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Noise Characteristics in Lubricated and Non-lubricated Gears to Assess the Lubrication Damping Effect in Gear Design

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기어설계시 윤활댐핑 효과 반영을 위한 윤활과 비윤활 상태에서의 소음특성에 관한 실험적 연구

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ABSTRACT

Gears, which rotate and transmit power by interlocking two cogwheels, were invented in BC. They have been used in various systems, including industrial machinery, transportation devices, and living facilities, through the industrial revolution. Regardless of how they are used, gears are a major source of noise and vibration. Many effective measures are being taken to reduce the radiation noise generated from gears, most commonly by lubrication. Lubrication in gear units reduces friction on interlocking gear surfaces, dampening radioactive noise. This can be very useful for quiet gear design if these lubricating damping effects can be reflected in the analytical phase for gear design. This study experimentally confirms the properties of lubricated and non-lubricated radioactive noise by designing a decelerator gearbox and analyzing the radioactive noise characteristics by torque, rotation, and the number of gears using computer analysis.

Key Words : Spur Gear(평기어), Noise(소음), Vibration(진동), Torque(부하), Lubrication(윤활), Non-lubrication (비윤활), Damping(감쇠), Gear Teeth(기어치)

1. Introduction

The gear system, which transmits power by interworking and rotating a set of toothed wheels, was invented in B.C., and since the Industrial Revolution, it has been widely implemented in various systems such as industrial machinery, transportation equipment, and facilities for domestic use. However, gears are a major cause of noise and vibration[8~10] regardless of how they are used. Therefore, a number of effective measures have been developed to reduce the noise radiation due to gear friction, and the most representative method is the use of lubrication. The details of the methods of lubrication are described

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in the main text.

If a gear system is lubricated, the friction on the tooth surface of the meshed gear is reduced, and the noise radiation is attenuated. Therefore, the reflection of lubrication damping effect in the analysis at the gear design stage is expected to yield highly useful outcomes for the design of a gear system with much reduced level of noise.

Cases of existing research related to this study include investigation of lubrication characteristics of lubricating bearings and rotating systems, performance prediction of lubricating bearings, measures for lubrication performance improvement, and cavitation models through flow analysis in lubricated state. In this study, an experimental reduction gearbox is designed, and its noise characteristics are numerically analyzed in terms of the gear rotation speed and torque; the designed gearbox is actually fabricated to perform an experiment on changing the torque and rotation speed. In the experiment, the characteristics of the gearbox-radiated noise are examined in lubricated and non-lubricated state, and the analysis results and experimental results between the two states are comparatively analyzed.

2. Gear design and noise analysis

2.1 Design of gear system

The type of gear applied to the gearbox design is a spur gear. A spur gear is a straight, cylindrical gear with tooth trace parallel to the shaft. This type of gear is most often employed for power transmission, and when the gears rotate in a meshing pair, the two teeth make line contact over the entire tooth width. At this time, the total elasticity of the teeth abruptly changes at the beginning and end of the line of action, and the load applied to the tooth surface shows a considerable variation, leading to noise and vibration[1].

Power transmission is not possible with the use of a single gear, and the gear function is properly exhibited by meshing at least one pair of gears. In the design, three pairs of gear meshing are applied, and the state with one pair of gears meshed is called the first-stage gear, which can be represented as shown in Fig. 1. For gear design, the information in the KHK technical data of Japan was used as a reference[2].

In the pair of gears shown in the figure, if the number of teeth of the driving gear is z_1, the number of rotations is n_1, the number of teeth ofthe driven gear is z_2 and the number of rotations of the driven gear is n_2 then the gear ratio i_1 is calculated as shown in Equation (1) below [2].

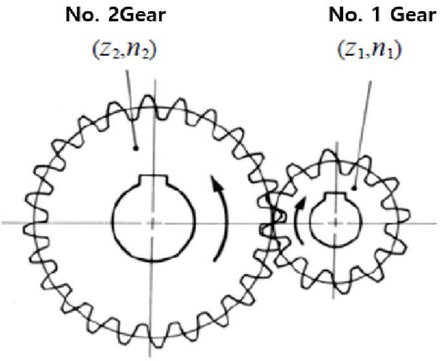


Fig. 1 One pair gear geometry

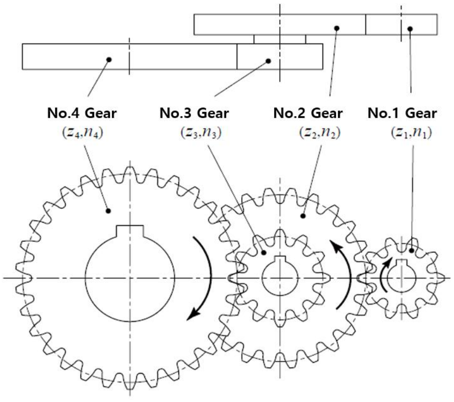


Fig. 2 Two pair gear geometry

$$\text{Gear ratio} \quad i_1 = \frac{z_2}{z_1} = \frac{n_1}{n_2} \tag{1}$$

The 2nd-stage gear indicates two pairs of the first-stage combination of gears described above and is illustrated in Fig. 2. In this case, the gear ratio i_2 is calculated as shown in Equation (2) below[2].

$$\text{Gear ratio} \quad i_2 = \frac{z_2}{z_1} \times \frac{z_4}{z_3} = \frac{n_1}{n_2} \times \frac{n_4}{n_3} \tag{2}$$

where, $n_2 = n_3$

The gear ratio for the 3rd-stage gear with 3 pairs of gears applied to the design is calculated and presented in Table 1, and the gear rotation speed is shown in Table 2. The gears and gearbox to be fabricated for this study were designed as shown in Fig. 3.

Lubrication is one of the commonly used methods to reduce vibration and gear noise. There are two main goals for the lubrication of gears. The first is to reduce the dynamic friction coefficient μ by making the wheels slide smoothly between the tooth surfaces, and the second is to achieve cooling by suppressing the temperature rise between the tooth surfaces due to rotational friction and sliding friction.

Table 1 Speed transmission ratio of designed 3 pair gear

Gear sets	Sign	Formula	Speed trans. ratio
1st $z_1 : 30ea, z_2 : 60ea$	i_1	$\frac{z_2}{z_1}$	2
2nd $z_3 : 30ea, z_4 : 60ea$	i_2	$\frac{z_4}{z_3}$	2
3rd $z_5 : 30ea, z_6 : 60ea$	i_3	$\frac{z_6}{z_5}$	2
Total	i	$i_1 \times i_2 \times i_3$	8

Table 2 Gear RPM of designed 3 pair gear

Gear	Sign	Formula	RPM
No.1 Gear	n_1	-	1750
No.2 Gear & No.3 Gear	n_2	$\frac{n_1}{i_1}$	875
No.4 Gear & No.5 Gear	n_4	$\frac{n_2}{i_2}$	438
No.6 Gear	n_6	$\frac{n_4}{i}$	219

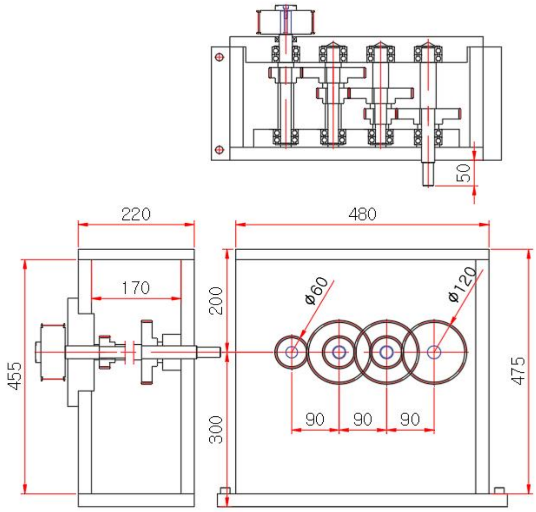


Fig. 3 Gear box of designed 3 pair gear

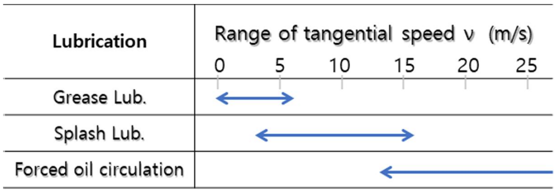


Fig. 4 Ranges of tangential Speed for spur gears[2]

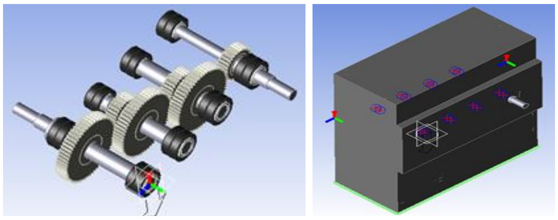


Fig. 5 Gear box modeling

Lubrication methods include grease lubrication, splash lubrication, and forced oil circulation lubrication, and an appropriate method is selected by considering the conditions of use of the gear. The criteria for the selection are based on the rotational speed of the gear, that is, the rpm [2]. In general, grease lubrication is applied at low rotational speeds, splash lubrication is applied at medium speeds, and forced oil circulation lubrication is applied at high speeds.

In this experiment, the forced oil circulation lubrication method was applied regardless of the rotational speed because the splash lubrication method was difficult to apply due to the structure of the designed gearbox.

2.2 Modeling for numerical analysis

A 3D modeling was performed as shown in Fig. 5 using ANSYS Motion, a gear analysis tool, to perform noise analysis according to the changes in the gear rotation speed and torque of the designed gearbox. The material used for the gears was SCM21 (carburized, hardness 58–62, pressure angle 20 degrees), and the number of teeth were 30 and 60, respectively, for small and large gears, similar to that in the design.

2.3 Numerical analysis and results

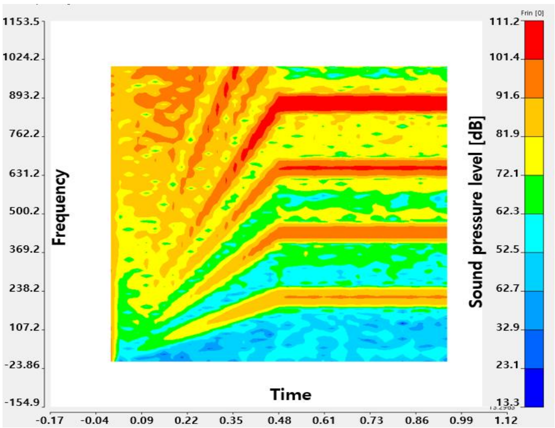
The boundary conditions for analysis, input power, end time, and start speed were set as outlined in Table 3, and it was assumed that there was no damping effect of the gearbox structure. In addition,

for the parameters affecting the noise level, the torque of the gear output shaft was changed from 1 N·m to 6 N·m, and the rotational speed of the input shaft was changed from 100 rpm to 1750 rpm at intervals of 200 rpm.

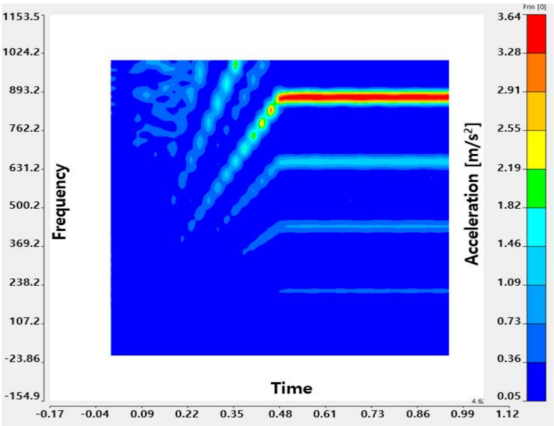
The whine nose in the gear system was measured at the gear mesh frequency (GMF) in the gear meshing or harmonic components [3]. Fig. 7 shows the result of applying SFFT to the whine vibration

Table 3 Boundary conditions and parameters

Description	Item	Dimension (Range)
Boundary conditions	Input power	1.5 kW
	Start speed	0 rpm
	Duration time	0.5 sec
	End time	1 sec
	Microphone position	360mm from gear box top
Parameters	Output Torque(Nm)	1 ~ 6 (Interval 1)
	Input rpm	100 ~ 1750 (Interval 200)



(a) Noise STET



(b) Acceleration

Fig. 6 Noise & Vibration analysis STFT

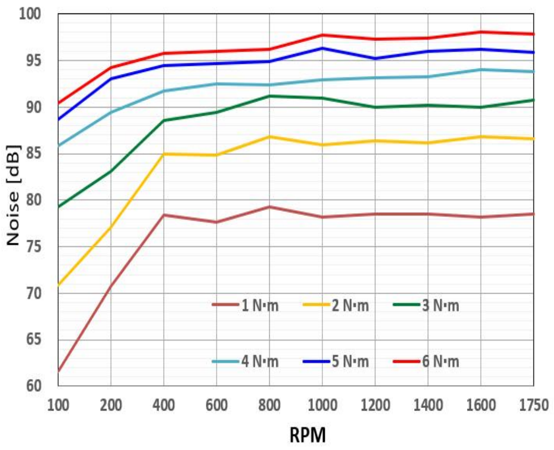


Fig. 7 Noise analysis result

pattern. When the torque to the output shaft load was 6 N·m, noise level of over 85 dB was measured at all rotation speeds except 200 rpm or less. In particular, from 800 rpm, the noise level was increased above 90 dB, and at 1750 rpm, the measured noise level was 98 dB. The trend of noise characteristics according to the torque change with respect to the total number of rpms is shown in Fig. 7. From the overall pattern, it can be seen that a stable distribution of noise values was measured above 400 rpm, and the noise level increased with the increase in torque.

3. Experimental setup and Methods

3.1 Experimental setup

In order to conduct an experiment based on changes in the torque and rotation speed of the gears and to comparatively analyze the characteristics of the noise radiation in lubricated and non-lubricated states in the experiments, a gearbox was custom-made as shown in Fig. 8 by a domestic specialized manufacturer based on the design plan; the detailed specifications are outlined in Table 4.

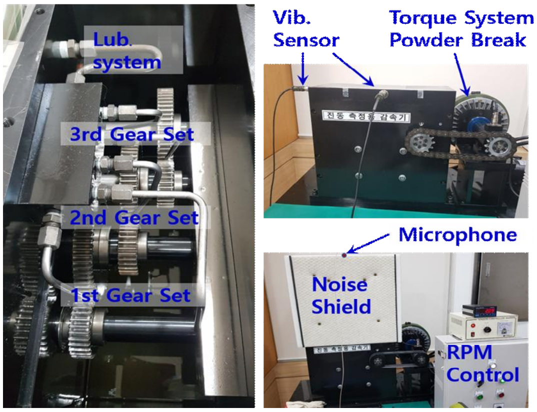


Fig. 8 Gear box and measuring system

Table 4 Equipment specifications

X axis length	1200mm
Y axis length	1300mm
Z axis length	700mm
Gear material(Hardness)	SCM21(58~62)
Torque sensor	DACELL, 0.5~3mV/V
Powder break	Nam Kyeong, NKPB-10
Input moter	Hyosung 1.5 kW(4P), 60Hz
Vibration sensor	KISTLER, 100.5 mV/g
Microphone	G.R.A.S., 51.98 mV/Pa

3.2 Methods

To measure the gear noise according to the change in rotation speed and torque, the gear rotation speed was changed from 100 rpm to 1750 rpm in the same way as in the numerical analysis, and the torque applied to the output shaft was increased from 1 N·m to 6 N·m. The experiments were performed repeatedly.

In addition, to determine the noise characteristics in the lubricated and non-lubricated state, which is the main purpose of this study, the lubricating oil was completely removed, the gearbox was washed and completely dried, and repeated experiments were performed in the same manner as described above[4].

Table 5 Experiment method for noise measurement

Test Step	Torque(N·m)						
	0	1	2	3	4	5	6
Lubrication	Progressive chage of RPM 100, 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1750						
Non-lubrication							

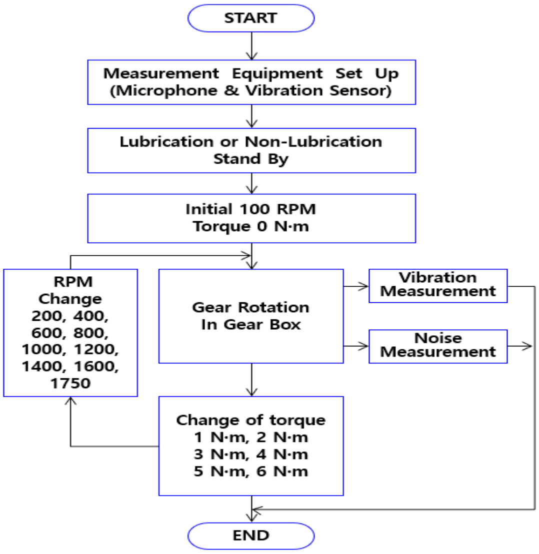


Fig. 9 Flow chart of measurement

4. Results and Discussion

4.1 Results of noise measurement in lubricated and non-lubricated states

As for the software for noise measurement and analysis, eZ-Analyst from IOtech was used, and the power spectral density (PSD), spectrum, time domain, and Auto spec. of the measured data were observed, as shown in Fig. 10, to identify the overall trend[5~7].

According to the processes described in the flowchart, the experiment was repeated six times to increase the reliability of the experimental results, and the average value of the measurements was used to obtain a graph representing the trend of noise characteristics with respect to the applied torque with an increase in rpm as shown in Fig. 11.

According to the results of noise measurement in the lubricated state at a low rotational speed (800 rpm or less) and a torque or 1 N·m, the noise level was 66.1–67.2 dB, and the range of noise level was 74.2–76.1 dB in the non-lubricated state, indicating a difference of 8.1–9.1 dB between the two states.

In addition, it was confirmed that the noise level increased in both lubricated and non-lubricated states as the rpm increased under the same applied load. When the rotation speed was 1600 rpm or higher, the noise level in the lubricated state was 74.5–75.8 dB and 78.5–79.4 dB in the non-lubricated state, indicating an increase of 3.6–4.0 dB. As the torque increased, a similar trend of difference was observed. At the low rotation speed (800 rpm or less) with the highest torque of 6 N·m, the noise level in the lubricated state was 71.5–75.2 dB, and that in the non-lubricated state was 83.5-84.6, showing the largest difference of 9.4–12 dB. As for the overall characteristics, the difference between the two conditions (lubricated vs. non-lubricated) was larger at low rotation speed than at high rotation speed with the application of the same load, and the difference ranged from a minimum of 6.3 dB to a maximum of 12 dB. In addition, the temperature of the lubricant measured during the experiment as well as the properties of the lubricant used are outlined in Table 6.

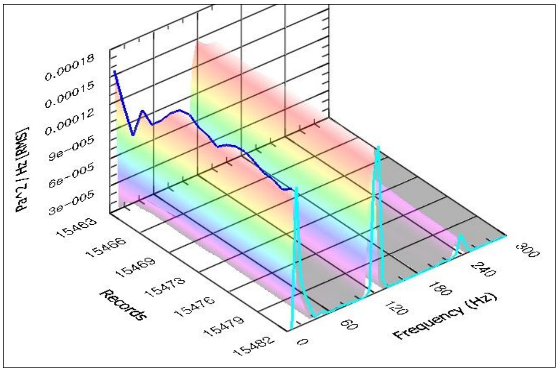


Fig. 10 Noise measuring and analysis system

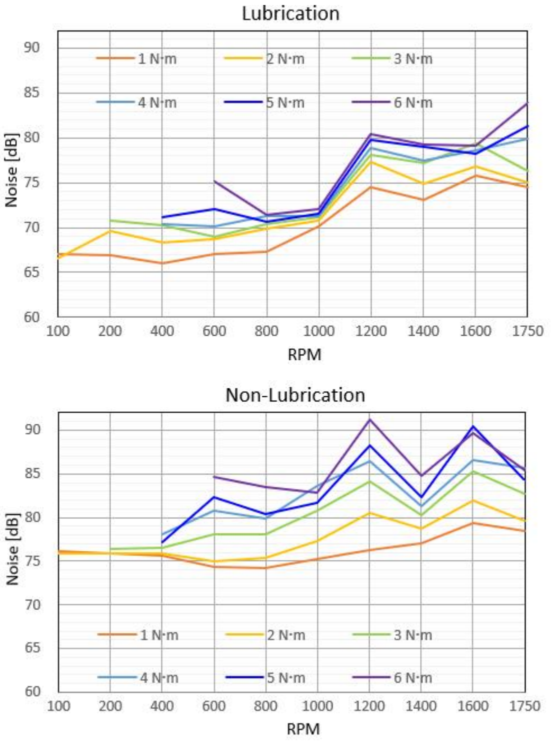


Fig. 11 Noise measurement result

Table 6 Gear Oil Specifications

SAE Viscosity		20W
Kinematic Viscosity (mm^2/s)	at 40℃	67.6
	at 100℃	9.25
Viscosity Index		113
Pour Point (℃)		-30
Flash Point (℃)		240
Oil Temp. during experiment(℃)		28
Supplied lubricant quantities(l/min)		6.7

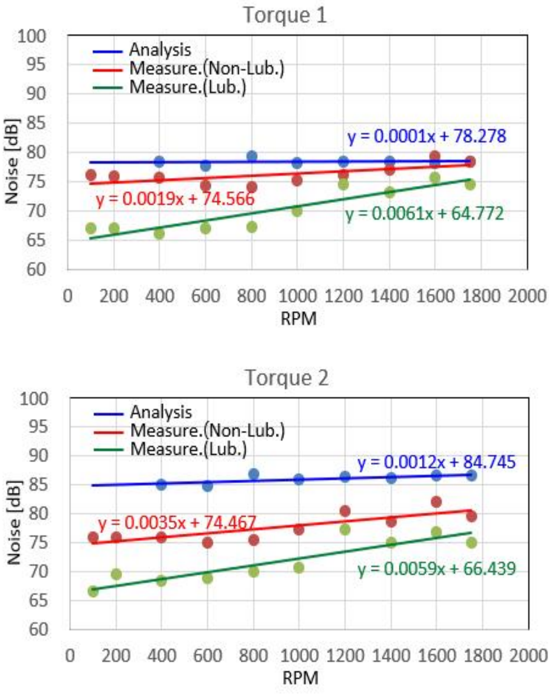
4.2 Comparative analysis between the numerical results and experimental results

When the trend of noise characteristics for each applied torque was analyzed with the trend line shown in Fig. 12 for the numerical analysis results and experimental results without considering the damping of the gearbox structure, the result confirmed that the noise level difference in in each condition is larger at low rpm than at high rpm. For all values of torque, noise levels are shown in the order of lubricated state, non-lubricated state, and numerical analysis results.

In addition, the analysis results from the equation derived from the trend line and the analyzed noise values in the lubricated and non-lubricated state were obtained as shown in Table 7, and the noise difference for each torque is shown in Table 8.

Based on the analysis results, the average noise level in the non-lubricated state was 9.47 dB, which is 11% lower in terms of the noise level, and the average noise level in the lubricated state was 17.1 dB, confirming a 19% reduction in noise compared to the analysis results.

That is, the difference with the analysis results was 10% or more for the non-lubricated state and 19% or more for the lubricated state.



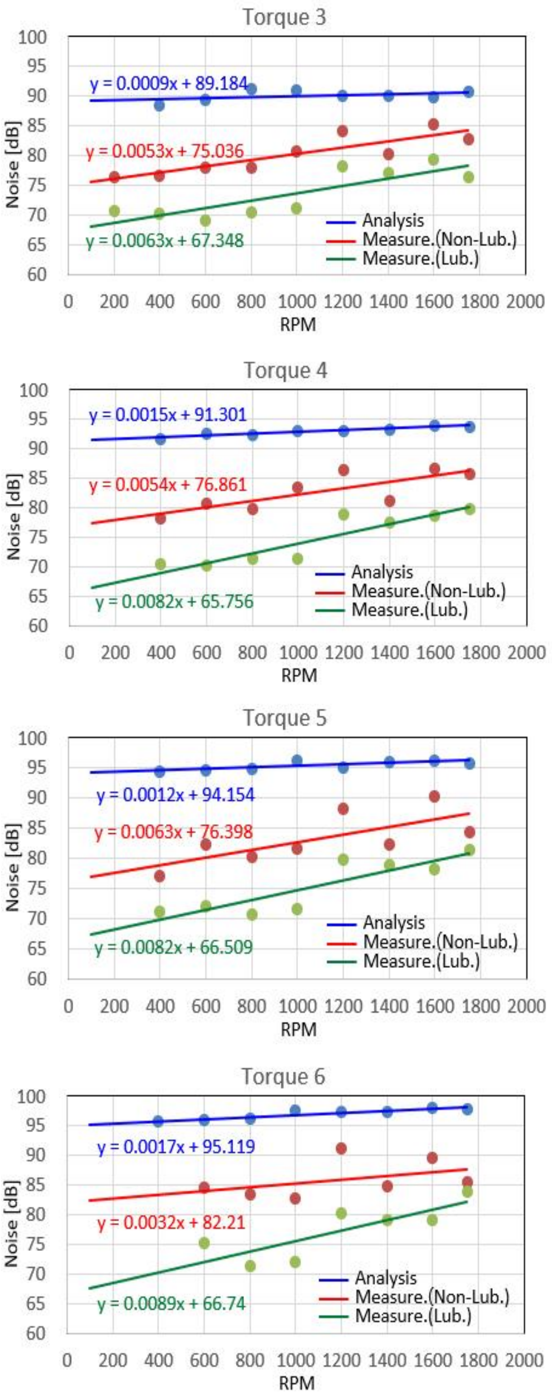


Fig. 12 Comparison of experimental results and analysis results

Table 7 Average of the meas. and analysis value

[Unit : dB]

		Analysis①	Non-Lub.②	Lub.③
Torq. [N·m]	1	78.37	76.23	70.11
	2	85.80	77.53	71.60
	3	89.97	79.67	72.86
	4	92.61	81.59	72.93
	5	95.20	81.91	73.68
	6	96.61	85.01	74.53
Average		89.76	80.32	72.62

Table 8 Deviation of the measurement and analysis average value

[Unit : dB]

		① - ②	① - ③	② - ③
Torq. [N·m]	1	2.14	8.26	6.12
	2	8.27	14.19	5.93
	3	10.30	17.11	6.81
	4	11.03	19.68	8.66
	5	13.29	21.52	8.23
	6	11.60	22.05	10.48
Average		9.44 (10.5 %)	10.48 (19.1 %)	7.70 (9.5 %)

5. Conclusion

In this study, an experimental reduction gearbox was designed, and the characteristics of the gearbox-radiated noise were analyzed for each rotational speed and torque through numerical analysis. Then, the designed gearbox was actually fabricated to perform experiments by changing the torque and rotational speed, and the radiated noise characteristics in the lubricated/non-lubricated state were investigated. In addition, through a comparative analysis between the numerical analysis results and experimental results, we aimed to investigate how much the lubrication damping effect should be considered in the analysis, and the conclusions from this study are outlined as follows.

1) When gears rotate in a meshing pair, the two teeth come into line contact over the entire tooth width. At this time, the total elasticity of the teeth changes abruptly at the beginning and end of the line of action, and the variation in the load applied to the tooth surface increases sharply, resulting in noise and vibration. Lubrication is applied as one of the countermeasures to reduce the noise level.
2) In the results of the numerical analysis based on short-time FFT, which converted the time domain data into frequency domain data for analysis of the acceleration and noise, when the torque applied to the output shaft load was 6 N□m, noise level of over 85 dB was measured at all rpms. In particular, beyond 800 rpm, the noise level increased to above 90 dB, and it further increased to 98 dB at a rotational speed of 1750 rpm.
3) In the experimental results, as the applied torque increased, the noise level difference between the two conditions decreased. At a torque of 6 N□m and low rotation speed (800 rpm or less), the noise level was measured to be 71.5–75.2 dB in the lubricated state and 83.5–84.6 db in the non-lubricated state, indicating a large difference of 9.4–12 dB. In the analysis of the overall characteristics, the difference between the two conditions (lubricated vs. non-lubricated) was found to be larger at low rotational speed than at high rotational speed under the same applied load, and the measured difference ranged from a minimum of 6.3 dB to a maximum of 12 dB.
4) When the trend of noise characteristics for each applied torque was analyzed using the trend line for the numerical analysis results and experimental results without considering the damping of the gearbox structure, the result confirmed that the noise level difference in in each condition was larger at low rpm than at high rpm.
5) On comparatively analyzing the numerical analysis results and noise values in the lubricated and non-lubricated states using the equation obtained from the trend line, it was found that the average noise level in the non-lubricated state was 9.47 dB, corresponding to 11% lower noise level, and the average noise level in the lubricated state was 17.1 dB, confirming a 19% reduction in noise compared to the analysis results.
6) The difference with the analysis results was 10% or more for the non-lubricated state and 19% or more for the lubricated state. Based on these results, it is possible to set the criteria for reflecting the lubricating damping effect in the gear analysis.
7) Furthermore, based on the above results, it is possible to estimate the noise reduction effect of lubrication in a similar gearbox reducer in the future, and the findings of this study are expected to provide useful data for the development of algorithms that reflect the lubrication damping effect in the numerical analysis tool.

Acknowledgement

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