CHARACTERISTICS OF HYDROGEN LEAKAGE SOUND FROM A FUEL-CELL VEHICLE BY HEARING

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ABSTRACT

Fuel-cell vehicle, run on hydrogen, is known that it has better energy efficiency than existing gasoline cars. The vehicles are designed so that hydrogen leaks from the tank are stopped automatically upon detection of hydrogen leakage or detection of impact in a collision. However, we investigated the characteristics of hydrogen leakage sound from a hydrogen-leaking vehicle and the threshold of discrimination of hydrogen leakage from noise at a crossing with much traffic to examine a method to rescue people safely depending on the sense of hearing in the event of a continuous hydrogen leak. We clarified that hydrogen leakage sound from vehicles has directivity, height dependence, and distance dependence. Furthermore, we confirmed the threshold flow rate for distinguishing hydrogen gas when hydrogen leakage is heard at a distance of 5 to 10 m from the center of the hydrogen leaking vehicle in a 74 dB traffic noise environment.

1.0 INTRODUCTION

The first mass-produced fuel-cell vehicle (FCV), which has better energy efficiency than existing gasoline cars, was sold in 2014, and other manufacturers are expected to release them in the future. Usually, the FCV will automatically stop hydrogen supply from the hydrogen tank in an accident and collision impact or when a hydrogen leak is detected [1, 2]. However, assuming that a hydrogen leak may occur continuously due to an unexpected failure, it is necessary to understand whether hydrogen leakage sound can be recognized or not as well as the volume of hydrogen leak and the distance from the vehicle.

A hydrogen leak detector is a means for recognizing hydrogen leaks but is not always at hand. Therefore, if the risk of a hydrogen leak can be judged by detecting hydrogen leakage by ear, it will become an influential source of information. However, there are few studies of gas leakage sound; only the jet sound of air from a nozzle has been studied [3], and no study has been conducted on hydrogen.

In this study, therefore, we investigated the characteristics of hydrogen leakage sound from a vehicle in order to examine a method to rescue people safely depending on the sense of hearing in the event of a continuous hydrogen leak from the FCV. Furthermore, we investigated the threshold flow rate and distance from the vehicle for discriminating of hydrogen leakage in a traffic noise environment at a crossing with much traffic.

2.0 METHOD

The noise level in towns is always changing, so it is impossible to evaluate thresholds at a constant noise level. Therefore, we safely conducted listening tests by 1) selecting a safe alternative gas for hydrogen leakage sound, 2) recording traffic noise, and 3) letting the alternative gas for hydrogen leakage leak in an anechoic room while reproducing the traffic sound recorded in 2) to reproduce the state in which hydrogen leaks from the vehicle in a traffic noise environment. Furthermore, we converted the flow rate of the alternative gas for hydrogen leakage as the threshold value for discrimination into the flow rate of hydrogen. Discrimination value means flow rate that humans are able to cognize the leakage sound in the traffic noise environment.

2.1 Selection of the alternative gas for hydrogen leakage sound

To select an alternative gas that has the closest possible acoustic characteristics to those of hydrogen gas, we measured the sound pressure level (SPL), frequency characteristics, and directivity while hydrogen gas and candidate alternative gases leaked from four different types of pipes and compared the results. Test conditions are shown in Table 1; devices used, in Table 2; examples of leak pipes, in Fig. 1; and a schematic diagram of measurement, in Fig. 2. Leak pipes were 1/4 inch (1/4 in, pipe bore 4.57 mm) and 3/8 in (pipe bore 7.045 mm), both of which are pipe diameters used for FCVs. To simulate cases in which the pipe is crushed and cut due to a collision, 1/4 in (cut) and 3/8 in (cut) pipes, produced by cutting 1/4-in and 3/8-in pipes by pressure, were also used. Cut pipes were too difficult to judge whether or not the area of 1/4 inch pipe is larger than that of 3/8 inch pipe. Because the areas were too small. However, it is considered that the area of 1/4 inch pipe is larger than that of 3/8 inch pipe, since diameter of 3/8 inch is larger. Because fluid noises increase in proportion with flow velocity [4], fluid noises increase as the pipe diameter becomes smaller if the flow rate is kept constant. In other words, if gas leaks at the same flow rate from non-cut pipes, the discrimination flow rate is considered to be increases during the listening test. Therefore this corresponds to the worst case. Pipes were installed in parallel with the ground. Gases that are relatively easily available and safe were used as alternative gases for hydrogen. The maximum allowable hydrogen leak volume in a collision as specified in Global Technical Regulation (gtr) is 118 NL/min, and this was used as the standard [5]. For the flow rates of alternative gases, the flow rate at which the noise level in the 0º direction is equal to that of hydrogen leak was used as the standard. Guidelines of noise levels are listed in Table 3 for your reference [6]. The frequency range of measurement is 20 to 40,000 Hz, but the human audible frequency range is 20 to 20,000 Hz.

Table 1. Example of table and table caption

Area	JARI* test course dirt track area
Candidate gases	Helium, air, argon
Pipe shape	1/4 in, 1/4 in(cut), 3/8 in, 3/8 in(cut)
Flow rate	Hydrogen: 1000, 750, 500. 250, 118, 60, 30 NL/min Candidate gases: The flow rate was set equal to the noise level of the hydrogen flow rate
Measurement distance	1.0 m
Measurement height	1.5 m
Measurement direction	7 (every 30°)
FFT analysis	
Frequency analysis range	20 to 40,000 Hz
Sampling frequency	96 kHz
Average number	200

JARI* : Japan Automobile Reserch Institute

Table 2. Instruments used in the test

Instrument	Manufacturer	Model
Mass-flow controller	Azbil	MQV0200
		MQV1000
Microphone	RION	UC29
	B&K	4939
Pre-amplifier	RION	NH-17
	B&K	2669
Amplifier	RION	NA-42
	GRAS	12QA
Noise-level meter	RION	NA-28

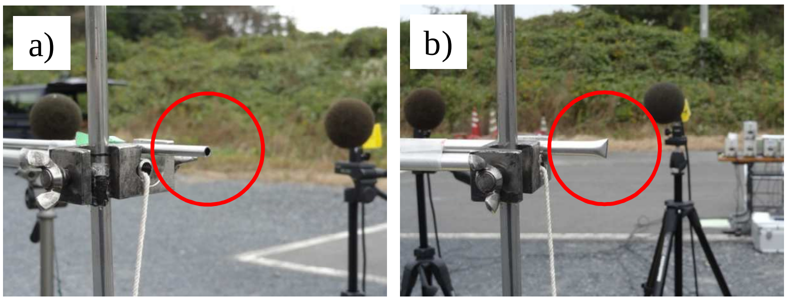

Fig. 1. Examples of pipes used in the tests (a) 1/4 in, b) 3/8 in (cut))

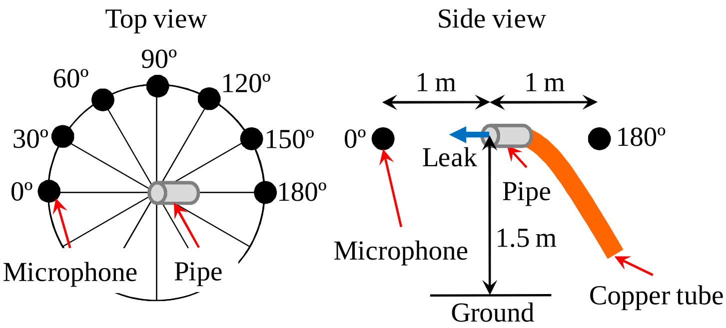

Fig. 2. Schematic of leakage sound measurement

Table 3. Example of noise level[6]

Noise level (dB)	Example
20	Whisper
40	Suburbs at night
60	Conversing voice
80	Crowded streets
100	Orchestra (10m)
120	Factory noise
140	Jet engine (3m)

The measured frequency dependence of sound pressure level when hydrogen leaks from the 1/4 in pipe at a flow rate of 118 NL/min is shown in Fig. 3. Here, the figure following each measurement direction is the overall sound pressure level and BGN represents Back Ground Noise.

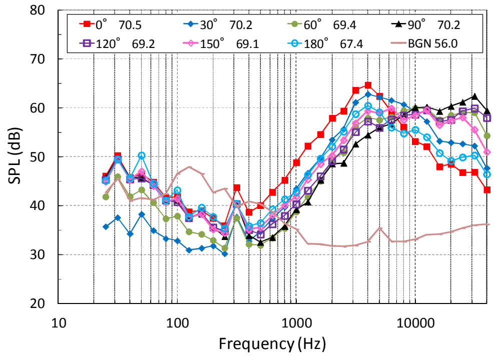

Fig. 3. Hydrogen leakage for 1/4 inch pipe

In Table 1, the frequency range of analysis is stated as 25 Hz to 40 kHz. ISO 3744 specifies that the sound pressure level to be measured shall be at least 6 dB lower than background noise and preferably 15 dB or more [7]. In Fig. 3, we set the lower limit of the analysis frequency range to 500 Hz for the tests that follow because the frequency where the highest noise level exceeds the background noise by 6 dB or more is over 800 Hz.

The flow rate of a candidate alternative gas for hydrogen at which the noise level in front of the leaking piping (0º) is equal to that of hydrogen for a 1/4 in pipe was 125 NL/mi for helium, 82 NL/min for argon, and 82 NL/min for air. The measured frequency characteristics of helium, argon, and air when they leak at these flow rates and the differences in SPL from hydrogen are depicted in Figs. 4 to 6.

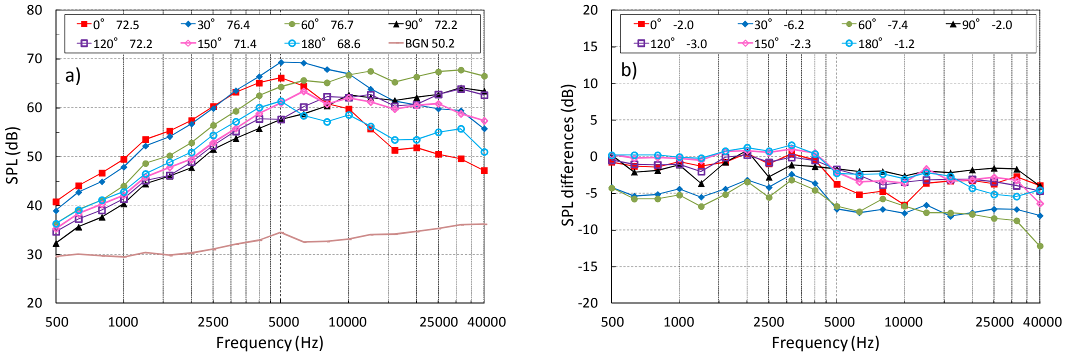

Fig. 4. Results of helium for 1/4 inch pipe (a) hydrogen, b) differences between hydrogen and helium)

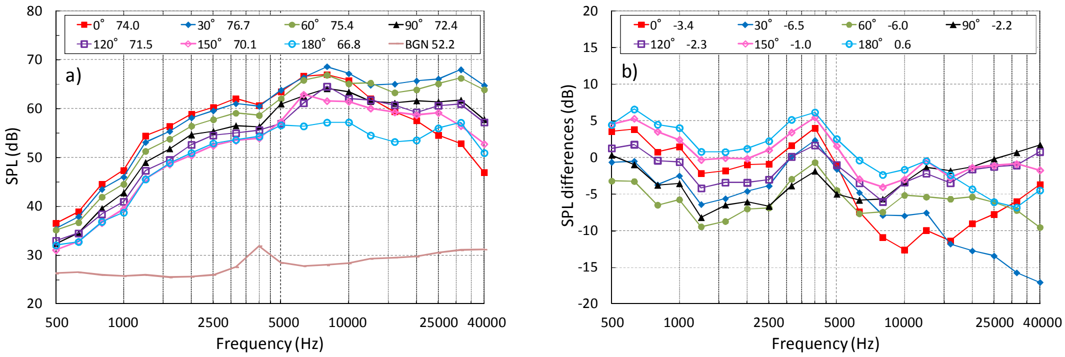

Fig. 5. Results of argon for 1/4 inch pipe (a) argon, b) differences between hydrogen and helium)

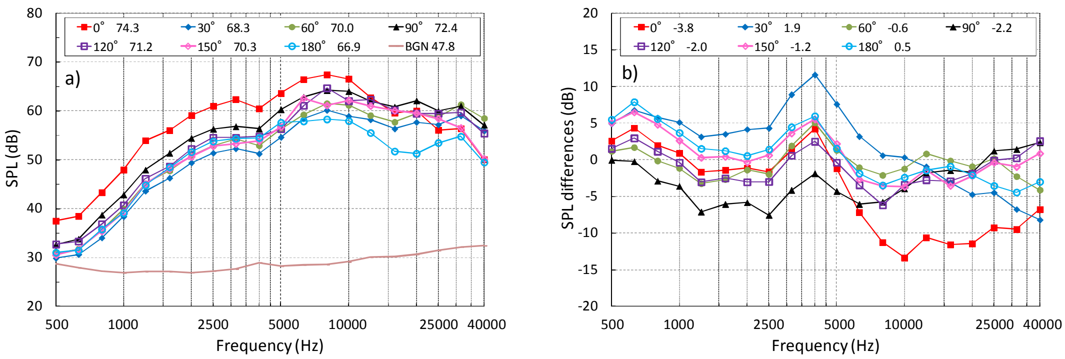

Fig. 6. Results of air for 1/4 inch pipe(a) air, b) differences between hydrogen and helium)

Helium has sound characteristics that are closest to those of hydrogen leaking when hydrogen leaks from the 1/4 in pipe at a flow rate of 118 NL/min. We therefore decided to use helium as the alternative gas for hydrogen. Figs.7 to Fig. 9 depict the frequency analysis results for hydrogen and helium leaking from the 1/4 inch, 1/4 in (cut), 3/8 in, and 3/8 in (cut) pipes at a flow rate of 118 NL/min.

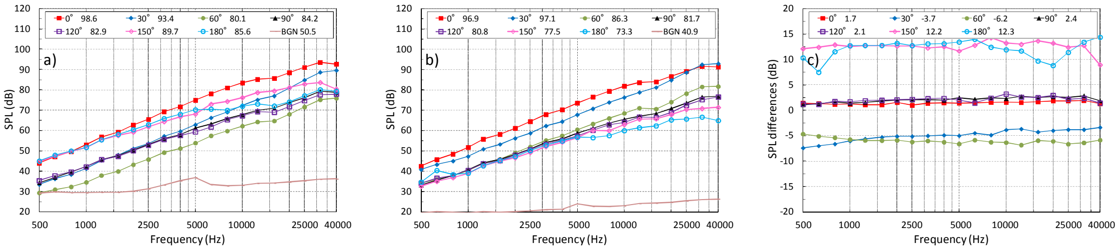

Fig. 7. Results of 1/4 inch cut pipe (a) hydrogen, b) helium, c) their differences)

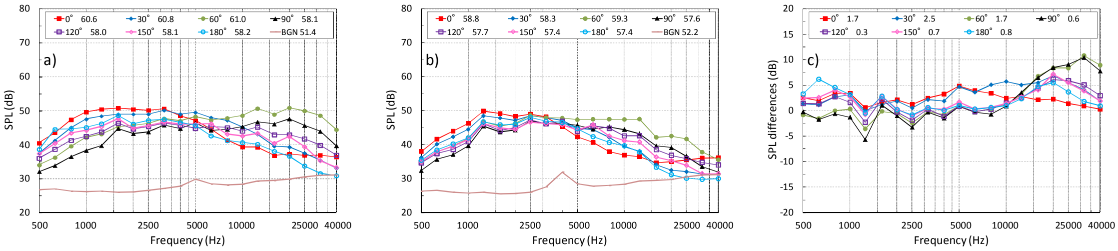

Fig. 8. Results of 3/8 inch pipe (a) hydrogen, b) helium, c) their differences)

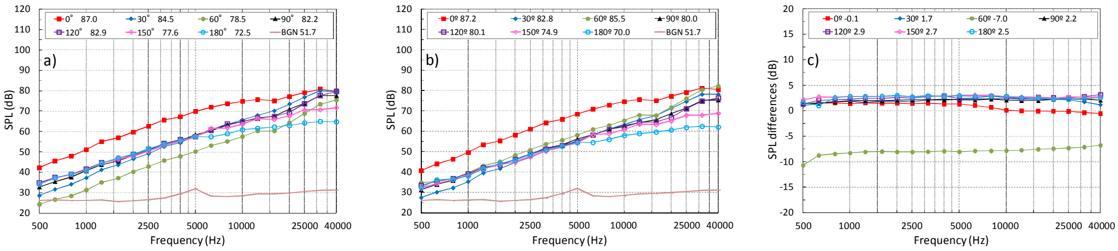

Fig. 9. Results of 3/8 inch cut pipe (a) hydrogen, b) helium, c) their differences)

These results indicated that the difference in SPL between hydrogen and helium is 5 dB or less for most combinations of pipe diameters and directions. However, the difference is 4 dB or more in some combinations. Therefore, relevance was also compared when hydrogen and helium leaked from pipes installed in the vehicle. The results will be described in "2.4.1. Verification of the relevance of helium."

The relationships between hydrogen flow rate and helium flow rate when the noise levels of hydrogen and helium are equal in front of the pipe are plotted in Fig. 10.

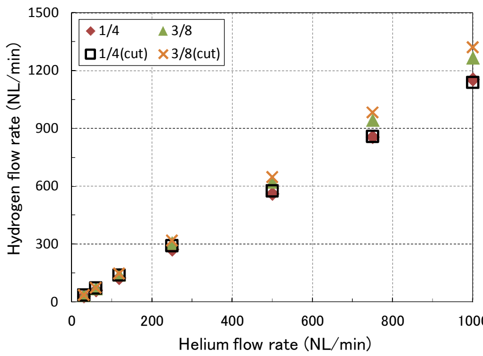

Fig. 10. Relationship between helium and hydrogen flow rates

These relationships can be expressed as follows using primary approximation:

$$F_{H(1/4)} = 1.1442 F_{He(1/4)} \quad (R^2 = 0.9995) \tag{1}$$
$$F_{H(3/8)} = 1.26026 F_{He(3/8)} \quad (R^2 = 0.9998) \tag{2}$$
$$F_{H(1/4cut)} = 1.1442 F_{He(1/4cut)} \quad (R^2 = 0.9999) \tag{3}$$
$$F_{H(3/8cut)} = 1.3122 F_{He(3/8cut)} \quad (R^2 = 0.9998) \tag{4}$$

Here, F_H represents hydrogen flow rate (NL/min); F_{He}, helium flow rate (NL/min); the figure in the parenthesis following the suffix represents the size of piping. Furthermore, no leak noise occurs when the helium flow rate is 0, so the hydrogen flow rate also was assumed as 0 in that case. The intercept of approximations was thus assumed as 0. Using these approximations, the helium discrimination flow rate from the listening test for helium in an anechoic room as specified in "2.4.2. Listening tests on alternative gases for hydrogen" was converted into hydrogen flow rate.

2.2 Hydrogen leakage sound from vehicles

2.2.1 Dependence on direction, distance, and height of hydrogen leakage

In this study, the pipes were aligned along car main axis, with the opening looking the front and the leak point, to the lower area of the left rear seat. The vehicle used for the test was a gasoline sedan. The leakage pipes depicted in Fig. 11 were installed in a lower part of the vehicle. The leakage sounds from these pipes were assumed to depend on the direction, height, and distance of measurement according to the shape of the leakage pipe, shape of the lower part of the vehicle, mounting positions, reflection of sounds from the ground, etc. Therefore, we investigated those dependencies by setting the maximum allowable hydrogen leak volume to 118 NL/min. The test was conducted on an asphalt pavement surface (APS) with a sufficient area that enables ignoring the reflection of surrounding sounds.

The maximum and minimum audible directions were determined by measuring the noise level at a distance of 5 m from the centre of the vehicle and at a 1 m height while walking around the vehicle carrying a hand-held noise meter. The results obtained by defining the vehicle running direction as 0º and clockwise as the positive direction are shown in Fig. 12.

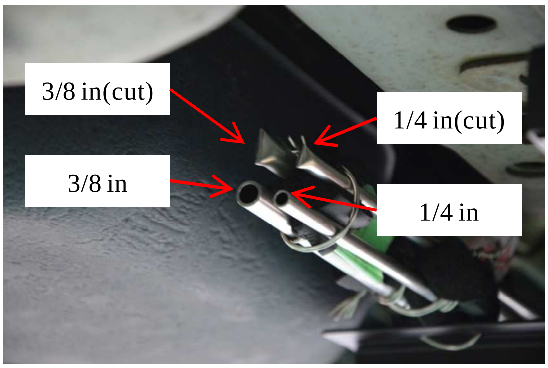

Fig. 12. Leakage pipes mounted on the vehicle

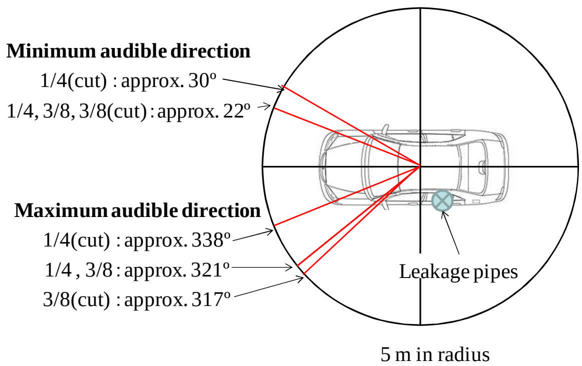

Fig. 11. Definitions of maximum and minimum audible directions (1.0 m height)

To determine direction dependency, we measured the noise level at a distance of 5 m from the centre of the vehicle at a height of 1.5 m while walking around the vehicle and stopping at intervals of 30º. The results are depicted in Fig. 13.

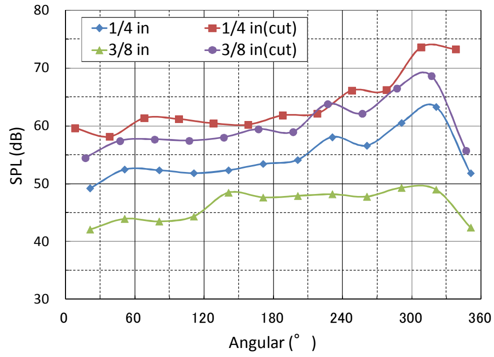

Fig. 13. Direction dependences of noise level (at 1.5 m height)

The result in Fig. 13 indicates that the noise level is the highest around 300 to 330º on the left of the vehicle where leakage pipes are installed. Therefore, noise will vary by 5 to 15 dB depending on the direction if the distance is the same and, therefore, the noise has directivity.

To confirm the height dependency of hydrogen leakage sound, the noise level at a distance of 5 m in the maximum audible direction was measured while varying the height using the four pipes depicted in Fig. 14. This result indicates that the sound is audible most easily at a height of 1.5 m.

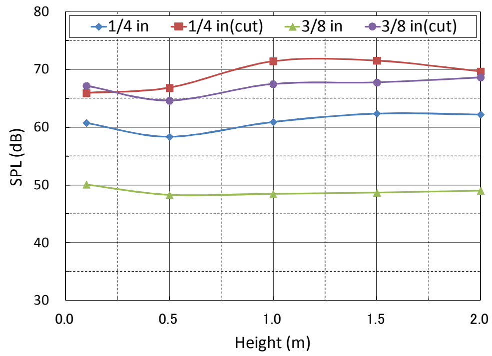

Fig. 14. Height dependence of noise level at maximum directions

To investigate the distance dependence of leakage sound, frequency characteristics were measured beside the vehicle (at the shortest distance from the vehicle), at distances of 5 m, 10 m, and 20 m. As a few examples, the measurement results in the maximum audible direction of 1/4 in and 1/4 in (cut) pipes and at a height of 1.5 m are plotted in Fig. 15.

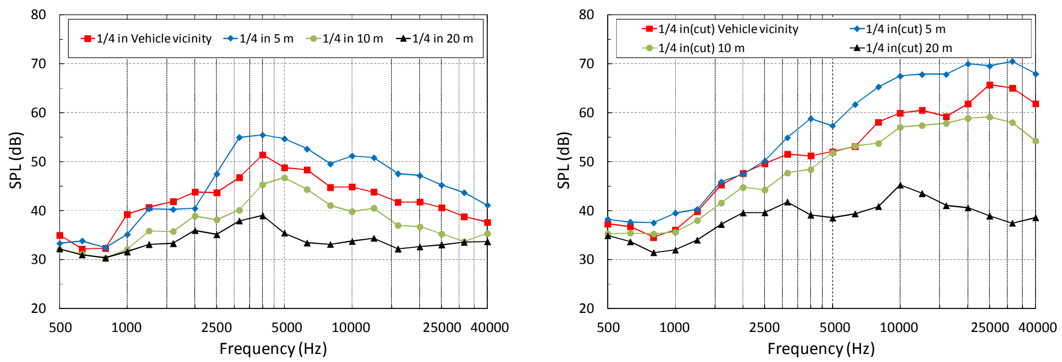

Fig. 15. Distance dependence of noise level

Fig. 15 suggests that the sound level rises as you approach the vehicle from a long distance, but the sound becomes harder to hear as you approach the position nearest to the vehicle. This is because the sound level at high frequencies above 2500 Hz is lower near the vehicle than at a distance of 5 m and thus diffraction attenuated the sound. Similar results were obtained from other sizes of pipes and in the minimum audible direction.

As described above, when you approach a hydrogen-leaking vehicle from a long distance, you should listen to the sound while walking around the vehicle and approach the vehicle from the maximum audible direction while standing upright. Furthermore, when you are near the vehicle, you should move away from the vehicle, listen to the sound while walking around the vehicle, and approach the vehicle from the maximum audible direction while standing upright.

2.3 Recording traffic noise

Traffic accidents occur most frequently at crossings in urban districts [8]. Therefore, we selected traffic noise recorded at a crossing of streets each having two lanes on one side in an urban district as background noise to be reproduced during "2.4.2 Listening tests on the alternative gas for hydrogen." Noise was measured and recorded for 10 min on the crossing pavement. The recorder was a D-50 made by SONY. The measured traffic noise is depicted in Fig. 16. Here, Leq represents the equivalent continuous sound level; L5, the 5% time rate noise level; L95, the 95% time rate noise level [9]; Lmax, the maximum noise level; and Lmin, the minimum noise level. Leq means time average of energy of noise level. During 10 minutes of recording, the noise level fluctuated between 65 and 85 dB and the equivalent noise level was 74 dB. Therefore, we decided to extract the time band of 74 dB from the recorded traffic noise and reproduce it as background noise.

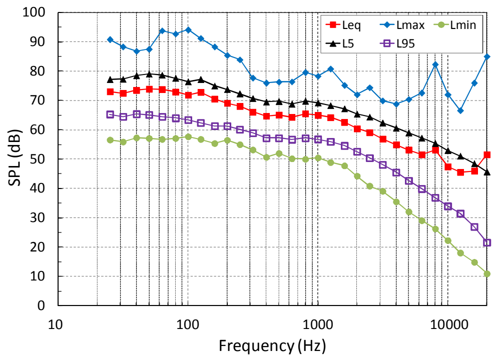

Fig. 16. Frequency analysis of 10 minutes on a highway

2.4 Reproduction of hydrogen leakage sound in a traffic-noise environment in an anechoic room

2.4.1 Verification of the relevance of helium

When hydrogen gas leaks from the vehicle, a single pipe is not the only sound source as in "2.1 selection of alternative gasses for hydrogen leakage sound." Sound is also generated when high-velocity leaking gas hits the lower part of the vehicle body and is heard when reflected from the ground. Therefore, when helium leaks from the lower part of the vehicle body, it is necessary to investigate how it differs from a hydrogen leak. To investigate to what extent the sound of helium leaking in an anechoic room reproduces the sound of hydrogen leaking, we subjected the hydrogen leakage sound from the vehicle as measured on an asphalt pavement surface (APS) to frequency analysis as well as the case in which helium leaks in the anechoic room (AR) and the background noise on the asphalt pavement surface is reproduced at the same time from speakers. Analyses were conducted by setting the flow rate converted to that of hydrogen to 118 NL/min, directions to the maximum and minimum audible directions, distance to 5 m from the vehicle, and height to 1.5 m. The analysis is depicted in Fig. 17, and the results, in Figs. 18 to 21. Two speakers were provided (Fig. 17). However, reproducing the same noise from two speakers simultaneously will cause interference.

Interference was therefore prevented by offsetting the time of reproduction between the left and right speakers.

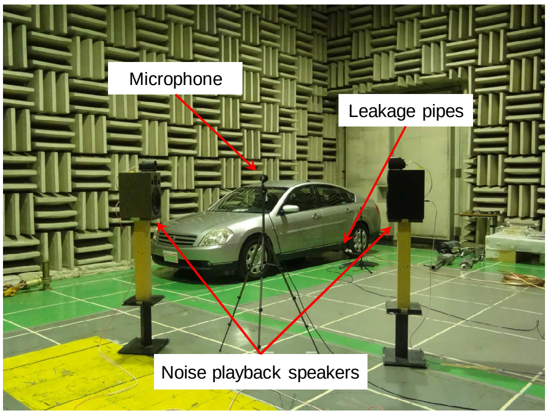

Fig. 17. Overview of listening experiment in the anechoic room

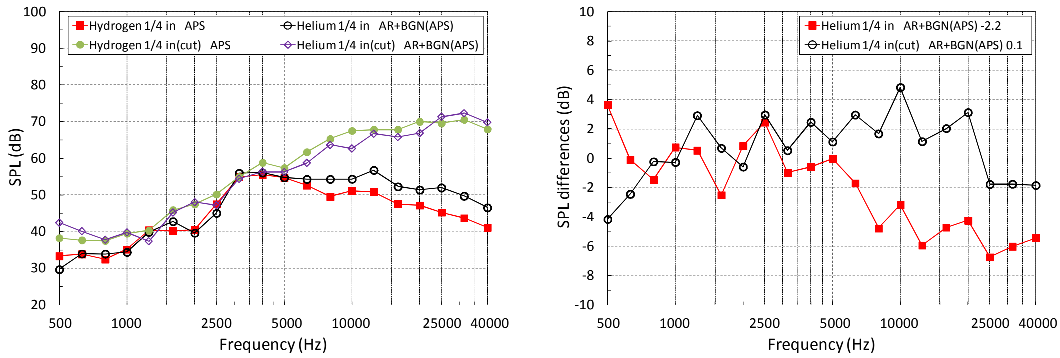

Fig. 18. Comparison of hydrogen (at APS) and helium (at AR with APS BGN) for 1/4 inch and 1/4 inch cut pipes at maximum audible direction

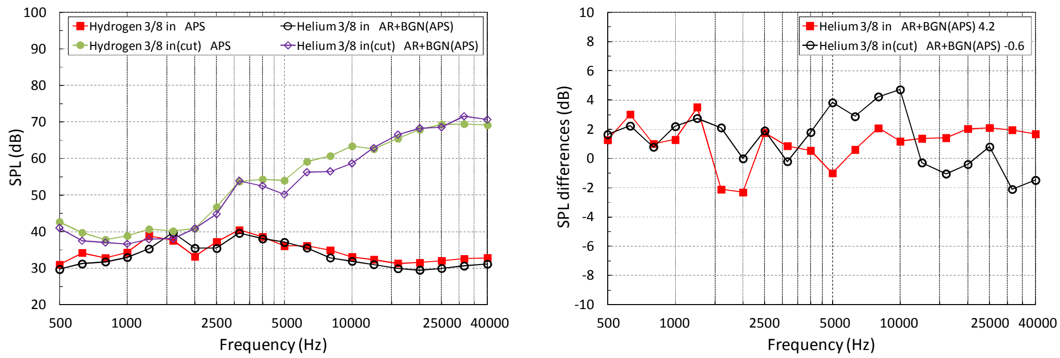

Fig. 19. Comparison of hydrogen (at APS) and helium (at AR with APS BGN) for 3/8 inch and 3/8 inch cut pipes at maximum audible direction

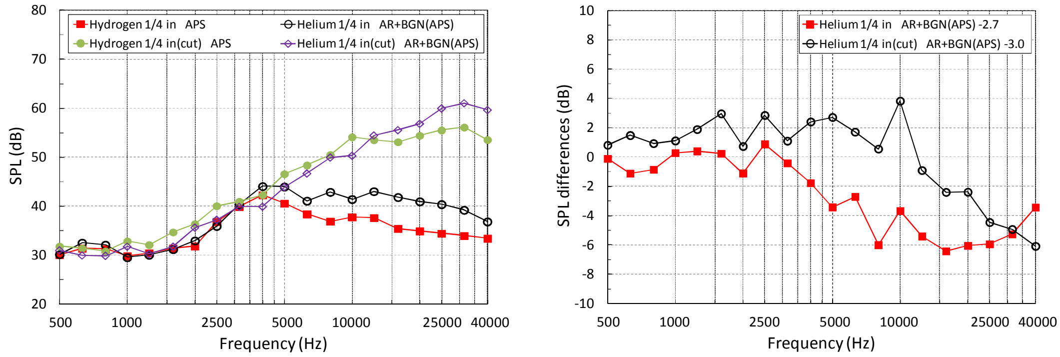

Fig. 20. Comparison of hydrogen (at APS) and helium (at AR with APS BGN) for 1/4 inch and 1/4 inch cut pipes at minimum audible direction

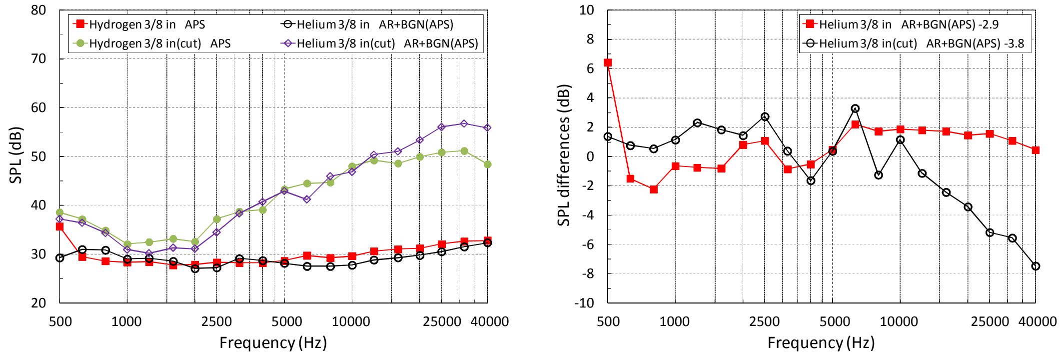

Fig. 21. Comparison of hydrogen (at APS) and helium (at AR with APS BGN) for 3/8 inch and 3/8 inch cut pipes at minimum audible direction

The above results indicate that the level difference between helium leakage sound and hydrogen leakage sound is 5 dB or more above 20 kHz in the minimum audible direction of cut pipes. According to IEC 61672-1, the maximum allowable uncertainty at each frequency in noise level is specified as 0.6 dB at 10 to 4 kHz, 0.7 dB at 4 to 10 kHz, and 1 dB at 10 to 20 kHz [9]. Furthermore, when overall sound level differences of several dB between hydrogen and helium are considered, hydrogen measurements are disturbed because they were made outdoors on an asphalt pavement surface, and the difference is 2 to 3 dB in the audible frequency range. It can then be considered that the helium leakage sound and hydrogen leakage sound in the maximum and minimum audible directions of pipes installed in the lower part of the vehicle are almost equal.

2.4.2 Listening tests on the alternative gas for hydrogen

The test subjects were three males aged around 30 years, and the flow rate at which two or more subjects could not perceive the leakage sound was defined as the discrimination flow rate. The listening test was conducted by leaking helium gas in an anechoic room while reproducing the background noise recorded in "2.3 Recording of traffic noises." The listening directions were set to the maximum and minimum audible directions of each pipe as decided from "2.2.1 Listening direction, distance, and height dependence of hydrogen leakage sound," the distance was set to 5 m and 10 m from the centre of the vehicle, and the listening area was set to the area with the central height of 1.5 m between two speakers to reproduce background noise (Fig. 17). To reproduce traffic noise, two different noises at an equivalent sound level of about 74 dB selected among from the recorded traffic noise were reproduced simultaneously from the left and right speakers to prevent sound interference. The results of the listening test are presented in Table 4. Relationships in expressions (1) to (4) were used here to calculate the hydrogen flow rate.

Table 4 Test results of audible threshold flow rate

Pipe	Audible direction	Distance (m)	Helium flow rate (NL/min)	Hydrogen corresponding flow rate (NL/min)
1/4 in (cut)	Maximum	5	28	33
		10	35	41
	Minimum	5	55	63
		10	65	75
3/8 in (cut)	Maximum	5	20	27
		10	35	46
	Minimum	5	55	73
		10	60	79
1/4 in	Maximum	5	40	46
		10	65	75
	Minimum	5	85	98
		10	100	115
3/8 in	Maximum	5	130	164
		10	180	227
	Minimum	5	200	253
		10	260	328

From Table 4, for a 3/8 in pipe, which has a leak diameter of 7.045 mm that assumes the worst case, the flow rate that enables recognition of hydrogen leakage sound at a distance of 10 m from the centre of the vehicle is 328 NL/min or over. Similarly, a hydrogen flow rate of 253 NL/min or over can be recognized at a distance of 5 m. For a cut pipe or a 1/4 pipe, which represents a leak diameter of 4.57 mm, hydrogen leakage sound can be perceived at a distance of 10 m from the centre of the vehicle if the flow rate is 115 NL/min or less, so it is less than the 118 NL/min defined as the maximum allowable leak volume in FCV gtr.

Even if 400 NL/min of hydrogen, which exceeds the maximum discrimination flow rate at a distance of 5 to 10 m, leaks at the center of the lower part of the vehicle and is ignited inside the bonnet, the sound pressure at a distance of 1 m from the front of the vehicle or the front wheel is at most on the level of causing ear pain [10]. Furthermore, the effect of ventilation in a sufficient volume to reduce the impact at the time of ignition is also examined [11].

3.0 SUMMARY

FCVs are designed so that hydrogen leakage from the tank is stopped automatically through detection of a hydrogen leak or detection of impact in a collision. However, we investigated the characteristics of hydrogen leakage sound from the hydrogen-leaking vehicle to examine a method of rescuing people safely by depending on the sense of hearing in the event of consecutive hydrogen leaks from the FCV. Furthermore, we also investigated the hydrogen flow rate as the threshold for discriminating hydrogen leakage sound under 74 dB from noise at a crossing of two lanes in an urban district. As a result, the following findings were obtained.

(1) In a traffic noise environment of about 74 dB, the hydrogen leak volume for the hydrogen leakage sound to be heard for the first time when approaching to a distance of 10 m from the centre of the hydrogen leaking vehicle is less than 328 NL/min for the 3/8 in pipe (7 mm bore), which assumes the worst case.

(2) Because the hydrogen leakage sound from the lower part of the vehicle has directivity depending on the pipe shape, it is better to recognize the sound in the maximum audible direction while walking around the vehicle. Furthermore, hydrogen leakage sound is height dependent and can be heard most easily at a height of 1.5 m.

(3) The hydrogen leakage sound from the lower part of the vehicle becomes harder to hear when you hear the sound far away from the vehicle, but it also becomes harder to hear due to diffraction when you approach too closely to the vehicle.

We are planning to obtain more credible data in the future by conducting tests on various forms of vehicles and various leak points and by increasing the number of subjects.

ACKNOWLEDGEMENT

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