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Noise reduction of a high-speed printing system using optimized gears based on Taguchi's method †

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Abstract

To meet the increasing demand for more quiet printers, a noise reduction method is required for high-speed laser beam printing. The driving-gear noise is one of the most important components influencing the noise level in laser beam printers. In this paper, optimized gear designs based on Taguchi's method are presented. The proposed optimized gears are applied to a high-speed laser beam printer. The design parameters for the plastic gear are selected during optimization as follows: a pressure angle of 20°, a helix angle of 20°, a module of 0.5, and a profile coefficient of 1.4/0.2/1.2 (cutter addendum × module / cutter tip radius × module / cutter dedendum × module). Through the Taguchi method, the prominence ratio and loudness in the sense of human hearing range, as well as the sound pressure level (SPL) are also reduced in the present printing system.

Keywords: Gear; Noise; Printer; Sound quality; Taguchi's method

1. Introduction

The general performance of laser beam printers can be expressed in terms of the printing speed, resolution, image quality with regard to the vibration, First-Print-Out-Time (FPOT), and printing noise [1]. As the printing speed of laser beam printers becomes faster, reducing the printing noise is a prerequisite for research of laser beam printer. Laser beam printers feature less noise and vibration than the impact type (e.g., dot-matrix printers) printers. However, they have many rotating parts such as OPC, belts, rollers, and gears, and their power is delivered mostly from a brushless DC (BLDC) motor by gears, which are the main machine element of power transmission. Although the speed of revolution of the gears varies with the printing speed, most gears in low-end laser beam printers (printing speed of 20 ppm) rotate at 100~300 rpm. The pinion on the BLDC motor revolves at more than 1000 rpm. However, a high-speed printer (printing speed of 40~60 ppm) has power transmission gears that rotate at 500 rpm.

In this research, plastic gears have been optimized through Taguchi's analysis to reduce the printing noise. Furthermore, the sound quality resulting from the optimization of the gears has been evaluated.

The sources of printer noise can be classified into three categories: driving noise, paper noise, and mechanical noise. Driving noise is produced by the operation of rotating parts such as motors, gears, the laser ccanning unit (LSU), and fans. Paper noise is caused by friction and the impact of paper through the paper path of the laser beam printer. Finally, mechanical noise is produced in the pick-up, actuator, clutch, cam, etc., which all control the rotating parts. A dominant source of driving noise is the vibrations due to transmission error (TE) of the gears. TE of the gears has been studied extensively in attempts to reduce printer noise and vibration. Usually, the gear noise that results from the meshing of gear teeth is transmitted via forces and motions to the shafting, bearing, and transmission housing where it is then radiated to the surroundings, as depicted in Fig. 1 [2, 3]. Non-measurable factors for gear design such as temperature and material humidity are not major contributors to TE. However, both TE and noise are influenced by the load on the gears [4]. In this sense, Houser designed optimal gears that gave minimum noise and stress by using a unique method such as Run-Many-Cases [5]. Also, an attempt was made to reduce the gear noise by either reducing the excitations at the mesh via minimizing the dynamic forces due to TE or by reducing the force transmissibility from the mesh to the noise-radiation surface [6]. Noise control factors related to

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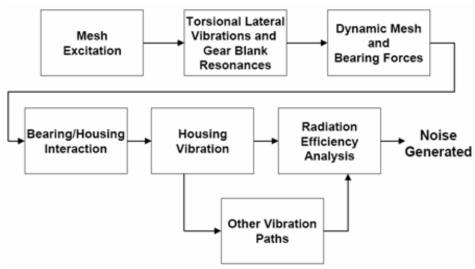


Fig. 1. Gear-noise transmission path [3].

Fig. 2. Gear design factors related to gear noise [3].

the contact ratio of helical gears were selected and analyzed by Taguchi's method [7]. Bonori and Beghini optimized the profile and tip relief of a gear tooth using a genetic algorithm [8] and then identified noise reduction in spur gears [9].

In our study, some dominant aspects relating to shock and noise error are selected among the gear design factors (see Fig. 2).

Furthermore, TE, backlash, contact ratio, and specific sliding were simulated by using KISSSoft, which is a gear analysis program. Then, the mesh frequency and noise reduction were investigated through experiments, which involved printers equipped with the optimized gears designed by Taguchi's method. In Taguchi's method, TE and backlash are used for characteristic values. Finally, it was verified that the sound quality of the printers was improved by the optimized gears.

2. Gear noise

The gear noise generated from the meshing of gear teeth is externally emitted through the gear-noise transmission path. (See Fig. 1) The main gear noise is produced at a specific frequency that corresponds to the natural mode of vibration of the gear's main frame under flexure. The gear noise also results from the noise at the mesh frequency, which is produced from each tooth of the gear pairs. In addition, the aerodynamics of rotating gears may be the reason for the gear noise. However, the noise at the mesh frequency and the noise due to sliding friction and wear arise mainly because a lubricant is normally not used for the plastic gears in laser beam printers. Usually, plastic gears are more advantageous than metal gears in terms of material cost, noise, and design flexibility. However, in light of the increasing requests from consumers with

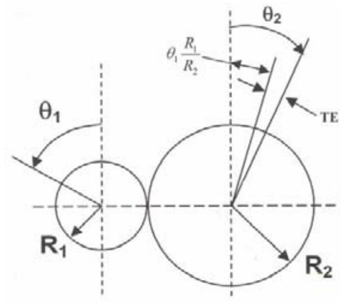


Fig. 3. Graphical definition of TE.

regard to product noise, there has been much effort to reduce noise in plastic gears.

The gears that are used in office automation appliances, such as laser beam printers, fax, and copier should yield only low noise at low-torque conditions of operation. In general, the noise can be reduced greatly by greasing the gears in poly-acetal or poly-amide gear driving. Also, provided that there is no problem of gear strength in the high-speed domain of operation, the application of pinions made of soft material would considerably reduce the noise. In addition, the noise level tends to be low when the accuracy of the gear is getting higher. However, if the accuracy of the gear exceeds JGMA 6, noise cannot be reduced markedly. In this case, improving the surface roughness of gear teeth would be more effective than improving the accuracy of gear for the noise-reduction.

The noise-reduction methods that are described above have limited applicability in high-volume mass production because of the resulting increase in production cost. Hence, considering cost, it is the most desirable to employ a method that changes the design of the gear teeth to reduce noise. Several gear-design factors among others are the module, number of teeth, pressure angle, profile shift, face width, temperature, torque, speed of revolution, and helix angle shown in Fig. 2. TE is the most dominant characteristic in gear noise. It is defined as "the difference between the actual position of the output gear and the position it would occupy if the gears were perfectly conjugate" and can be expressed either in angular units or as a linear displacement along the line of action. TE is illustrated graphically in Fig. 3.

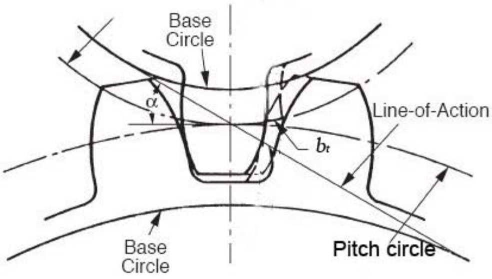
The respective equations for TE are given as [10]

$$\mathrm{TE} = \theta_2 - \frac{Z_2}{Z_1}\theta_1 \, [rad], \tag{1}$$

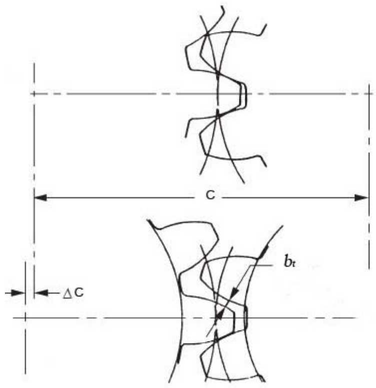
$$\mathrm{TE} = R_2\left(\theta_2 - \frac{Z_2}{Z_1}\theta_1\right)[mm], \tag{2}$$

where θ_1 denotes the angular position of pinion, θ_2 denotes the angular position of gear, Z_1 denotes the number of teeth of pinion, Z_2 denotes the number of teeth of gear, R_1 denotes the radius of pitch circle of pinion, and R_2 denotes the radius of pitch circle of gear.

In addition, backlash is an important characteristic in gear



(a) Linear backlash



(b) Backlash caused by opening of center distance

Fig. 4. Graphical definition of backlash.

noise. Backlash is the clearance between mating components and is sometimes described as the amount of motion lost due to clearance or slackness when movement is reversed and contact is re-established. Backlash is illustrated graphically in Fig. 4.

The equations for backlash are given as [2]

$$b = b_t + b_c \,, \tag{3}$$

$$b_t = t_i - t_a \,, \tag{4}$$

$$b_c = 2(\Delta c)\tan\alpha \tag{5}$$

where b denotes the total backlash, b_t denotes the backlash due to tooth thickness modifications, b_c denotes the backlash due to operating center distance modifications, t_i denotes the tooth thickness on the pitch circle for ideal gearing, t_a denotes the actual tooth thickness, Δc denotes the difference between actual and ideal operating center distances, and α denotes the pressure angle.

In this paper, gears are designed and optimized through Taguchi's method using characteristic values of TE and backlash.

3. Taguchi's method

This section describes the Taguchi method for optimizing gear-design factors. The flow chart using Taguchi's method is given in Fig. 5.

3.1 The evaluation-characteristics for gear noise

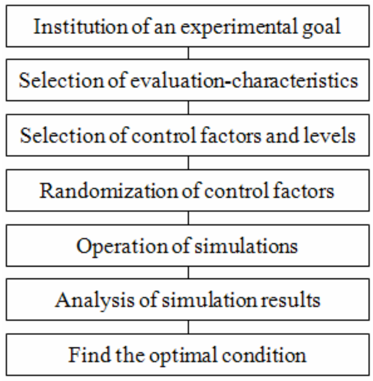


Fig. 5. Flow-chart using Taguchi's method.

The value of evaluation-characteristics denotes a specific characteristic of the target system to be optimized. Determination of the evaluation-characteristics is the most important step in order to realize the purpose of an experiment. The evaluation-characteristics of a system can be expressed in terms of static characteristics of nominal-is-best type characteristics, smaller-is-better type characteristics, and larger-is-better type characteristics. Previously, TE and backlash were defined to be the most dominant characteristics in gear noise.

Accordingly, TE and backlash are chosen as the evaluation-characteristics. As mentioned earlier, these characteristics are defined as the difference between ideal state and actual state of gear. In this context, the characteristics are classified as smaller-is-better type.

3.2 The control factors and the orthogonal array for Taguchi analysis

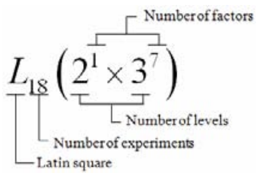
There are three kinds of design factors for Taguchi's method: the control factor, noise factor, and signal factor. These are the variables that influence product performance and should be used as variables in experiments. The control factor is a controllable variable in the design for stabilization of performance characteristics. The noise factor cannot be controlled and disperses the function of system according to the time and the space. As shown in Fig. 2, there are various design factors for a gear. In this research, control factor is defined to control gear noise among design factors.

An orthogonal-array design reduces the number of experiments by detecting interaction between pairs of control factors so that one can simplify the design of experiments. An orthogonal array is developed on the basis of the selection of the number of levels for control factors, the effect of interaction, and the number of control factors that pertain to an experiment. The formation of an orthogonal array is given as follows:

$$L_m\left(N^n\right), \tag{6a}$$

where L denotes the abbreviation of Latin square, m denotes the number of experiments, N denotes the number of levels for control factor, and n denotes the number of control factors.

The L_9, L_{18}, L_{39} matrices are mostly used in the orthogonal array using the level of three steps. Among these matrices, the $L_{18}(2^1X3^7)$ matrix is mostly used because the number of the corresponding experiments is less than those of other matrices and the matrix produces excellent repeatability of results.



(6b)

3.3 Taguchi's analysis

In this research, as described earlier, only the smaller-is-best type characteristic is considered. First, the S/N ratio of the smaller-is-best type characteristics with regard to the level of each control factor is obtained. Regarding this type of characteristics, the S/N ratio, η, is chosen for all undesirable features such as defects for which the ideal value is zero. When the ideal value is finite and its maximum value or minimum one is defined, the difference between the measured values and ideal ones is expected to be as small as possible. The general form of the S/N ratio then is defined as [11]

$$\eta = -10\log\left(\frac{1}{m}\sum_{i=1}^{m} y_i^2\right). \tag{7}$$

η is taken as a negative number to increase the S/N ratio as the variance is small.

It is possible to observe the robustness and stability of the gear design in relation to performance characteristics for each control factor. The contribution ratio is defined as below:

$$\gamma = \frac{\eta_{\max} - \eta_{\min}}{N} \times 100(\%), \tag{8}$$

where $\eta_{\max}$ denotes the maximum S/N ratio and $\eta_{\min}$ denotes the minimum S/N ratio.

4. Sound quality

Noise analysis has traditionally been defined as the measurement of SPL in A-weighting and the frequency analysis, such as FFT/octave analysis. These are well-known methods for noise analysis and yield a great deal of information on noise-signal analysis. However, those measurements do not produce information on how the noise-signal is perceived by humans. For example, two different noises can sound the same to the human ear even if the respective SPL of those differ by 15 dB. Moreover, if the SPL is increased by 10 dB (from 60 dB to 70 dB) at 1 kHz, a human can perceive roughly twice the previous level of sound. Thus, several decades ago, a new algorithm was developed to overcome this problem because human perception of sound is not expressed properly in the traditional representation of noise. Specifically, Zwicker [12] developed methods that calculate the loudness that appears as a "sone/bark" and the total loudness that appears as a "sone". The "Zwicker-Loudness" is selected by an international standard (DIN 45631, ISO 532 B). In addition, Zwicker developed parameters, such as sharpness, roughness, fluctuation strength for displaying the sound quality. Although the parameters are not yet selected in accordance with an international standard, they are gainfully employed in a variety of applied fields. These parameters provide the magnitudes and specific characteristics of noise as well as the degrees of annoyance and the evaluations of sound quality.

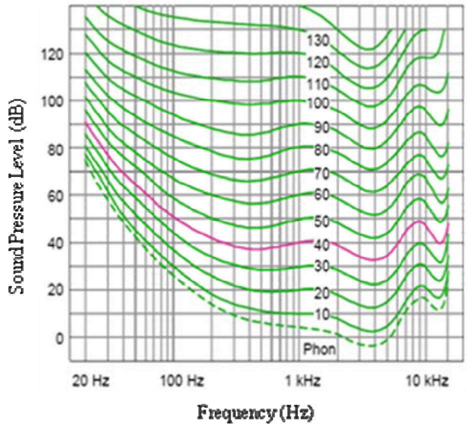


Fig. 6. Equal loudness contours [13].

There are two methods that estimate the sound quality subjectively and objectively. Subjective sound quality measurement through clinical demonstration is not suitable for printer noise. Moreover, it is difficult to set up a countermeasure for sound quality from measurement. Therefore, an objective sound quality index is preferable to analyze the cause of printer noise and to find a suitable countermeasure [14].

Loudness, recognized in the ISO (International Standardization Organization), and the prominence ratio that evaluates the pure tone frequency of information-communication equipment are selected as the objective sound quality indexes in this study. Loudness is illustrated graphically in Fig. 6.

The SPL of the 1kHz tone for each equal-loudness contour is defined as the loudness level. A unit of loudness level has been adopted called a phon. Total loudness level, in sones, is calculated as follows [12]:

$$sone = 2^{(Phon-40)/10}. \tag{9}$$

The prominence ratio is defined as the difference between the sound power of the critical band centered on the tone and the average sound power of the adjacent critical bands in ECMA 74 [15]. In other words, the prominence ratio refers to the boundary value that pertains to the difference between the average noises in the surrounding area and in the independent sound source, to control the prominent sound. The prominence ratio is illustrated graphically in Fig. 7.

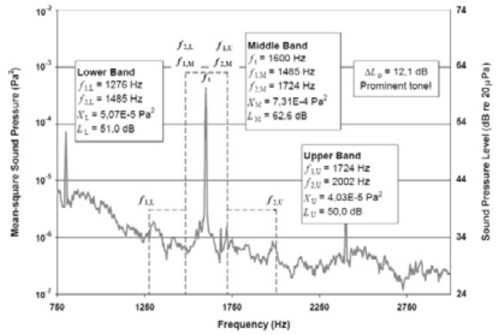


Fig. 7. Illustration of the prominence ratio method for prominent-tone identification [15].

The prominence ratio, in decibels, is calculated as follows [15]:

$$\Delta L_p = 10\log\left(\frac{X_M}{(X_L + X_U)\times 0.5}\right)[dB], \tag{10}$$

where X_M denotes the mean-square SPL of the middle critical band, X_L denotes the mean-square SPL of the lower critical band, and X_U denotes the mean-square SPL of the upper critical band.

In terms of SPL, the above equation renders:

$$\Delta L_p = 10\log\left(10^{0.1L_M}\right) - 10\log\left(\left(10^{0.1L_L} + 10^{0.1L_U}\right)\times 0.5\right)[dB], \tag{11}$$

where L_M denotes the SPL of the middle critical band, L_L denotes the SPL of the lower critical band, and L_U denotes the SPL of the upper critical band.

The prominence ratio is allowed to be 3 dB, which increases per octave under 1 kHz, while it is prescribed for 9 dB over 1 kHz, which is the most sensitive frequency of hearing.

A discrete tone is classified as 'prominent' according to the prominence ratio method if

$$\Delta L_p \geq 9.0\,[dB], \qquad \text{for } f_t \geq 1kHz, \tag{12}$$

$$\Delta L_p \geq 9.0 + 10\log\left(\frac{1000}{f_t}\right)[dB], \quad \text{for } f_t < 1kHz, \tag{13}$$

where f_t denotes the frequency of tone.

Furthermore, the discrete tone meets the audibility requirement in Fig. 8. The criteria in Eqs. (12) and (13) are illustrated graphically in Fig. 8. The sound qualities, which are generated from the standard and optimal gear, are compared in terms of the loudness and the prominence ratio. Finally, it is confirmed that the sound quality influences humans during the printing with laser beam printers.

5. Experiments

Table 1. Control factors.

Control factors	Unit	Level 1	Level 2	Level 3
Pressure angel	degree	14.5	20	-
Helix angle	degree	14.5	20	24
Module	mm	0.5	0.6	0.8
Profile coefficient	mm	1.2/0.38/1.0	1.4/0.2/1.2	1.6/0.2/1.4

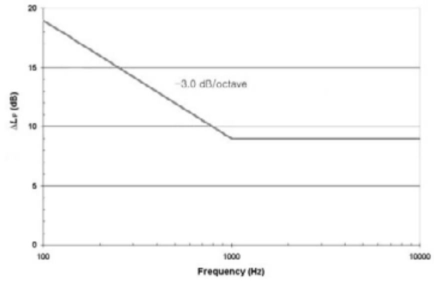


Fig. 8. Criteria of prominence for the prominence ratio as a function of frequency.

5.1 Selection of control factors and levels

Firstly, Taguchi's method is applied to design factors affecting the gear noise. Various design factors for cylindrical gear analysis in KISSsoft are as follows: face width, module, pressure angle, helix angle, center distance, number of teeth for the gear and pinion, speed of revolution, torque, operating temperature.

Those design factors are introduced in the design of the optimal gear in general. Among them, three of the design factors such as the center distance, speed of revolution, and torque are classified as variables that are frequently subjected to change under actual driving conditions. Several design factors are excluded from the set of control factors since they do not relate to the conditions of mass production with regard to cost and time. Therefore, the following control factors are chosen in present study: module, pressure angle, helix angle, and profile coefficient. The noise factors of temperature variation, humidity in Taguchi's method are neglected since the difference between levels for control factors is assumed to be the noise error under present experimental condition.

The levels of the control factors are determined by the conditions of gear hob, which is the cutting tool for gear. The control factors and levels are listed in Table 1.

5.2 Taguchi's analysis and KISSsoft simluation

The orthogonal-array table is composed through Taguchi's method. A mixed orthogonal array table is chosen such that it has a number of different levels for setting up an experiment after the control factors and levels are determined. The mixed orthogonal array table is shown below for one of the two-level factor (2^1) and three of the three-level factors (3^3):

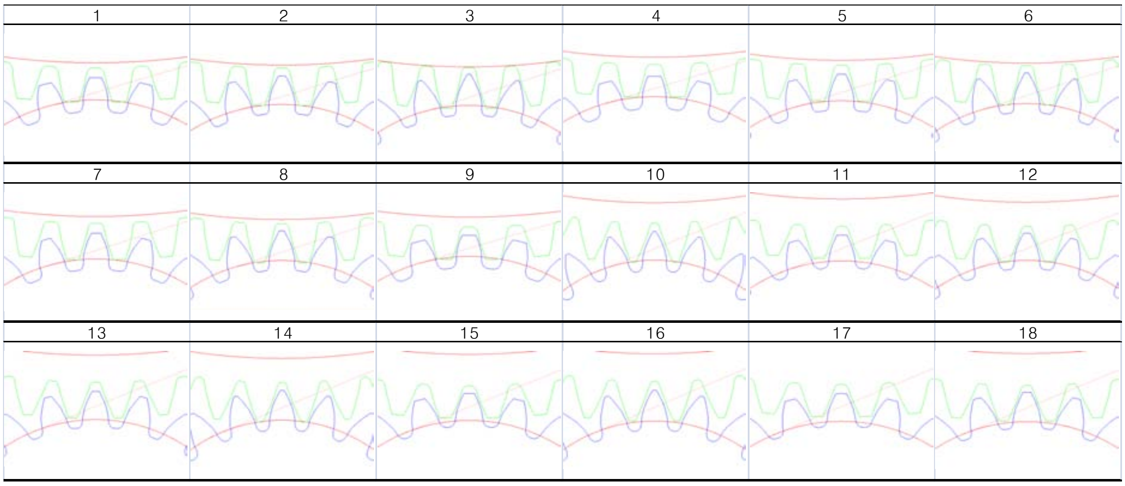


Fig. 9. Tooth profiles from KISSsoft.

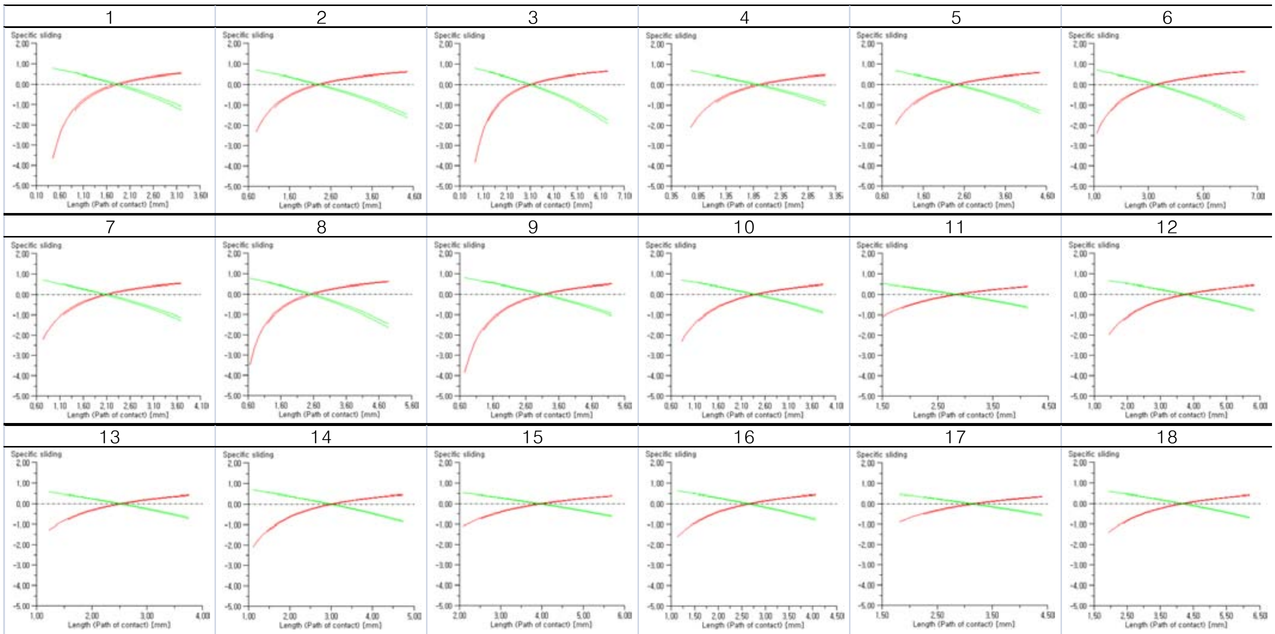


Fig. 10. Specific sliding from KISSsoft simulation.

$$L_{18}(2^1 \times 3^3)\ . \tag{14}$$

The experiments are performed eighteen times with the above orthogonal array. According to each experimental condition, control factors and levels are used as input for KISSsoft. After that, the simulations for TE and backlash are conducted.

In the preceding example, the KISSsoft simulation was run eighteen times using control factors that were selected from the relevant mixed orthogonal array table. When there is a change in the speed ratio between the rollers in a laser beam printer, printing becomes impaired. Hence, the numbers of teeth in the gear and pinion are fixed. From the simulation, the evaluation characteristics, such as TE, contact ratio, backlash, tooth profile, and specific sliding were obtained.

Fig. 9 depicts the shapes of the gear and pinion based on the control factors from Taguchi analysis, which is simulated by KISSsoft. The gears are displayed in the lower half (in blue), while the pinions are displayed in the upper half (in green). The figure confirms that the shapes of the gear teeth vary with the design.

Fig. 10 is an illustration of specific sliding in gear pairs based on the control factors from Taguchi analysis. Specific sliding is defined as the ratio of the sliding velocity to the rolling velocity of the meshing gear and is an indicator of scoring and noise generation. If the value of specific sliding exceeds 3, the noise due to sliding friction will increase, and the ensuing frictional heat will cause a deformation of the teeth of the gear.

TE and backlash from the simulation are arranged in an orthogonal array in Table 2. Then, the S/N ratios of the control factors are obtained from Minitap, which is a statistical analy-

Table 2. Layout of the orthogonal array table of $L_{18}(2^1 \times 3^3)$ for analysis of gear noise control factors.

Analysis no.	Pressure angle	Helix angle	Module	Profile coefficient	TE	Backlash	S/N ratio
1	1	1	1	1	0.3244	0.051	12.68
2	1	1	2	2	0.1106	0.051	21.30
3	1	1	3	3	0.3557	0.082	11.76
4	1	2	1	1	0.2316	0.050	15.52
5	1	2	2	2	0.2735	0.012	14.26
6	1	2	3	3	0.1060	0.015	22.42
7	1	3	1	2	0.0597	0.052	25.04
8	1	3	2	3	0.2552	0.042	14.76
9	1	3	3	1	0.3212	0.042	12.80
10	2	1	1	3	0.2828	0.056	13.81
11	2	1	2	1	0.1802	0.056	17.49
12	2	1	3	2	0.1823	0.044	17.55
13	2	2	1	2	0.2003	0.056	16.65
14	2	2	2	3	0.1188	0.056	20.64
15	2	2	3	1	0.1880	0.044	17.30
16	2	3	1	3	0.0681	0.056	24.10
17	2	3	2	1	0.4206	0.044	10.49
18	2	3	3	2	0.3005	0.044	13.36

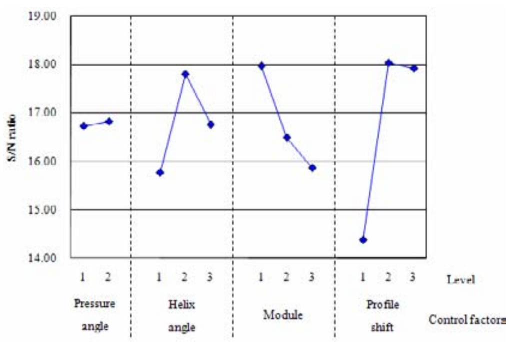


Fig. 11. S/N ratio versus the level of control factors.

sis program. Since TE and backlash are the smaller-is-best type characteristics, the S/N ratios are obtained through Eq. (7). The values at which the S/N ratio is large yield the optimal design conditions (See Fig. 11).

The contribution ratios of control factors are calculated in Table 3. From the analysis on the contribution ratio of the control factors with regard to the gear noise, the control factors are arranged in the following order: profile coefficient (46.3%), module (26.7%), helix angle (25.8%), and pressure angle (1.2%). Therefore, profile coefficient is considered as the most dominant control factor among the selected ones. Furthermore, we confirmed that the second level (20°) in pressure angle, the second level (20°) in helix angle, the first level (0.5 mm) in module, and the second level (1.4/0.2/1.2 mm) in profile shift are the best conditions for the optimal gear design, as depicted in Table 3 and Fig. 11.

5.3 Instruments for experiments and measurements

An experimental jig device was installed as in Fig. 12 and Fig. 13 to measure the SPL that is generated in the gear pair.

Table 3. S/N ratio and contribution ratio.

Control factors	Level	S/N ratio	Contribution ratio
Pressure angle	1	16.73	1.8%
	2	16.82	
Helix angle	1	15.77	25.6%
	2	17.80	
	3	16.76	
Module	1	17.97	26.5%
	2	16.49	
	3	15.86	
Profile coefficient	1	14.38	46.0%
	2	18.03	
	3	17.92	

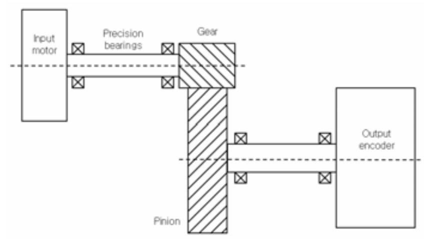


Fig. 12. Schematic diagram of the experimental gear jig.

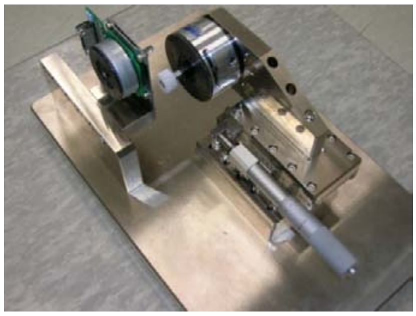


Fig. 13. Experimental gear jig.

As most laser beam printers use the BLDC motor as the main power source, we used the BLDC motor to input power to the gear. Also, the shaft of the pinion was fixed to the torque clutch, which controls the rotational torque in the range, 0~6 kg · cm. This pinion block is coupled with a micrometer so that it can be moved towards the motor block in increments of 5 ㎛, because the gear pairs in the experiment have to satisfy various center distances. The motor and pinion blocks are fixed to the bracket base, which is made of aluminum (A6061), to prevent the noise and vibration that are caused from the rotating gears in the jig.

The gear noise is measured using the above experimental jig through the methods used for measuring the noise of laser beam printers. After the experimental jig is settled on a standard table in a semi-anechoic chamber, the noise is measured with four microphones, which are placed at a height of 1.5 m

Fig. 14. Measurement of SPL of the experimental gear jig in a semi-anechoic chamber.

Fig. 15. Measurement of SPL of a laser beam printer in a semi-anechoic chamber.

Fig. 16. Measurement of sound quality level of a laser beam printer in a semi-anechoic chamber.

around the table at a distance of 1m from the table (See Fig. 14).

The overall noise level is defined as the average of the values that are measured in the four directions. It is calculated as follows [16]:

$$SPL = 10\log_{10}\left(\left(\frac{1}{4}\right)*\left(10^{0.1*SPL1}+10^{0.1*SPL2}+10^{0.1*SPL3}+10^{0.1*SPL4}\right)\right). \quad (15)$$

To reduce the noise generated from the drive unit of a high-speed laser beam printer, the most suitable gears verified earlier were used. The optimal gears for the laser beam printer were produced under Taguchi's method. Fig. 15 is an image of the measurement of the noise of a laser beam printer in a semi-anechoic chamber. Sound quality levels, such as prominence ratio and loudness were measured with the instrument of torso type (See Fig. 16).

Table 4. Condition of the experiment for a gear jig.

	Gear 1	Gear 2
Number of teeth	25	53
Speed	1213.3	572.3

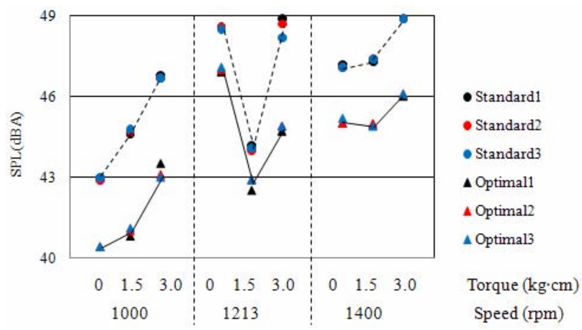


Fig. 17. Comparison of SPL of the standard gears and optimal ones in the experimental jig.

6. Results and discussion

According to the driving condition, such as the torque for the pinion and the rotational speed of the gear, we found that the SPLs of the optimal gear were lower than those of the standard gear by about 1.2~3.8 dBA (in overall frequency) in Fig. 17.

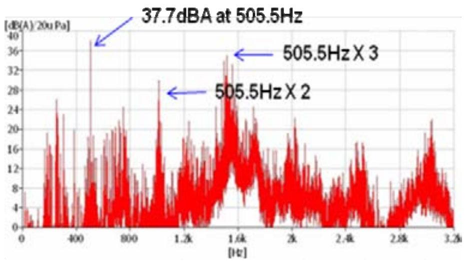
In this result, as the torque and the rotational speed of gears becomes larger, the difference between SPL of standard condition and that of optimal one has become larger in general. It is expected that the optimal gears can be a positive effect for printing noise reduction of a laser beam printer, since a laser beam printer consist of a developer unit and a fuser unit induced a large torque.

A typical noise spectrum is shown in Fig. 18. The experiment condition which is the medium among the whole experiment is selected to analyze the frequency spectrum. In this experiment, two gears are used as follows:

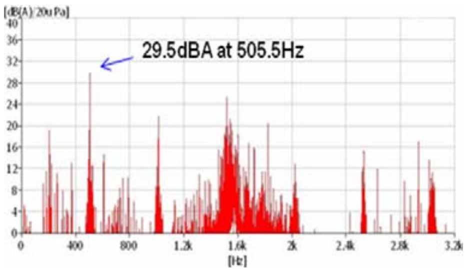
The plots are on a linear scale to show the comparison between the standard gears and optimal ones. The SPL magnitude of the optimal gear was less than half that of the standard gear at the mesh frequency (505.5 Hz). In addition, the similar trend occurs in other frequency ranges.

$$mesh\ frequency = \frac{Number\ of\ teeth \times rpm}{60}. \quad (16)$$

In Fig. 19, the prominent components in the standard gear pair disappeared in the optimal gear set. That is, the prominence ratio at 505.5 Hz was greater than the criterion value at the frequency in the experiment of the standard gear pair. However, the prominence ratio of the optimal gear pair was decreased in the experiment. Therefore, as the prominence of

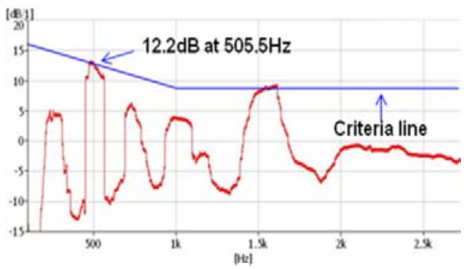


(a) Standard gear

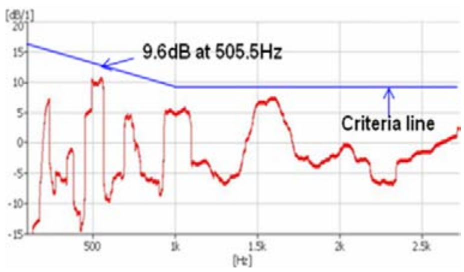


(b) Optimal gear

Fig. 18. Frequency spectrum of SPL for the standard gears and optimal ones.



(a) Standard gear



(b) Optimal gear

Fig. 19. The prominence ratio for the standard gears and optimal ones in a gear set only.

noise peak was improved with the optimal gear pair, the annoyance felt by humans could be reduced accordingly.

In a high-speed laser beam printer, 14 gears were changed from standard type to optimal one in a gear train. The printing noise and the driving noise for standard gears and optimal ones were measured. The driving noise is defined as the printing noise without the feeding of paper in the laser beam printer. Fig. 20 shows the result from three repeated experiments carried out to attain reliability. The SPL was decreased

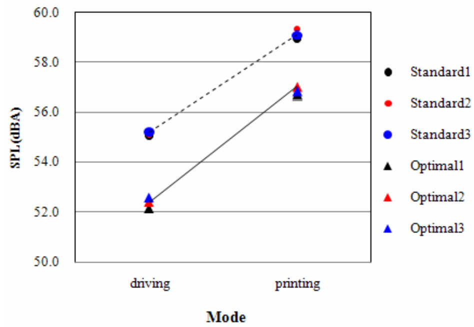
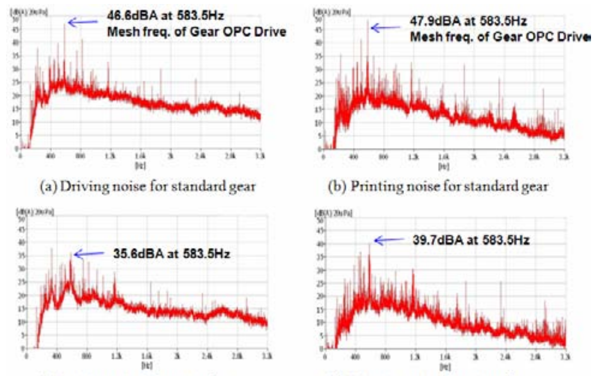


Fig. 20. Comparison of SPL of the standard gears and optimal ones by mode in a laser beam printer.



(a) Driving noise for standard gear (b) Printing noise for standard gear

(c) Driving noise for optimal gear (d) Printing noise for optimal gear

Fig. 21. Frequency spectrum of SPL for the standard gears and optimal ones in a laser beam printer.

by 2.7 dBA (in overall frequency) in the driving mode and 3.1 dBA (in overall frequency) in the printing mode, respectively, for the optimal gears. In this context, optimizing the tooth profile through Taguchi's method is the effective method for productive efficiency in the printing industry because printing noise can be dropped without adding mechanical parts and cost compared with conventional noise-reduction methods such as installation of guide in paper path, change of the hard material into flexible type at the positions generating impact noise, attaching of sound-proof material on the cover of laser beam printer.

As shown in Fig. 21, the magnitude at the gear mesh frequency of the laser beam printer was decreased, as observed in the experimental gear jig. The magnitudes of the highest peak were remarkably dropped at 583.5Hz.

583.5 Hz was the mesh frequency between MOTOR-BLDC and GEAR-OPC DRIVE (See Fig. 22).

Fig. 23 depicts the loudness spectra measured during the driving mode for each type of gear. The mean values of the total loudness are 6.22 sone (Left) and 5.87 sone (Right) with standard type. They are 4.65 sone (Left) and 4.46 sone (Right) with optimal type. In average value of Left and Right, the gap is approximately 1.5 sone. It is greater than 0.5 sone which is the just noticeable difference of loudness [24]. Therefore, loudness is improved with optimal gears. As a loudness of 2 sone is 10 dB higher than that of 1 sone at 1kHz, we can con-

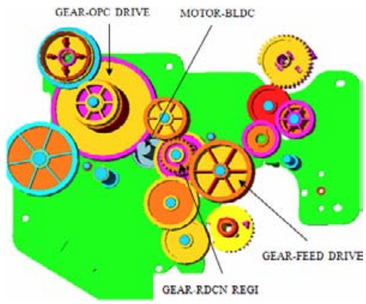
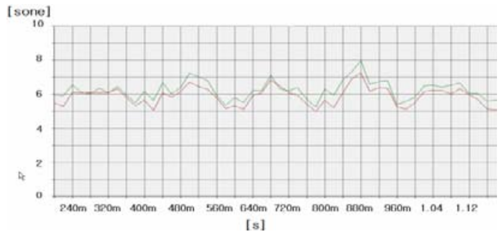
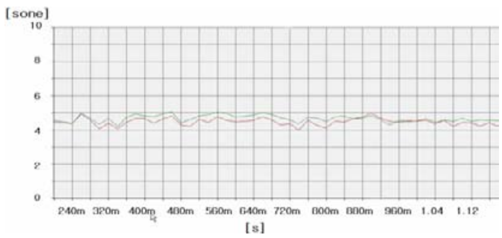


Fig. 22. Gear train for a high-speed printing system.



(a) Standard gear



(b) Optimal gear

Fig. 23. Stationary spectrum of total loudness for the standard gears and optimal ones in a laser beam printer.

sider reduction of 10 dB level for driving noise with optimal gears at 1 kHz, which is the most sensitive frequency of hearing.

7. Conclusions

Generally, TE is considered to be an important excitation for inducing gear noise. In addition to TE, backlash is considered to be an equally important excitation mechanism of noise. In this study, we found the optimal conditions for the mitigation of noise of a gear pair using Taguchi's method. Then, these conditions were applied in a high-speed laser beam printer. Among the gear design factors, the pressure angle, helix angle, module and profile coefficient were selected as the control factors in Taguchi analysis. TE and backlash of gears, which were obtained from KISSsoft, were simulated in the optimal conditions through Taguchi's method. According to the torque and speed of gears, the SPL was reduced by about 1.3~3.7dB using the optimal gear set. Moreover, when the gears were applied in a high-speed laser beam printer, the noise in the printing and driving modes was also reduced in terms of SPL and sound quality, as measured by the prominence ratio and loudness.

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