The section curve data on the path of contact of the tooth surface is shown in Fig. 7(a). Here, the x-axis represents the position in the path of contact length direction, and the y-axis represents the shape in the tooth surface normal direction. Meanwhile, the frequency analysis results for the data from Fig. 7(a) are given in Fig. 7(b), with the x-axis representing the cycle order number for one meshing cycle and the y-axis representing the amplitude in the tooth surface normal direction. In the graph, a number of cycles at different orders are present in addition to those near the 7.5-order, corresponding to the high-frequency noise generated in the vehicle. From this, it is no simple task to quantitatively evaluate the cycle order and amplitude values, which are the peaks as obtained in the measurements, as the property values of waviness.

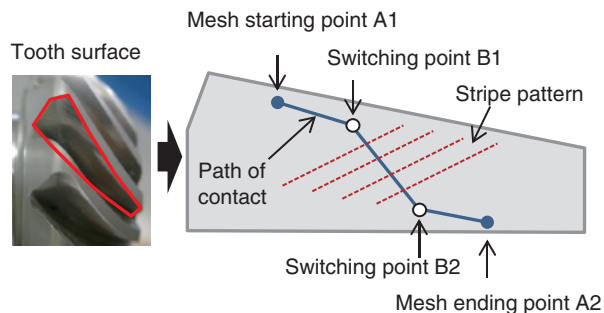


Fig. 5 Sketch of tooth surface and path of contact

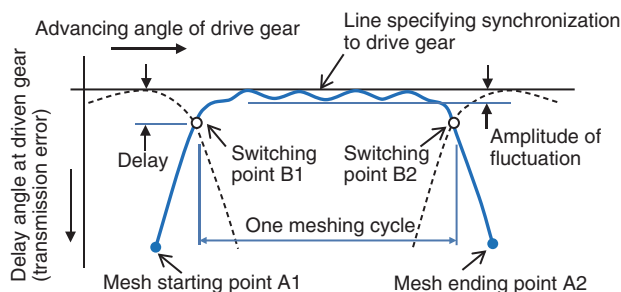


Fig. 6 Motion graph during one meshing cycle

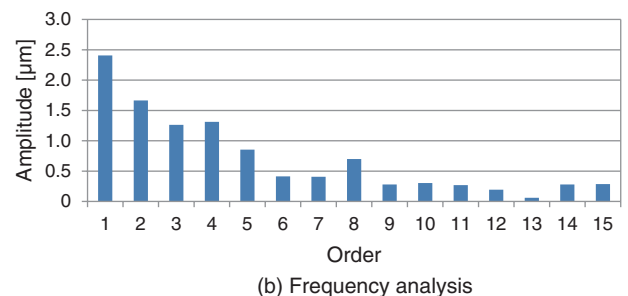
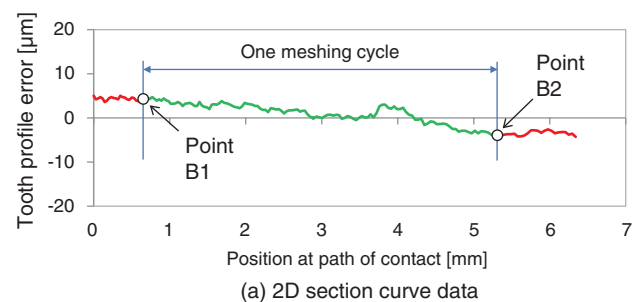


Fig. 7 Measurement results

Passing through gear cutting, heat treatment, and other steps in the manufacturing process, hypoid gears have irregularities of differing wavelengths in various directions on their tooth surfaces. The main properties, shown in the tooth surface sketch in Fig. 8, are: (1) tooth profile and crowning, (2) waviness, and (3) machining lines. Machining line is a collective term, including milling patterns generated at the cutting point and lines transferred to the tooth surface from surface properties in the cutter blade. With the above method, with all property data on the path of contact being captured in the measurement stage, the comparatively small waviness gets drowned out by other roughness levels and cannot be manifested. As this makes it challenging to evaluate waviness with the tooth surface alone using the existing method, waviness was evaluated with transmission error as measured in meshing tests of a completed gear set⁽¹⁾. For this study, a new method was created to take tooth surface shape data with various properties of differing directions and cycles, and extract from it only those minute, specific waviness components radiating gear noise in order to quantitatively evaluate them. Therefore, in place of the traditional 2D measurements on the path of contact, the tooth surface was measured extensively in 3D. From the 3D data taken for the tooth surface, an image filtering technique was used to extract waviness and analyze their direction.

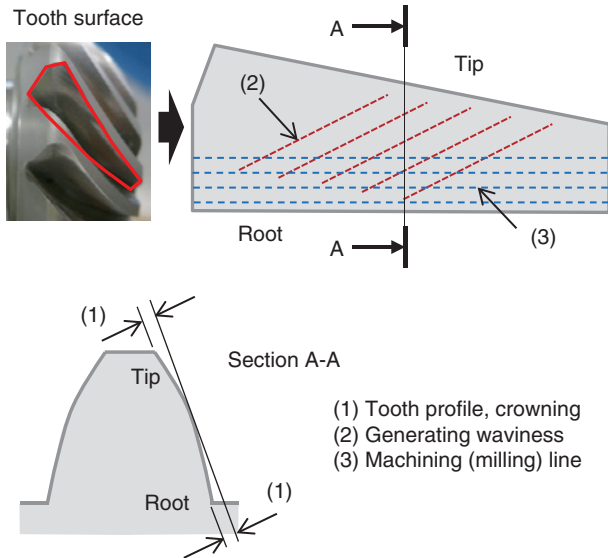


Fig. 8 Sketch of tooth surface and property

3. Creation of Methods to Measure and Evaluate Tooth Surface Waviness

3.1. Three-dimensional Measurement of Tooth Surface Shape

An Alicona optical non-contact 3D measurement device, capable of taking accurate 3D measurements of the tooth surface shape, was used for measurements. This

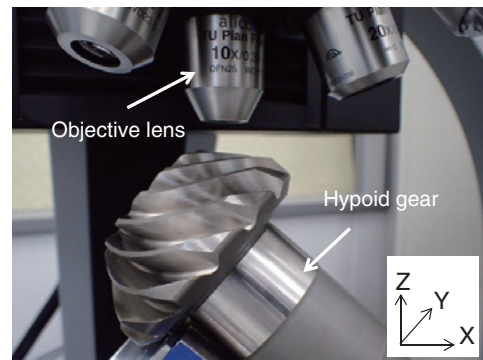
measurement device uses a moving focus measuring system. An image of measurement and basic specifications for the device are shown in Fig. 9. The imaging sensor captures images of the tooth surface via an objective lens that moves along the z-axis of the measurement device. While in motion, the objective lens shoots images at each height position in continuous shooting mode, then creates 3D property data by combining the pixel and height information for the parts in focus in the data for the multiple images taken. This method permits measurement of places with large height differences in a short period without damaging the measured part. Additionally, moving the measurement table in the X- and Y-directions and splicing multiple 3D images will produce extensive tooth surface data.

3.2. Tooth Profile Removal Using Polynomial Approximation

The captured image data contains long wavelength components due to the tooth profile, including crowning and bias. If measurement is greatly affected by these tooth profile components, it can be challenging to manifest the waviness component. To remove these shape deviations, polynomial approximation using the least squares method was applied. Defining the surface coordinates $Z = f(x, y)$, the n th polynomial is expressed by Eq. (1). Polynomial indices i and j were calculated using the least squares method.

$$Z_n(x, y) = \sum_{j=0}^n \sum_{i=0}^n a_{ij} x^{ij} \quad (1)$$

For this measurement, an n of 3 was used in calculations. Removing the shape components resulted in flat tooth surface data unimpacted by crowning (Fig. 10).



Horizontal resolution	1.76 μm
Vertical resolution	0.1 μm
Viewing range (X)	10 mm
Viewing range (Y)	5 mm

Fig. 9 Measuring equipment and basic specification

3.3. Detection of Waviness Components with Two-dimensional Fast Fourier Transform

With shape deviations removed, the 3D image data had evident marks thought to be waviness produced by cutting blade runout during cutting. Additionally, short wavelength marks running in a different direction were covering the waviness marks. To detect the frequency components of these two marks, a two-dimensional Fast Fourier Transform (2D FFT) was used. An overview of the 2D FFT is shown in Fig. 11. 2D images have two frequency components: horizontal and vertical. Thus, one-dimensional frequency analyses were run for each of the vertical and horizontal directions.

How to read the graph of the 2D FFT analysis results will now be explained while referring to the rough sketch in Fig. 12. The vertical and horizontal axes in the graph represent the vertical and horizontal directions, respectively, in the image data. Note that the top of the image data is

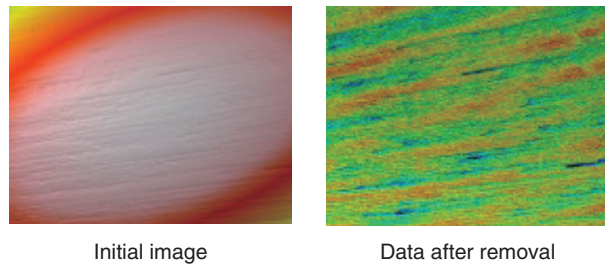


Fig. 10 Removal with polynomial approximation

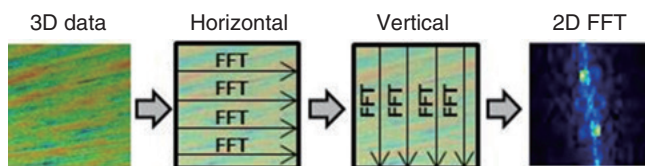


Fig. 11 Calculation procedure of 2D FFT

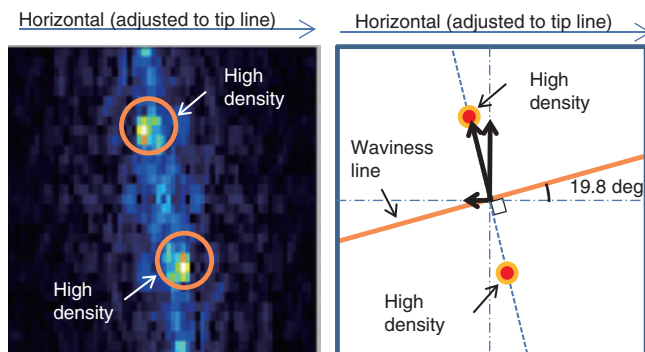


Fig. 12 Calculation result of 2D FFT

aligned with the face line for measurement. Distance from the center point represents the frequency of waviness; the further from the center, the higher the frequency component. Now, if the image data has an isocontour connecting the cyclical waviness peaks in a uniform direction, the isocontour will appear as a bright point in a position from the center corresponding to its wavelength, as in the graph on the right. Brightness here represents amplitude. The straight line vector connecting the center point and the bright point runs perpendicular to the waviness peak isocontour. In this data, the waviness is at a 19.8-degree slant with the face line.

3.4. Extraction of Three-dimensional Data with Inverse FFT

After first extracting to only isolate the waviness component of the bright point from the software-analyzed 2D FFT data, an inverse FFT is run using the same software to generate 3D data for the isolated waviness component. The 3D waviness component data, as extracted from the 3D tooth surface data with various properties of differing direction and cycles by the above filtering process, is shown in Fig. 13. The data captures an extensive area around the tooth surface waviness, including the mesh trajectory (“path of contact” in Fig. 13) corresponding to one meshing cycle. The top of the data is aligned with the face line (“tip” in Fig. 13), and the left and right sides give the measurement range in the perpendicular direction. Finally, the color tones in the contour diagram depict the waviness height in the tooth surface normal direction. This 3D data clearly captures waviness at the same angle and arranged at regular intervals across the path of contact, with approximately seven waviness in one meshing cycle. This method allows for extraction to isolate only the waviness components generating gear noise, achieving the objective of quantitatively evaluating waviness.

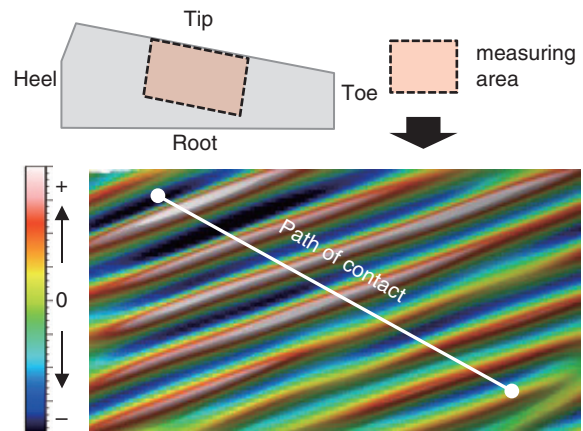


Fig. 13 3D data of tooth surface waviness

4. Quantitative Evaluation Results for Waviness and Actual Unit Validation

This method was used to measure and evaluate tooth surface waviness in an actual hypoid gear, and both the method and the gear noise generating mechanism were validated. A frequency analysis was run from the waviness on the path of contact in the extracted 3D tooth surface waviness data. The cyclical waviness order number and amplitude for one meshing cycle were calculated and evaluated. A section corresponding to one meshing cycle was identified in the 3D data based on the path of contact coordinates obtained from the Klingelnberg AG software and used to cut out the section curve.

Detailed conditions of the test hypoid gear set used in verification are shown in Table 1. In mass production, runout accuracy for the cutter blade mounted on the cutter head is normally controlled to within a few microns; the test gear, however, was intentionally cut such that significant tooth surface waviness would be reproduced. The test gear had the same specifications as the gear that the conventional method was unable to quantitatively evaluate, as described in Section 2.2.

4.1. Comparison of Cyclicities between Sound Radiation in Actual Gears and Tooth Surface Waviness

Analysis results for the shape data on the path of contact for the tooth surface waviness extracted with this method and their frequencies follow below. Figure 14 is a section curve graph with its x-axis showing the length direction of the path of contact for the 3D tooth surface data extracted to show waviness only and its y-axis showing shape in the tooth surface normal direction. Figure 15 contains the frequency analysis results for the data from Fig. 14. Here, the x-axis represents the cycle order number for one meshing cycle and the y-axis represents the amplitude in the tooth surface normal direction. Using this method, the tooth surface waviness occurred on the test gear was successfully evaluated to have an average pitch of 0.65 mm with a cycle peak near the 8th order for the one meshing cycle and maximum amplitude of 0.55 μm . Next are the test results with the same hypoid gear assembled in the actual unit, given in Fig. 16. This data is for sound radiation as measured by a microphone in a set location with the transmission and power transfer unit mounted to a test bench. The y-axis shows the average sound pressure levels, and the x-axis shows the order numbers for the frequency of one meshing cycle of hypoid gear. As denoted with an arrow on the data, significant sound radiation from gears was confirmed, peaking near a 7.6-order frequency. This result matches the property values obtained from the measurements and evaluations of the tooth surface waviness. Based on the above verification results, the generating mechanism for high-order sound radiation from gears due to tooth surface waviness has been clarified and

Table 1 Detailed conditions of hypoid gear for inspection

	Pinion	Gear
Number of teeth	21	29
Module	5 mm	3.724
Pinion offset		
Mean spiral angle	36.1 deg	30.8 deg
Sum of pressure angle	40 deg	40 deg
Cutter head type	Stick blade	Stick blade
Cutter head radius	2.25 inch	2.25 inch
Number of cutter blade pairs	11 pairs	11 pairs
Cutter rotation speed	211 rpm	239 rpm
Generating feed speed	4.54 deg/sec	5.71 deg/sec
Cutter runout on machine	0.03 mm	0.03 mm

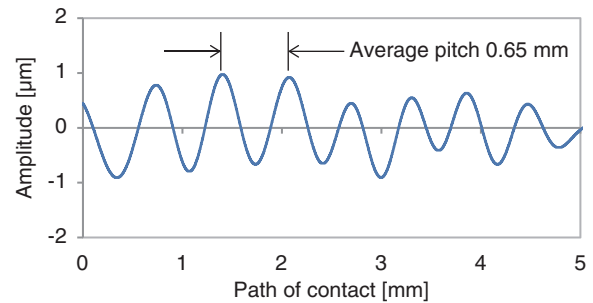


Fig. 14 Section curve data of waviness extracted

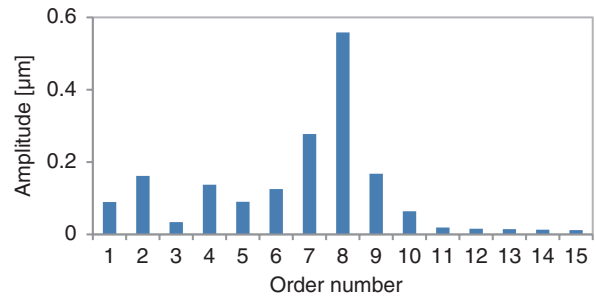


Fig. 15 Frequency analysis result of waviness extracted

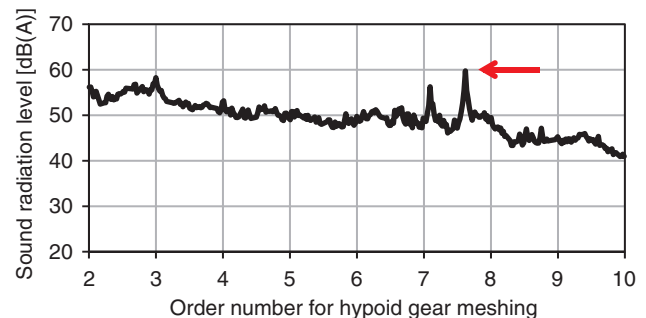


Fig. 16 Result of power transfer unit test

the detection accuracy of this evaluation method has been successfully verified.

4.2. Relationship between Pressure of Sound Radiation from Actual Gears and Amplitude of Tooth Surface Waviness

The same test measurements and assembled tests for tooth surface waviness were performed for multiple hypoid gears of the same specifications as the test gears in Section 4.1. These gears were selected at random, per mass production management criteria. From the results, a summary of the relationship between tooth surface waviness and high-order gear noise is given in Fig. 17. The x-axis of the graph shows the amplitude of tooth surface waviness, and the y-axis gives the pressure levels of peak sound radiation from gears in actual gearbox unit. As with the peak cycle order for waviness, the pressure levels of the sound radiation from gears plot to 7.6-order levels. This graph shows a positive correlation between sound radiation and amplitude of the waviness and quantifies the tendency of peak pressure levels of sound radiation from gears to increase as waviness amplitude increases.

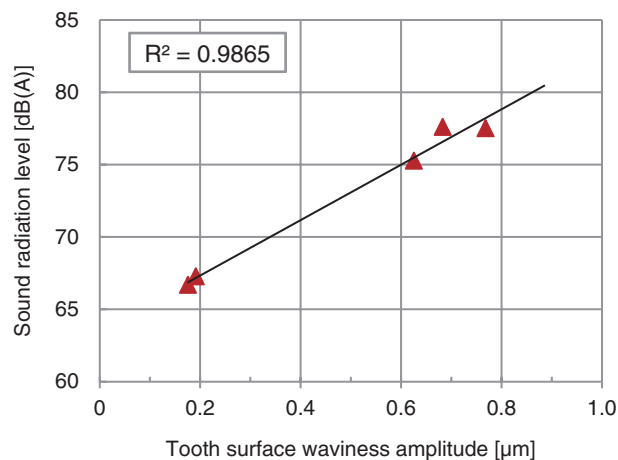


Fig. 17 Relationship between waviness amplitude and sound radiation level

5. Conclusion

In this study, through examination of an evaluation method for waviness, the following points have been achieved regarding the empirically known relationship between cyclical waviness as occurred by tooth surfaces in hypoid gears and high-order gear noises:

- (1) A new method for quantitative evaluation of tooth surface waviness has been created, using image filtering methods with 2D FFT and inverse FFT to extract the waviness component from 3D tooth surface

measurement data. Using measurement results from this method, it was revealed that tooth surface waviness is a generating mechanism for high-order gear noise.

- (2) The correlation between peak order waviness amplitude as evaluated with this method and pressure levels of sound radiation from actual gears was quantified, and indicator criteria for waviness amplitudes were obtained. The above has made quantitative evaluation of gears in isolation possible.

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