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Improvements for reduction of the brake squeal noise at Seoul metro rolling stock on tracks †

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Abstract

Experimental and theoretical methods were applied to find and understand the phenomenon of brake squeal noise of the Seoul Metro rolling stock on tracks. Generally, it is well known that brake squeal noise is strongly related to stick and slip between brake pad and disk. In most cases for rolling stock on tracks, trailer cars needed more particular attention through the tests, because they were the major sources of brake noise due to frictional braking. There are two types of rolling stocks in Seoul Metro: chopper and VVVF. Both types of rolling stocks for lines 1 and 3 in the Seoul Metro were used for experimental analyses. To study brake squeal noise under various braking conditions, dynamometer tests were performed at the S&T Brake, Co., which is one of major manufacturers of brake pads for rolling stock on tracks. For measuring brake squeal noise, acoustic tests were performed with a microphone in the Gunja depot. And modal tests for brake parts, which consisted of brake lining, brake lining pad, and back plates, were executed to obtain the natural frequencies related to the brake squeal noise. Also, modal tests of the whole brake assembly and lining block were performed at the heavy maintenance shop of the Gunja depot. The mode analysis using an ANSYS was simulated to determine the relations between the mechanisms of brake squeal noise. As the results of the tests and the simulations, it was found that specific natural frequencies of the brake parts affected squeal noise, and also, the reason to create squeal noise. Finally, improvements for reducing squeal noise were proposed, and applied to lines 2and 3 at Seoul Metro rolling stock on tracks.

Keywords: Brake squeal noise; Rolling stock on tracks; Trailer cars; Dynamometer test; Modal test; Mode analysis; Disc; Pad; Bracket; Brake assembly

1. Introduction

By the remarkable development of computer systems and semi-conducts with a heavy electric power, the running ways for rolling stock on tracks have been gradually improved as the IGBT control applied to micro-processor from resistant control early [1]. Together with the development of such advanced technologies, the quality of life of passengers has been improved, and the need for noise limitation and fresh environmental conditions inside rolling stock has been increased.

The periodic noises created by running rolling stock are motor noise, dehumidifier releasing noise, and contact noise of a dust collector. Also, non-periodic noise is squeal noise created between disc and lining pad when braking, or wheel and rail when steering. Generally, the periodic contact noises are improved and removed by changing the type of motor from DC to AC, reducing the noise source by installing a silencer, and producing new lubricants. However, the studies on the non-periodic noises of running rolling stock have been not much yet [2, 3].

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It has been well known that it is very difficult to study the squeal noise created between a disc and lining pad among the non-periodic noises because passengers inside the rolling stock are exposed to the squeal noise, and it is created differently with rail and wheel conditions.

In this study, squeal noise at braking is understood for trailer cars in chopper typed and VVVF typed rail stocks to be running on lines 1 and 3 in Seoul, and improvements are proposed.

Fig. 1 shows a schematic diagram of the braking system at Seoul Metro. Two or four discs are attached to the shaft of railroad stock, and braking works by pushing lining pads at both sides.

2. Analyses of brake squeal noise

To measure brake squeal noise under real running conditions for driving and trailer cars of lines 1 and 3 at Seoul Metro, the tests were performed with a microphone in the Gunja and Suseo depots.

Table 1 shows experimental equipment of the noise tests. Positions of noise tests with microphone are 0.7 m height and 0.6 m away from the rail, and Fig. 2 shows squeal noise tests with microphone [4-8].

Table 1. Experimental equipments for noise tests.

Item	Model	Manufacturer
Potable real time FFT analyzer	DI-2200	Diagnostic Instrument
Microphone	Type 4155	B&K
Microphone amplifier	Type 2804	B&K
Recorder	PC204	Sony
4CH microphone module	Type 3028	B&K
Software for analysis	Pulse	B&K

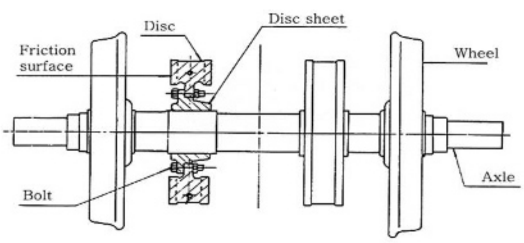

Fig. 1. Schematic diagram of the braking system at Seoul Metro.

2.1 Materials of brake pads

Tests for brake squeal noise were performed for two types of lining pads, DH2004NA and SBK14, which were used at Seoul Metro, and brake squeal noises were measured under real environmental conditions. Table 2 shows material properties of lining pads used in the tests. Table 3 shows material differences of those lining pads measured at the specification tests.

Table 2. Material properties of brake pads.

Type of strength (kgf/㎟)	DH2004NA for Chopper	SBK14 for VVVF
Compressive strength	3.3	5.1
Flexural strength	94	131
Tensile strength	44	67
Shear strength	9	12
Impact strength	17.8	9.6

Fig. 2. Experimental set-up for squeal noise with microphone under real running conditions.

Table 3. Test results of brake pads at S&T.

Items for tests		Specification	DH2004NA (Chopper)	SBK14 for VVVF
Noise		must be no	no	no
Coef. of friction	50℃	0.290-0.370	0.367	0.421
	200℃		0.32	0.342
Wear 10^{-2} ㎟	A	30-100	32.7	15.4
	B		37.0	11.2
Maximum temperature		below 400℃	255	280

Fig. 3. Old model brake pad and brake lining head for chopper railroad stock (DH2004NA ; density : 2.05 g/cm^3, area : 376 cm^2, and thickness : 30 mm).

2.2 Shapes of lining pads for railroad stocks

Fig. 3 and Fig. 4 show shapes of lining pads which are currently being used at Seoul Metro railroad stick.

Since braking forces in the trailer cars are created by restoring braking of driving cars in VVVF railroad stock, the restoring braking forces are large.

However, the squeal noise generated frequency number in VVVF railroad stock is basically similar to that in chopper railroad stock due to using air braking by lining shoes in the final stopping stage. Generally, the phenomenon of squeal noise is changed by brake shoes and shapes of head assembly of brake shoes.

Fig. 4. New model brake pad and brake lining head for VVVF railroad stock (SBK14 ; density : 2.18 g/cm^3, area : 400 cm^2, and thickness : 35 mm).

2.3 Results of squeal noise tests

The brake system types for lines 1 and 3 at Seoul Metro are composed of electric common braking that is forward and backward movements 4 notches, and has 7 stages uniformly, including electric powered braking, emergency braking, and security braking. Braking method using disc is currently applied to lines 1, 2 and 3. Two discs are built to an axle of railroad stock, and they are rotated simultaneously. Also, the braking system works by cooperation of the disc and lining assembly.

In this study, squeal noises were measured for four braking types under the same braking forces. Through the noise tests, squeal noises were primarily created under the conditions that speed was below 10 km/h, braking pressure was 1.5 kg/cm^2, and braking stage was the 3rd among whole 7 stages. Also, as braking pressure was lower or higher for stopping the railroad stock, squeal noise created frequency decreased. According to the results, it was found that squeal noise might depend on the braking pressure and the speed.

Fig. 5 shows the results of squeal noise tests for chopper type railroad stock in time and frequency domains. Fig. 6 shows the results of squeal noise tests for VVVF type railroad stock in frequency domain. As for the results of the noise tests, the frequencies relating to the squeal noise for chopper type railroad stock are 0.8 kHz, 1.6 kHz, 2.0 kHz and 3.15 kHz, and the frequencies relating to the squeal noise for VVVF type railroad stock are 0.4 kHz, 0.8 kHz, 2.0 kHz and 5.0 kHz.

In comparing the tests for chopper and VVVF type railroad stocks, the squeal noise created frequency for chopper type was larger than that for VVVF type.

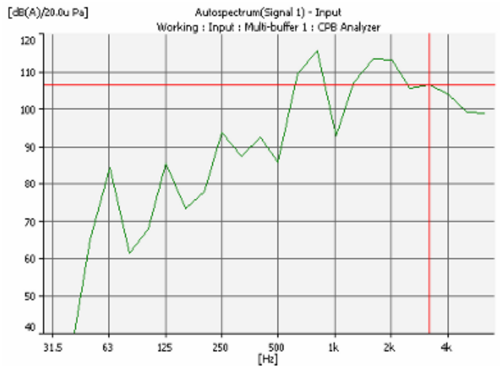

Fig. 5. Squeal noises for chopper typed railroad stock in frequency domain.

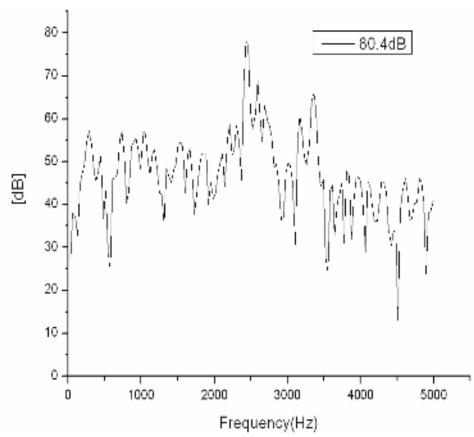

Fig. 6. Squeal noises for VVVF type railroad stock in frequency domain.

3. Modal tests

Natural frequencies of each part of the braking system were measured by applying Maxwell's reciprocity theorem at the Laboratory of Machine Dynamics in Seoul National University of Technology by modal tests of brake lining, brake lining head, and back plate, because the part might have an effect on squeal noise. And, the natural frequencies for disc assembled body and lining block were measured at the heavy maintenance shop of the Gunja depot. Especially, in order to perform modal tests of disk assembled body and lining block at the applied braking force, a real VVVF type rail stock was used at the heavy maintenance shop inside the rolling stock site.

3.1 Modal tests for parts and disc assembled of brake system

3.1.1 Test conditions

Table 4 shows experimental equipment for modal tests. Figs. 7, 8 and 9 show modal tests of half disc, brake pad for VVVF type and disk assembled body, respectively.

Objects for the tests were lining pad for VVVF, back plate, head of lining pad, and disk assembled body. Disk assembled body was composed of shaft, wheels, disks, and lining assembly for VVVF type rolling stock, and new modeled lining pad, head and back plate were applied. Test condition for disk assembled body was that braking step was the 3rd, and pressure was 1.5 kg/cm^2.

3.1.2 Results of modal tests

Table 5 shows the measured natural frequencies of each part of the braking system related to squeal noise. Fig. 10 shows auto-spectrum and frequency response function of old and new lining pad for VVVF type rail stocks.

Table 4. Experimental equipments for modal tests.

Item	Model	Manufacturer
Impact hammer	Type 8202	B&K
Accelerometer	Type 4671	B&K
DC Amplifier NEXUX	Type 2804	B&K
Accelerometer amplifier	Type 2825	B&K
4CH input module	Type 3022	B&K
Software for analysis	Pulse	B&K

Table 5. Natural frequencies of the braking parts related to squeal noise.

Braking parts	Natural frequencies (Hz)
Half disc with free condition	460, 3,000
Full disc with fixed condition	448, 1,984, 4,944
Lining pad for VVVF	944, 1,744
Back plate	1,248
Head of lining pad	1,792

Fig. 7. A half disc for modal test.

Fig. 8. Modal test of lining pad for VVVF type at SNUT.

Fig. 9. Modal test of disc assembled body at Gunja depot.

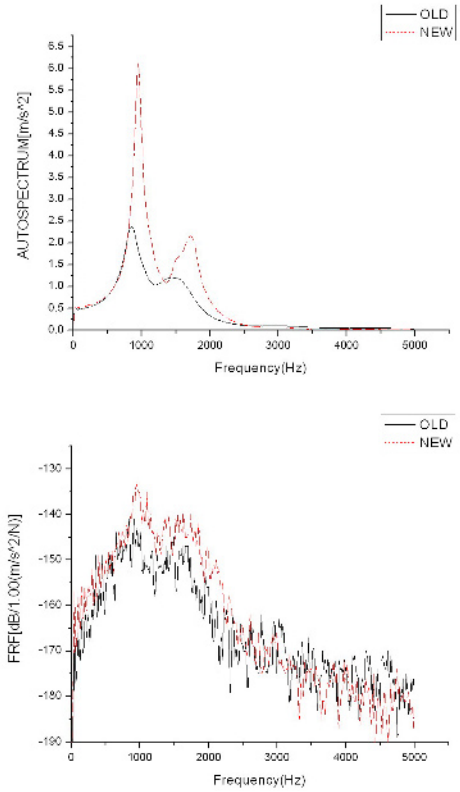

Fig. 10. Auto-spectrum and FRF of old and new lining pads for VVVF (944 Hz and 1,744 Hz).

According to the results of modal tests for a disc assembled body, the natural frequencies related to noise squeal were 1.8 k, 3.0 k, 3.6 k, 4.0 k, 5.0 k and 5.8 kHz. Fig. 11 shows the auto-spectrum and FRF of disk assembled body.

3.2 Dynamometer tests

By dynamometer as shown in Fig. 12, the tests for squeal noise were measured at the S&T brake.

3.2.1 Test conditions

Two types of lining pads and two types of heads of lining pads were used, and dynamometer tests for four different combinations were performed. Test conditions are shown in Table 6. The four different combinations are as shown in Table 7. Squeal noise and modal tests for the combination of an old head of lining pad and DH2004NA for chopper and the combination of a new head of lining pad and SBK14 for VVVF had already been measured in previous tests under real running situations as shown in Figs. 5, 6 and Fig. 10.

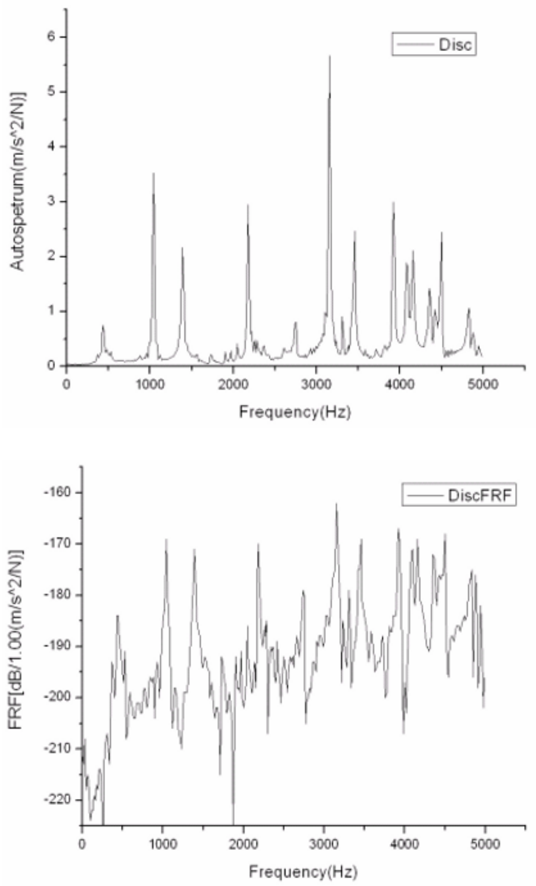

Fig. 11. Auto-spectrum and FRF of disk assembled body with a new modeled lining pad for VVVF.

Fig. 12. Experimental set-ups for dynamometer tests.

3.2.2 Test results

The resonant frequency for the 1st combination was 0.428 kHz, and that for the 2nd combination was 1.8 kHz. Squeal noise for the 1st combination was never created. By comparing measured amplitudes at resonant frequencies, the amplitude for the 1st combination was much less than that for the 2nd combination. In the 3rd combination, squeal noise was almost not created and the amplitude at the resonant frequency was very low like the 1st combination. Fig. 13 shows auto-spectra for the 1st and the 2nd combinations.

Table 6. Conditions for dynamometer tests.

Items	
Initial temperature	Below 100°C
Braking forces	4, 8, 12, 17 (kN, Maximum used braking force)
Initial speed for braking	20, 40, 60, 80, 100 (km/h)

Table 7. Four different combinations for dynamometer tests.

Combination	conditions
1st	A new head of lining pad + SBK14
2nd	A new head of lining pad + DH2004NA
3rd	An old head of lining pad + SBK14
4th	An old head of lining pad + DH2004NA

The measured auto spectra and frequency response functions are shown for the 3rd and 4th combinations in Fig. 14.

In the dynamometer tests for a new and an old head of lining pad with SBK14, squeal noise was almost not created. However, the magnitude of squeal noise for the test with a new head of lining pad was a little smaller than that for the test with an old head. In the dynamometer tests for a new and an old head of lining pad with DH2004NA, squeal noise was created occasionally, but the magnitude of squeal noise for the test with a new head of lining pad was a little smaller than that for the test with an old head like the previous test. Through the dynamometer tests for four different combinations, it was found that the effects of material properties of lining pads were much higher than those of heads of lining pads for squeal noises and vibrations.

4. Simulation

4.1 Aim and condition for simulation

Mode analysis for a full model of a disc was performed to obtain its natural frequencies and the mode shapes by using the ANSYS. The aim of this simulation was to find the natural frequencies and the mode shapes of a disc related to the squeal noise. Through the modal test and simulation for a half disc, the

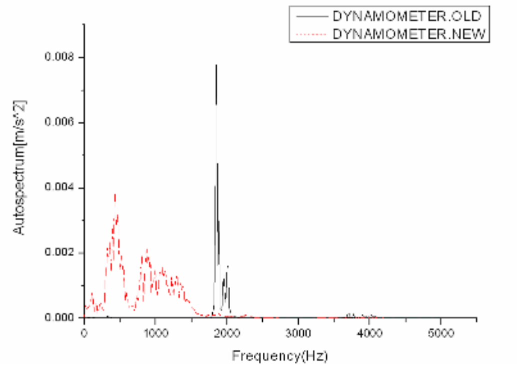

Fig. 13. Auto spectra for the 1st combination (0.428 kHz) and the 2nd combination (1.8 kHz).

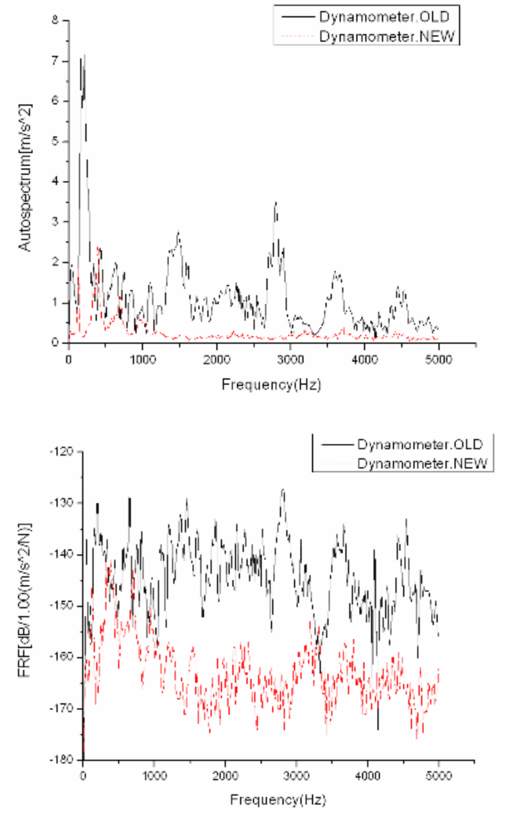

Fig. 14. Auto spectrum and frequency response function for the 3rd and 4th combinations.

correct theoretical FE model for a half disc was made. With the theoretical model of a full disc, mode analyses were executed to find how the disc had an effect on squeal noise. The material of the disc was gray cast-iron. The boundary conditions were perfectly the same as the experimental tests, and the part of a disc connected to the railroad shaft was fixed.

Table 8. Comparison of the results of mode analysis and modal test for a full disc.

Number of natural frequency	Simulation (Hz)	Modal test (Hz)
1	532.11	448
2	629.30	-
3	670.99	-
4	1,149.9	896
5	1,231.8	944
6	1746.9	1,728
7	1,886.8	1,984
8	2,402.1	-
9	2,508.3	2,464
10	3,069.2	3,200
11	3,359.4	3,392
12	4,225.8	4,272
13	4,330.9	-
14	4,812.0	4,944
15	5,404.8	-

4.2 Results of simulations

The finite element model of the disc is shown as Fig. 15, and the results of the simulation and modal test for a full disc are compared in Table 8.

Among the natural frequencies, it was found that the 1st, the 7th and 14th natural frequencies were related to the squeal noise from compared with the previous squeal noise tests. The 1st mode is to show the 1st bending of a disc like Fig. 16, and the 7th mode is (8, 0) ring motion like Fig. 17. The 14th mode is (16, 0) ring motion like Fig. 18.

5. Improvement of squeal noise

According to the results of the previous dynamometer tests, the 1st combination, which was a new head of lining pad and SBK14, was the best combination, ; and the 3rd combination, which was an old head of lining pad and SBK14, was the second best for squeal noise. Since 2006, those two combinations had been applied to Seoul Metro rolling stock on tracks. The combination of an old head of lining pad and SBK14 was applied to the chopper type rail stocks at line 2, and the other combination of a new head of lining pad and SBK14 was applied to the VVVF type rail stocks at line 3. Fig. 19 shows measured intensity of squeal noise for the chopper type rail stocks applying an old head and an old pad like DH2004NA at line 2, and Fig. 20 shows measured intensity of squeal noise for the copper type rail stocks applying an old head and a new pad like SBK14 at line 2. From

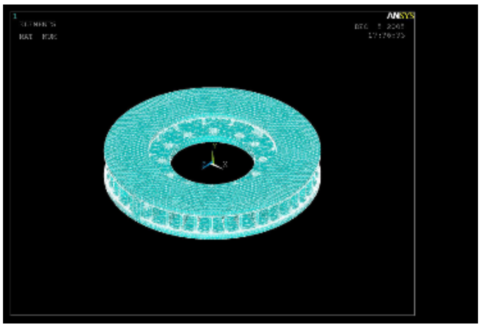

Fig. 15. The finite element model of a disc.

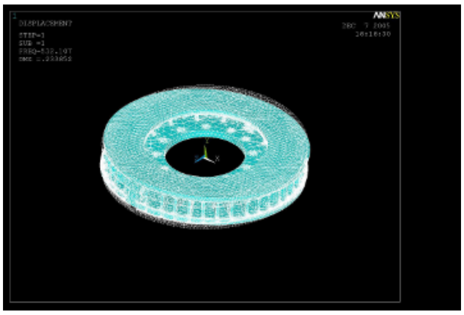

Fig. 16. The 1st mode shape of a full disc (The 1st bending of a disc).

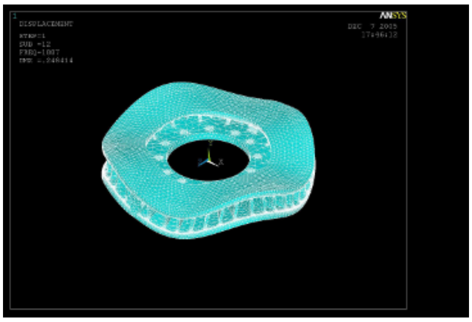

Fig. 17. The 7th mode shape of a full disc ((8, 0) ring motion of a disc).

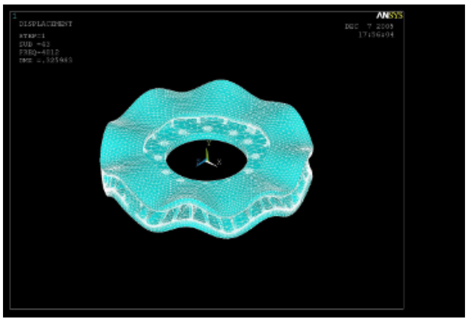

Fig. 18. The 14th mode shape of a full disc ((16, 0) ring motion of a disc).

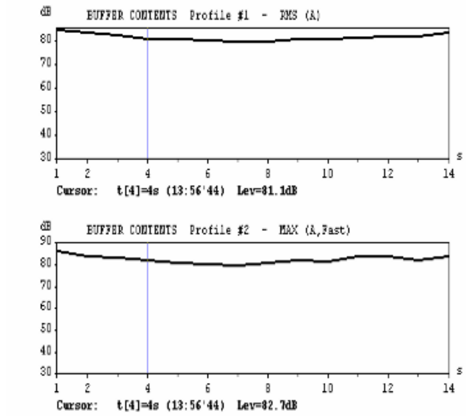

Fig. 19. Measured intensity of squeal noise for the copper type rail stocks applying an old head and an old pad like DH2004NA at line 2.

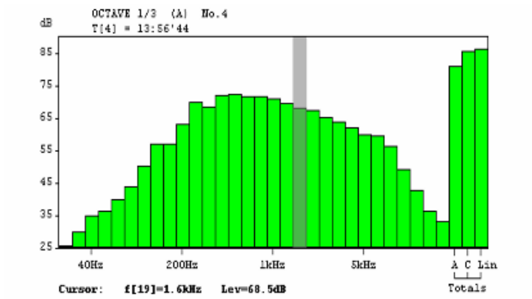

Fig. 20. Measured intensity of squeal noise for the copper type rail stocks applying an old head and a new pad like SBK14 at line 2.

comparing those two results, the average intensity was 78 dB for an old head and an old pad, but 68.5 dB for an old head and a new pad. The squeal noise created frequency was changed and reduced 74% to 20% while rail stocks were running for two hours at line 2.

After applications of those combinations, there were no more civil petitions. It was found that the two best combinations by dynamometer tests were very useful to real environmental conditions. To reduce or remove the squeal noise of Seoul Metro rolling stock on tracks, the material of the lining pad should be improved like SBK14, and a new head for SBK14 also should be designed.

6. Conclusion

Generally, squeal noise is quite annoying to passengers. In this study, the squeal noise created at braking is understood for trailer cars in the chopper type and the VVVF type rail stocks running at lines 1 and 3 in Seoul, and the improvements are proposed, and applied.

Through the squeal noise tests, its frequencies were around 0.8 kHz, 1.6 kHz, 2.0 kHz and 3.15 kHz in case of the chopper type rail stocks, and were around 0.4 kHz, 0.8 kHz, 2.0 kHz and 5.0 kHz in case of the VVVF type rail stocks. The squeal noises were primarily created under the conditions that speed was below 10 km/h, braking pressure was 1.5 kg/cm^2, and braking stage was the 3rd among whole 7 stages. Also, as braking pressure was lower or higher for stopping the railroad stock, the squeal noise created frequency decreases. According to the results, it was found that squeal noise might depend on the braking pressure and the speed.

Through modal tests of parts and disk assembled body of the braking system, the structural frequencies related to the squeal noise were obtained. To verify the experimental results, mode analysis for a full disc was performed, and it showed a good match. This disc model will be used for redesigning it.

A lining pad of a new material like SBK14 and a new lining head of the pad were proposed to reduce or remove the squeal noise in this paper. According to comparison with the existing combinations using a dynamometer, the best one for reducing the squeal noise was a new combination. Also, among the existing ones, the combination of an old lining head and SBK14 showed a good result.

Two good combinations from this study were applied to lines 1, 2 and 3 at Seoul Metro rolling stock on tracks since 2006, and there were no more civil petitions.

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