

Mechanism of Occurrence of Ghost Noise in Helical Gears Resulting from Thread-type Tool Machining

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ABSTRACT

Specifying the origins of ghost noises produced at non-integral multiples of gear meshing order frequency from the order at which they occur represents a challenge, and determining countermeasures for these forms of noise has involved a process of trial and error. Today, with the widespread use of a method of continuous generation involving the use of a multiple-thread-type tool for high production efficiency in the process of grinding the flanks of the helical gears used in automotive transmissions, new ghost noises have appeared. The research discussed in this paper clarified the mechanism behind the production of the ghost noises that have become noticeable as a result of the use of the multiple-thread-type tool, and identified the relationship between the conditions used in the grinding process and the orders at which the noises occur. By verifying these findings in an actual transmission and studying countermeasures, the project demonstrated that ghost noises could be reduced by modifying the conditions used in the grinding process.

1. Introduction

Gear noise normally occurs at the meshing order frequency and integral multiples of the meshing order frequency. When noise is generated at non-integral multiples of the meshing order frequency, it is termed ghost noise⁽¹⁾. Ghost noises result from cyclical undulations produced on the surface of the gear teeth during machining; it is known that ghost noises can be produced even if the amplitude of these undulations is extremely low ($1 \mu\text{m}$ or less)^{(2), (3)}. Their cycle per tooth is not an integer, and as such, a complex periodicity is displayed in which the frequency orders at which ghost noises are produced are non-integral multiples of the meshing order frequency. Because of these, it is challenging to specify the cycles of the undulations using usual tooth form measurements^{(2), (3)}. In addition, this complex periodicity makes it challenging to infer the mechanisms by which these undulations are produced. In this paper, these undulations on the surface of the gear tooth, for which the cycle per tooth is not an integer and which represent a factor in the production of ghost noises, will be termed ghost undulations.

Ghost undulations have been shown to be produced by

transmission errors generated by gears on shafts of continuous generating grinding machine using thread-type tools⁽⁴⁾. Today, with the widespread use of multiple-thread-type tools in order to achieve production efficiency in the process of grinding the flanks of the helical gears used in automotive transmissions, ghost noises of unknown origin have appeared. It has therefore become necessary to determine the origin of these ghost noises, and to examine methods of reducing their incidence.

2. Characteristics of Data Concerning Tooth Forms Generating Ghost Noises

Figure 1 shows the drive train pathways of an automotive transmission. Figure 2 shows transmission case vibration data measured in order tracking analysis using this transmission. The horizontal axis shows order frequencies for the benchmark driveshaft rotation, and the vertical axis shows driveshaft rotation speed. At the benchmark rotation of the driveshaft, the meshing order frequency of the final gear set is the 71st order and the meshing order frequency of the 4th gear set is the 137.6th order, and these orders appear as peaks in transmission case vibration. The 331st and 662nd orders that appear in

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Fig. 2 are ghost order frequencies which are not harmonics of gear meshing order frequency. By a cross-check between transmissions that produce these ghost noises and transmissions that do not, it turned out that they originate in final driven gears, the flanks of which have been ground in a process of continuous generation grinding using a thread-type tool.

The ghost undulations that have been shown to be produced by transmission errors in the drive shafts of machine and other factors are produced on both the tooth profiles and the lead forms. Research has been conducted on a method of evaluating the cycle and the amplitude of the undulations using tooth profile measurement data⁽²⁾. However, the ghost noises that formed the subject of the research discussed in this paper are produced by ghost undulations in the lead form, not the tooth profile.

Figure 3 shows continuous lead form measurement data for four teeth of the final driven gear that produced the ghost noises shown in Fig. 2. The undulations have cycles of approximately 3 mm in wavelength. In addition, the undulations display regularity: the phase of the undulations on each successive tooth differs by approximately 1 mm, and the phases of the undulations on the first and fourth teeth are virtually identical.

The order frequency of the undulations is able to be specified by FFT analysis of the lead form measurement data. As shown in Fig. 4, one pitch of the lead length on the plane of action is termed L_p , and this length L_p is extracted from the lead form measurement data. This extracted data is connected for all teeth in the direction of movement of the contact line, and lead form

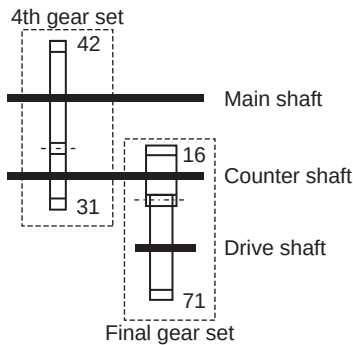


Fig. 1 Drive train of transmission in 4th gear

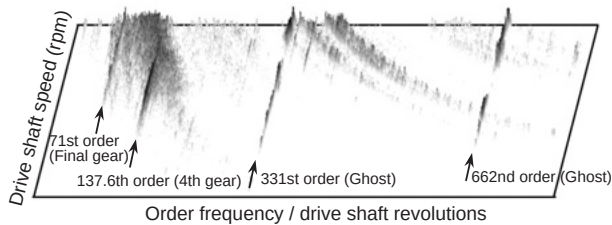


Fig. 2 Waterfall plots of transmission case vibration

measurement data for one rotation of the gear is subjected to FFT analysis as a single set of continuous waveform data. Figure 5(a) shows the results of an FFT analysis of all teeth using lead form measurement data for the gear that produced the ghost noises shown in Fig. 3. Figure 5(b) shows the results of an FFT analysis of all teeth for a gear that did not produce ghost noises. The order frequencies at which the peak amplitudes of the undulations occur in Fig. 5(a) correspond to the ghost order frequencies shown in Fig. 2, while no conspicuous undulation peaks are observed at ghost order frequencies in Fig. 5(b). This indicates that it is the cyclic undulations on the lead forms of the gear teeth that produce the ghost noises.

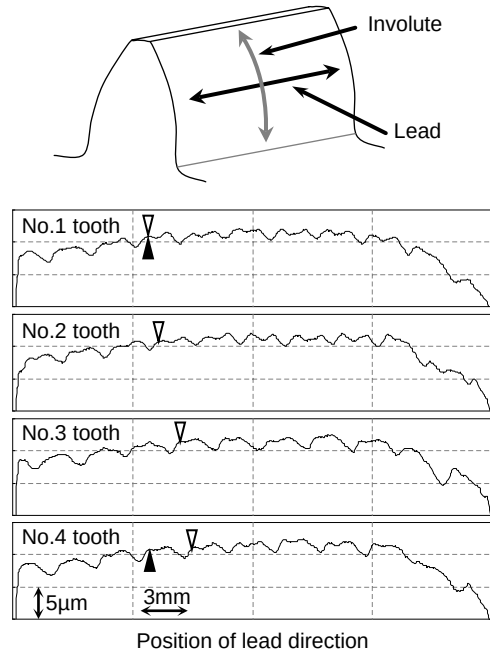


Fig. 3 Measured lead form of 'Ghost' gear

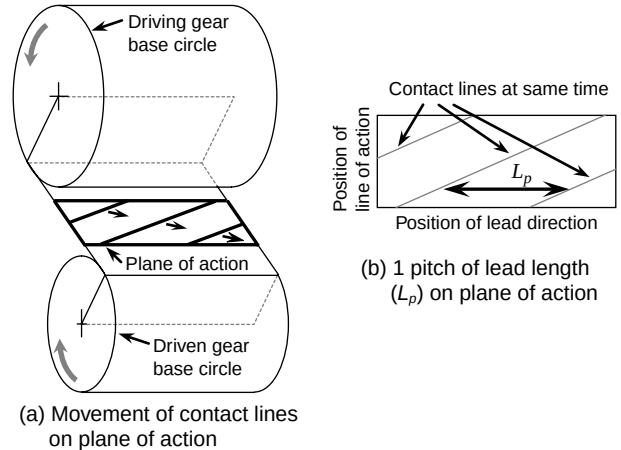


Fig. 4 Contact lines on plane of action

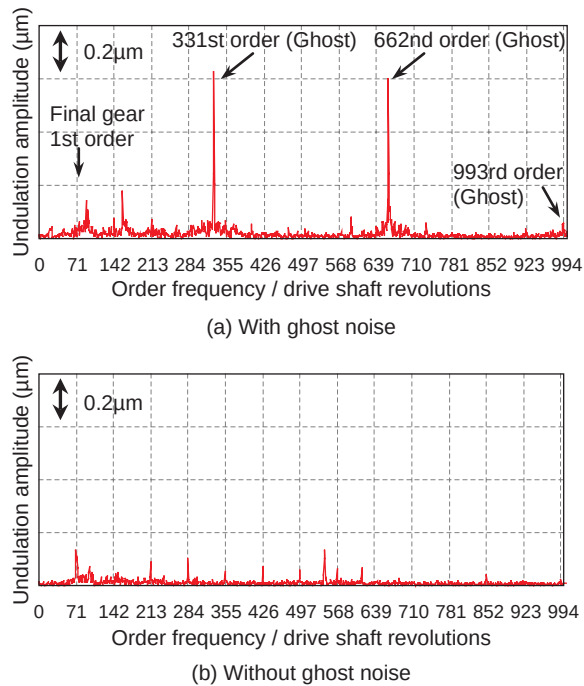


Fig. 5 Spectra of FFT analysis for compound data of lead forms of all teeth

3. Mechanism of Occurrence of Ghost Undulations by Continuous Generation Gear Grinding Using Thread-type Grinding Wheel

3.1. Mechanism of Occurrence of Ghost Undulations by Grinding Wheel Feed Pitch

Figure 6 shows the motion of the work and the grinding wheel during continuous generation gear grinding using a thread-type grinding wheel. The work and the grinding wheel rotate as if meshing to generate the tooth profile, and the feeding action of the grinding wheel in the direction of the work axis generates the lead form.

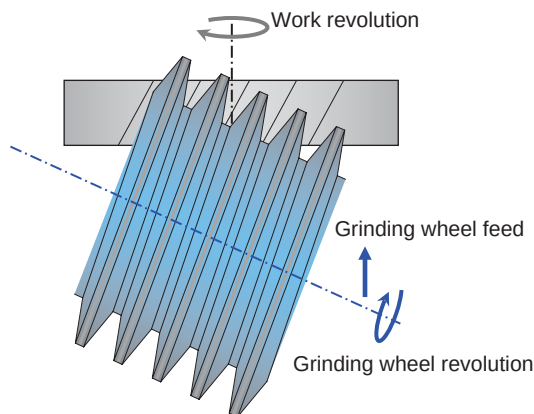


Fig. 6 Motion of grinding wheel and work during continuous generation process in gear grinding

Table 1 Simulation conditions

(a) Gear specifications

Number of teeth (Z_w)	10
1 pitch lead length (L_p)	3 mm

(b) Grinding conditions

Feed pitch (F_p)	1 mm / work rev.
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Because the grinding wheel acts discontinuously on the lead form, the feed pitch of the grinding wheel produces undulations of the type shown in Fig. 7 on the surface of the tooth. F_p represents the pitch of grinding wheel feed per rotation of the work. The feeding action of the grinding wheel continues while generating the same point of profile on the remaining teeth. Because of this, if the number of work teeth is designated Z_w , the phase of the undulations on the neighboring tooth shifts by δ_1 , as determined by Eq. (1).

$$\delta_1 = \frac{F_p}{Z_w} \quad (1)$$

Figure 8 shows the lead form undulations on a helical gear of the specifications and produced under the machining conditions shown in Table 1 as sine waves. Three-cycle feed pitch undulations are generated for each one pitch of lead length (L_p), and the phase of the

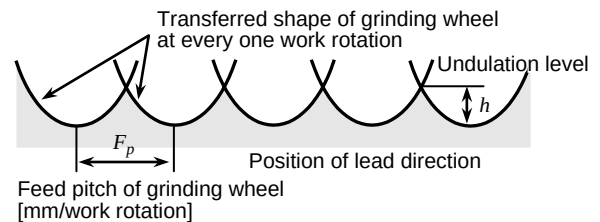


Fig. 7 Undulation of wheel feed pitch generated on lead form

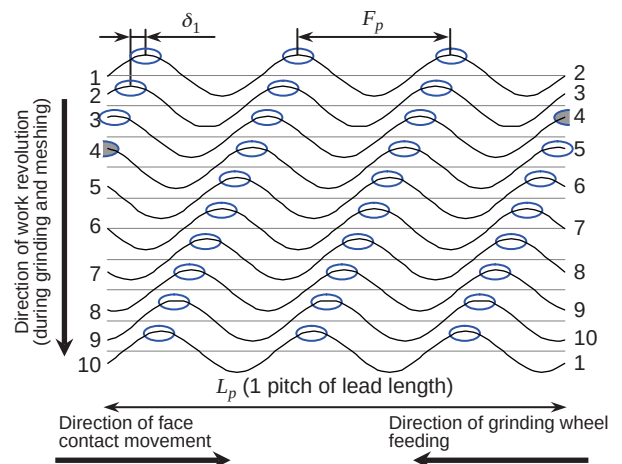


Fig. 8 Mechanism of ghost order generation by feed pitch undulation cycle

undulations shifts by δ_1 on each neighboring tooth. Figure 9 shows the results of an FFT analysis of data connected in the same direction as the movement of the contact line. A peak can be observed at the 31st ghost order frequency. This peak occurs just one order frequency from the 30th order, the triple order of the meshing frequency, because δ_1 , the phase difference between neighboring teeth, overlaps to the extent of the integral of the number of teeth, and becomes equivalent to the wavelength F_p . In the example shown in Fig. 8, the feed direction of the grinding wheel is opposite direction of the contact line movement. Because of this, as each tooth meshes, each phase difference δ_1 builds up, and the undulation for a wavelength increases per rotation of the work. By contrast, under machining conditions in which the direction of meshing and the feed direction of the grinding wheel are the same, the undulation for a wavelength decreases per rotation of the work. Given this, the ghost order frequency produced by the grinding wheel feed pitch undulations, G_1 , can be expressed by Eq. (2).

$$G_1 = Z_w \cdot N_1 \pm 1 \quad (2)$$

$$N_1: \text{Integer} \doteq \frac{L_p}{F_p}$$

Regarding the plus/minus sign in the equation, the sign will be minus when the direction of meshing and the direction of grinding wheel feed are the same, and will be plus when the directions are not the same. When the

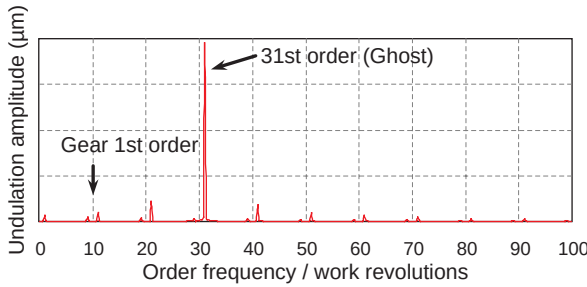


Fig. 9 Spectra of simulated ghost undulation (with Table 1 conditions)

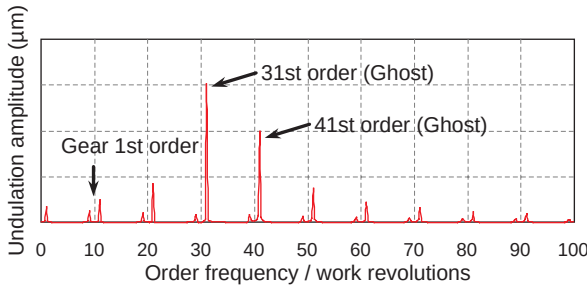


Fig. 10 Spectra of simulated ghost undulation (with Table 1 conditions when $F_p = 0.857$)

direction of rotation of the work during machining is opposite that of the work during meshing, the direction in which the phase difference δ_1 is produced is reversed, and the plus and minus signs will therefore be reversed. Figure 10 shows the results of an FFT analysis of simulated 3.5-cycle-per-pitch undulations (as sine waves) under the conditions shown in Table 1, and with $F_p=0.857$ (mm/work rev). In this case, the integer N_1 in Eq. (2) is 3 or 4, and there are amplitude peaks at the 31st and 41st orders. N_1 is determined by the grinding wheel feed pitch, F_p , and the plus or minus sign of the second right-hand term is determined by the direction of the grinding wheel feed and direction of rotation of the work. As a result, the ghost orders vary with machining conditions.

The undulation level h shown in Fig. 7 can be calculated approximately from the geometric form of the grinding wheel acting on the work, and the grinding wheel feed pitch. Figure 11 shows the shape of the spiral surface on the grinding wheel approximated as a disk. With the grinding point on the work as the point of origin, the x axis shows the direction of the lead, the y axis shows the direction of the disk axis, and the h axis shows the direction of tooth surface normal. A conic plane is formed

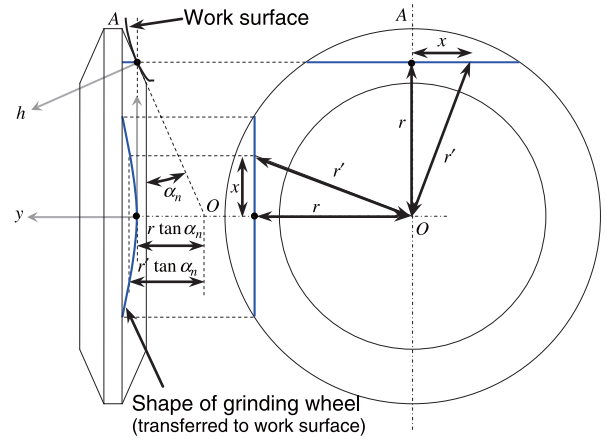


Fig. 11 Shape of grinding wheel transferred to lead shape on work

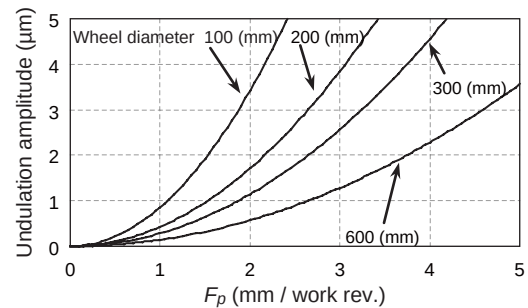


Fig. 12 Relation between F_p and undulation amplitude ($\alpha_n=20\text{deg}$)

with point O as the apex and OA as the generatrix. By projecting a cross-section of plane xy onto plane xh , the shape of the undulations transferred onto the lead form can be obtained. The following equation can then be obtained from the geometric relationship.

$$x^2 + r^2 = r'^2, \quad y = (r' - r) \cdot \tan \alpha_n, \quad h = y \cdot \cos \alpha_n$$

Reordering the simultaneous equations for h gives Eq. (3). (Because $h < r \sin \alpha_n$, an approximation of $(r \sin \alpha_n + h)^2 \doteq (r \sin \alpha_n)^2 + 2rh \sin \alpha_n$ is employed).

$$h = \frac{x^2 \cdot \sin \alpha_n}{2r} \quad (3)$$

With F_p representing the pitch feed, the undulation level, h , is obtained by substituting $x = F_p/2$ for Eq. (3). Figure 12 shows examples of quantitative calculations of undulation level. Undulation level h increases in proportion to the square of the feed pitch F_p , and in inverse proportion to the diameter of the grinding wheel.

3.2. Mechanism of Occurrence of Ghost Undulations by Errors in Multiple-thread Grinding Wheels

An example of a single-thread wheel is shown at the left of Fig. 13, and a double-thread wheel is shown at the right. The lead angle of the thread is larger on the double-thread wheel than on the single-thread wheel. Because of this, when grinding at the same wheel rotation speed, the rotation of the work is twice as fast for the double-thread wheel, increasing production efficiency. This type of multiple-thread grinding wheel is today extensively used in the grinding of gear flanks.

It is normal to set a number of tool threads that does

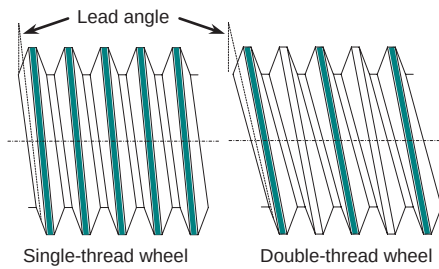


Fig. 13 Single-thread wheel and multiple-thread wheel

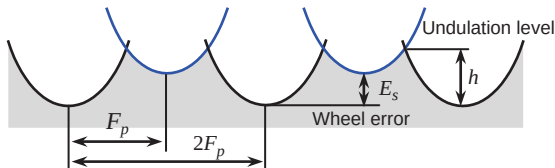


Fig. 14 Undulation of lead form generated by grinding with double-thread wheel

not represent a divisor of the number of teeth in the work. When this is the case, a different thread surface on the grinding wheel grinds the work tooth surface each rotation of the work. If there is pitch error or offset error in the thread surfaces of grinding wheel, the grinding depth varies with each rotation of the work, so undulations are produced. Figure 14 shows the relationship between grinding wheel error, E_s , and the level of undulation, h , when a double-thread grinding wheel is employed.

In order to predict the ghost order frequencies per rotation of the work, it is necessary to establish patterns based on determination of how many threads have left grinding marks on the finished work surface. These

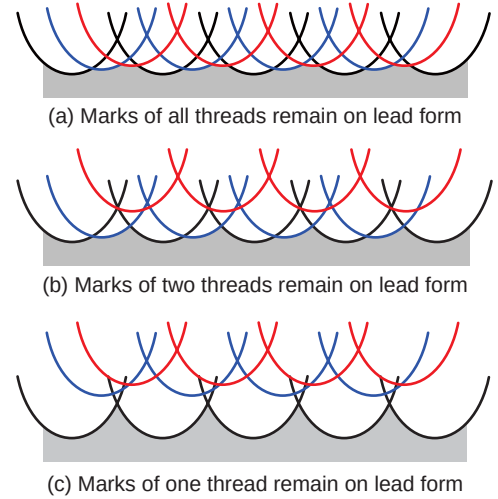


Fig. 15 Ghost undulation patterns in case of grinding with triple-thread wheel

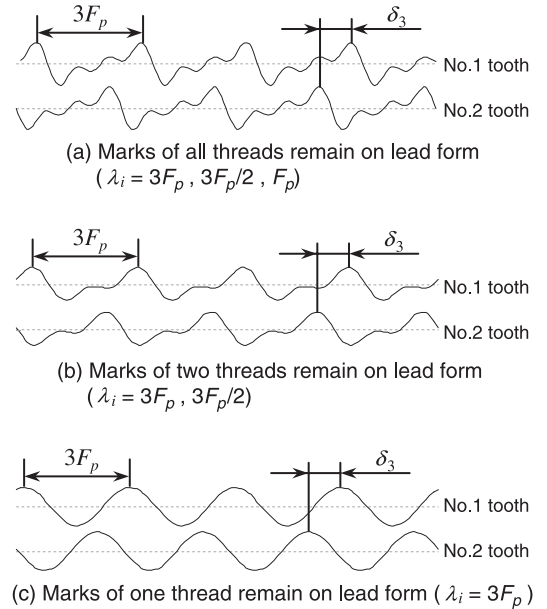


Fig. 16 Simulated ghost undulation patterns in case of grinding with triple-thread wheel

Table 2 Value of N_m

	$Z_j = 2$	$Z_j = 3$	$Z_j = 4$	$Z_j = 5$
$m = 1$	1	2	3	4
$m = 2$	–	1	–	2
$m = 3$	–	–	1	3
$m = 4$	–	–	–	1

Table 3 Relation between ghost undulation pattern and ghost order number in case of grinding with triple-thread wheel

Undulation pattern	Wavelength of synthetic wave	Ghost order frequency
Fig. 16(a)	$F_p, 3F_p/2, 3F_p$	G_1, G_{32}, G_{31}
Fig. 16(b)	$3F_p/2, 3F_p$	G_{32}, G_{31}
Fig. 16(c)	$3F_p$	G_{31}

patterns exist for the number of threads on the grinding wheel, Z_j . Figure 15 shows ghost undulation patterns that might be produced when $Z_j=3$. The waveforms of these ghost undulation patterns can be expressed by Eq. (4), where x represents the position of the lead form.

$$h = \sum_{i=1}^{Z_j} a_i \cdot \sin\left(\frac{2\pi}{\lambda_i} \cdot x\right), \quad \lambda_i = \frac{Z_j \cdot F_p}{i} \quad (4)$$

Differences in the patterns of the ghost undulations can be expressed by changing the value of a_i . Figure 16(a) shows a pattern produced under the conditions $Z_j=3$ and $a_1=a_2=a_3$. In this pattern, there are errors in all three threads, and all the threads leave grinding marks on the finished work surface. Figure 16(b) shows a pattern produced when $Z_j=3$ and $a_1=a_2 \neq 0, a_3=0$. In this pattern, one thread has a larger error than the other two threads, and two threads leave grinding marks on the finished work surface. In Fig. 16(c), $Z_j=3$ and $a_1 \neq 0, a_2=a_3=0$. In this pattern, one thread leaves grinding marks on the finished work surface.

Because the sequence of the threads grinding the teeth changes for each rotation of the work due to the combination of the number of teeth in the work, Z_w , and

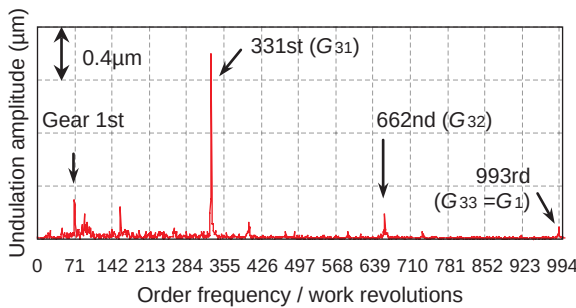


Fig. 17 Example of ghost order frequency in case of grinding with triple-thread wheel

the number of threads on the tool, Z_j , the phase difference between ghost undulations on neighboring teeth is determined by Z_w and Z_j , in addition to the feed pitch, F_p . The relationship between Z_w and Z_j can be expressed as Eq. (5), using the natural numbers n and m .

$$Z_w = n \cdot Z_j + m \quad (5)$$

The phase difference between the ghost undulations on neighboring teeth δ_{Zj} , can be found using Eq. (6), substituting values for the integer N_m determined from the values of Z_j and m as shown in Table 2.

$$\begin{aligned} \delta_{Zj} &= \frac{F_p}{Z_w} + N_m \cdot F_p \\ &= \delta_1 + N_m \cdot F_p \end{aligned} \quad (6)$$

Using Eqs. (4) and (6), the waveform of the ghost undulations on the k^{th} tooth, h_k , can be found from Eq. (7).

$$h_k = \sum_{i=1}^{Z_j} a_i \cdot \sin\left(\frac{2\pi \cdot i}{Z_j \cdot F_p} \cdot (x \mp k \cdot \delta_{Zj})\right) \quad (7)$$

The plus or minus sign in the equations that determine the phase is determined by the direction of rotation of the work and the direction of feed during grinding. The ghost order frequencies can be specified by the FFT analysis for the waveform which connected and united the waveform in Eq. (7) of all the teeth. The ghost order frequency produced when $a_i \neq 0$, G_{ji} , can be found from Eq. (8).

$$\begin{aligned} G_{ji} &= \frac{N_{ji} \cdot Z_w \pm i}{Z_j} \\ N_{ji} &= Z_j \cdot N \pm i \cdot N_m \div \frac{i \cdot L_p}{F_p} \end{aligned} \quad (8)$$

(N : Integer)

Table 3 shows the relationship between the ghost undulation patterns produced by a triple-thread wheel shown in Fig. 16 and the ghost order frequency. The FFT analysis for all teeth that was shown in Fig. 5(a) in chapter 2 was conducted on a gear ground using a triple-thread wheel. For the ghost undulation shown in Fig. 5(a), the 993rd-order ghost frequency corresponds to G_{33} ($=G_1$), the 662nd-order ghost frequency corresponds to G_{32} , and the 331st-order ghost frequency corresponds to G_{31} . Of these, the amplitudes of the 331st-order (G_{31}) and 662nd-order (G_{32}) are dominant, and it can be conjectured that the grinding during machining was close to the pattern shown in Fig. 16(b). Figure 17 shows the results of an FFT analysis for all teeth of the reverse faces of the teeth

of the same gear as shown in Fig. 5(a). In Fig. 17, the 331st order (G_{31}) is dominant compared to the 662nd order (G_{32}) and 993rd order (G_{33}), and it can be conjectured that the ghost undulations follow a pattern of the type shown in Fig. 16(c).

The ghost undulation level is highest when only one thread leaves grinding marks on the finished work surface, as in Fig. 15(c). Denominating the wheel diameter D and substituting $x = Z_j \cdot F_p / 2$ in Eq. (3), the maximum ghost undulation level, $h_{\max}$, can be found from Eq. (9).

$$h_{\max} = \frac{Z_j^2 \cdot F_p^2 \cdot \sin \alpha_n}{4D} \quad (9)$$

4. Multiple-thread Hobs

In addition to the grinding wheels discussed up to this point, the hobs used in the hobbing process are another type of multiple-thread tool. The mechanism of production of ghost undulations during hobbing with a multiple-thread hob is the same as that of the grinding wheels discussed in this paper. Figure 18 shows the results of an FFT analysis of lead form measurement data for all teeth of a 44-tooth work hobbed using a five-thread hob. The ghost undulations produced are the type determined from Eq. (8) as G_{ji} . This demonstrates that the order frequencies of ghost undulations on the lead forms can be accurately predicted, even in the case of hobbing using a five-thread hob.

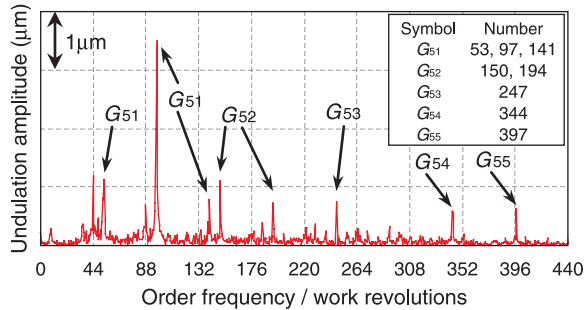


Fig. 18 Example of ghost order frequency in case of hobbing with five-thread hob

5. Measures to Ameliorate Ghost Undulations Produced by Multiple-thread Grinding Wheels

As indicated above, the ghost undulation level that occur on the lead forms of gear teeth during grinding using multiple-thread grinding wheels is affected by the feed pitch and the precision level of the grinding wheel. Figure 19 shows the undulation level reaches a maximum when there is a large degree of error in a double-thread

wheel. Figure 20 indicates that the amplitude of the undulations could be reduced by reducing the feed pitch. The effectiveness of reducing the feed pitch in ameliorating ghost undulations and ghost noises was therefore examined.

Figure 21(a) shows the results of an FFT analysis for all gear teeth machined at a feed pitch F_p , which produced a 310th-order ghost noise at the benchmark work rotation, and two reduced feed pitches, $F_p \times 0.77$ and $F_p \times 0.62$.

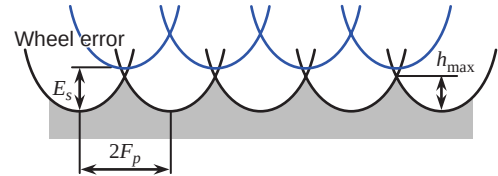


Fig. 19 Ghost undulation when marks of one thread remain on lead form ground by double-thread wheel

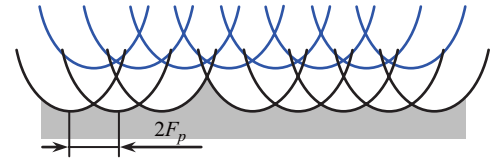
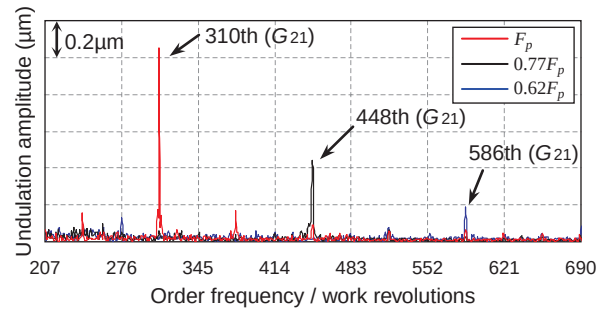
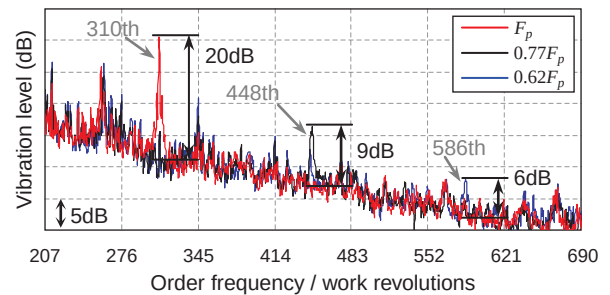


Fig. 20 Enhancement of undulation by reduction of feed pitch



(a) Spectra of FFT analysis for measured lead forms in case of changing feed pitch of grinding wheel



(b) Spectra of transmission case vibration occurring when changing feed pitch of grinding wheel

Fig. 21 Experimental results for reduction of ghost noise by reduction of wheel feed pitch

With the reduction of the feed pitch, the ghost order frequencies change to the 448th order (G_{21}) and 586th-order (G_{21}), and the amplitude of the ghost undulations is reduced. The ghost order frequencies change due to changes in the value of N_{ji} in Eq. (8). Figure 21(b) shows a comparison of transmission case vibration spectra measured when these gears were employed in a transmission. As a measurement condition, the frequencies at which ghost noises were produced were adjusted taking into consideration the frequency characteristic of the transmission case. The reduction of feed pitch reduced the vibration peak level of ghost orders against the background vibration level. This demonstrates the effectiveness of the method in reducing ghost noises even in an actual transmission.

6. Conclusion

The research discussed in this paper examined the mechanism of occurrence of undulations on tooth flank, which are a factor in the occurrence of ghost noises, during grinding the gears using a thread-type wheel. The following results were obtained:

- (1) The order frequency of ghost undulations was found to be determined by the number of threads on the grinding wheel, the feed pitch, level of precision and feed direction of the grinding wheel, and the direction of rotation of the work; the principles of determination of the order frequencies were formulated as equations.
- (2) The order frequency of ghost undulations predicted by the formulated equations corresponded to that of ghost undulations produced on gear teeth during actual machining.
- (3) The reduction of the feed pitch of the grinding wheel was shown to be effective in reducing undulations on the surfaces of gear teeth and ameliorating ghost noise in an actual transmission.

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