ISSN 1347-4065

JAPANESE JOURNAL OF
APPLIED
PHYSICS

Available online at iopscience.org/jjap

Change of sound characteristics of yidaki (didgeridoo) coated with thick films of lacquer (Wajima-nuri)

Kiyoshi Yatsui, Hidehiko Asaoka, Yuta Yoshida and Takashi Yatsui

Reprinted from ***Japanese J. Appl. Phys.*** **59** (2020) 077002 (6pp)

JJAP

The Japan Society of Applied Physics | **IOP** Publishing

Japanese Journal of Applied Physics **59**, 077002 (2020)
https://doi.org/10.35848/1347-4065/ab9277

REGULAR PAPER

Change of sound characteristics of yidaki (didgeridoo) coated with thick films of lacquer (Wajima-nuri)

Kiyoshi Yatsui[1*], Hidehiko Asaoka[2], Yuta Yoshida[3], and Takashi Yatsui[4*]

[1]Tohka-doh, Yatsui Shikki Honten, 2-47-2 Kawai, Wajima, Ishikawa 928-0001, Japan
[2]Yidaki Japan, 4679 Myohga-hara, Yatsuo, Toyama, Toyama 939-2335, Japan
[3]Industrial Research Institute of Ishikawa, Kanazawa, Ishikawa 920-8203, Japan
[4]School of Electrical Engineering, School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan

*E-mail: kyatsui@jf6.so-net.ne.jp; yatsui@lux.t.u-tokyo.ac.jp

Received March 21, 2020; revised April 26, 2020; accepted May 12, 2020; published online June 12, 2020

Thick films of lacquers were coated by Wajima-nuri on a yidaki (didgeridoo), a woodwind instrument loved by indigenous Australians from ancient times. An investigation of frequency spectra of fast Fourier transform before and after the coating revealed a significant enhancement of sound pressure from the yidaki coated by Wajima-nuri, particularly in the low-frequency region of 500 Hz–1 kHz. All peaks of the sound pressures were shifted to higher frequencies by the Wajima-nuri. The improvement of sound characteristics was greater by Wajima-nuri both inside and outside the yidaki than by Wajima-nuri on the outside only. It might have been due to the fact that the lacquers soaked through the perforated holes and cracks inherent to the original yidaki. Urushiol in lacquers tends to solidify by oxidative polymerization, which resulted in a smooth surface that suppressed the turbulence of the air breathed. These results could be useful for other musical instruments. © 2020 The Japan Society of Applied Physics

1. Introduction

One of the authors (Kiyoshi Yatsui; KY) has been working to manufacture and sell various lacquerwares of Wajima-nuri.[1] Wajima-nuri developed in Wajima in Ishikawa, Japan, from more than about 450 years ago. The word "nuri" in Japanese means coating or preparation of films by lacquers. Nowadays, Wajima-nuri is famous worldwide for being robust and solid lacquerwares, as well as for the beauty of its decoration, made by sprinkling gold (makie) or inlaying gold in lacquerware engraved by knives (chinkin). The basic materials used for Wajima-nuri are normally wood, for example, zelkova, *Thujopsis dolabrata*, or Japanese cherry birch.

On July 20, 2011, an unknown person visited KY's shop, and asked him to coat films by lacquers on yidakis, woodwind instruments used for ceremonies by indigenous Australians from ancient times.[2,3] Yidakis have been used by Aborigine, particularly in Arnhem Land, in the Northern Territory of Australia. The name in English is didgeridoo. The original material is eucalyptus. Its inside is fully eaten by white ants. The yidaki has a cylindrical shape. When someone breathes into the yidaki, a low whistling sound emerges from the outlet at the bottom. Later, the visitor was found to be Hidehiko Asaoka (HA), a professional yidaki player. HA brought KY four yidakis.

From that meeting, the coating and processing of thick films by Wajima-nuri on the yidakis started in 2011.[4] The reason why KY was interested in the coating of films on yidakis was that he had worked on the coating of various kinds of thin films and nanosized powders by using intense pulsed ion-beam evaporation (ablation).[5,6]

It took more than half a year to finish the coating and processing of three yidakis. Many professional players of yidakis thus prepared by Wajima-nuri have reported to KY that surprisingly a significant improvement of sound characteristics can be observed after coating by Wajima-nuri. Furthermore, they have noted a frequency shift toward a higher-frequency range. To investigate such a drastic change of sound characteristics, thick films have been coated on a yidaki by Wajima-nuri from the acoustic point of view. From studies of frequency spectra before and after coating and processing by Wajima-nuri, we have observed significant changes of sound characteristics on the yidaki.

2. Shape and size of yidaki

Figure 1 shows a photograph of the yidaki. The shape was a cylinder 1245 mm long. The shape of the inlet was almost circular, and the size of the inlet was 39 mm (outer diameter) and 28 mm (inner diameter). The shape of the outlet was distorted, and the sizes were 61–67 mm (inner diameter) and 81–90 mm (outer diameter). The weight was 2.1 kg.

3. Coating of thick films on yidaki by Wajima-nuri

Basically, Wajima-nuri consists of 124 processes all together. However, it can be divided mainly into eight processes: wood crafting (ki-ji), base coating (shita-ji), polishing (ji-togi), middle coating (naka-nuri), middle polishing (naka-togi), wiping up (fuki-age), top coating (uwa-nuri), and final polishing (ro-iro).

Now, an original yidaki was given, which was just pasted with acrylic paint. Therefore, wood crafting (ki-ji) was not necessary, and the seven subsequent processes were selectively carried out: base coating (shita-ji), polishing (ji-togi), middle coating (naka-nuri), middle polishing (naka-togi), wiping up (fuki-age), top coating (uwa-nuri), and final polishing (ro-iro). These seven processes are briefly explained as follows.

Before the Wajima-nuri process, an initial sound test was carried out at the Industrial Research Institute of Ishikawa (IRII) in Kanazawa, which will be indicated by ① hereafter.

3.1. Base coating (shita-ji)

Basically, this process is the accumulated work of painting lacquers (urushi), drying, polishing, and smoothing the yidaki repeatedly. Without going into detail, the following work was carried out by hand for the yidaki: sharpening small cracks and knots by knives (kiri-hori) → pasting wooden powders with chopped lacquers (koku-so) → sinking raw lacquers (kiji-katame) → polishing by coarse paper to smooth (kiji-migaki) → reinforcing the outside surface by a 200 μm thick cheesecloth (nuno-kise) → sharpening overlapped cheesecloth to smooth (kisemono-kezuri) → painting slimming lacquers

© 2020 The Japan Society of Applied Physics

Fig. 1. (Color online) Photograph of the yidaki tested. This figure is reproduced from Ref. 4. Copyright © 2020 The Japan Society of Applied Physics.

(sohmi-tuke) → polishing by sandpaper (sohmi-migaki) → base coating of films by mixing raw lacquers with rice glue and diatomaceous earth (ji-no-ko) by use of spatula (ippenji-tuke) → sharpening the whole by a coarse grindstone (kara-togi) → second coating of films by spatula (nihenji-tuke) → sharpening by sandpaper (nihenji-togi) → and painting rust lacquers mixed with wet abrasive lacquers and raw lacquers (mesuri).

In the above process, two key technologies inherent to Wajima-nuri are involved. The first one is to use cheesecloth covered on the outer surface of the yidaki, called reinforcing cheesecloth (nuno-kise). In addition to robustness of the yidaki, a good soak of the lacquers can be achieved with the cloth attached onto the yidaki. The second is to use diatomaceous earth (kei-soh-do) mixed with rice glue and raw lacquers, called ji-no-ko. Here, the main component of the diatomaceous earth (kei-soh-do) is silicon dioxide. It has the unique characteristics of being porous, heat insulating, adsorbent, abrasive, and filtering, yielding a compact preparation mixed with rice glue and raw lacquers. Such a fundamental method was found 350 years ago and was developed in Wajima.

3.2. Polishing (ji-togi)

After drying by shita-ji, polishing was carried out by using a whetstone and waterproof sandpaper.

3.3. Middle coating (naka-nuri)

Middle coating was carried out by painting lacquers on the outer surface of the yidaki. The yidaki was then carried into a highly humid room to dry and solidify the lacquers.

3.4. Middle polishing (naka-togi)

Water sanding was carried out with the use of a blue whetstone.

3.5. Wiping up (fuki-age)

Smoothing was carried out on the yidaki by Suruga charcoal to remove fat content.

3.6. Top coating (uwa-nuri)

The outer surface of the yidaki was coated with the highest quality of lacquers (top coating A). So as to dry and solidify the lacquers, where the main component of liquid urushiol ($C_{21}H_{34}O_2$) changes to solid by oxidative polymerization, we needed a suitable temperature (22 °C–28 °C) and high humidity (70%–85%). For such a requirement, a big humid room called nushi-buro was prepared. It rotated once per 6 min to prevent dripping of the lacquers.

It should be noted here that dehydration of lacquers does not take place by mere drying, but by drying by humidity. The reasons why lacquers are so popular and have been developed particularly in Wajima are pointed to by the following four conditions: (1) plenty of lacquers are produced in Wajima, (2) a lot of zelkova and *T. dolabrata* have been obtained as the basic materials, (3) diatomaceous earth (ji-no-ko) was found 350 years ago, which promotes the hardness of lacquers if mixed with rice glue and raw lacquers, and (4) Wajima is highly humid throughout the year.

Here, the thickness of the lacquers painted can be estimated as follows: 40 μm by koku-so, 35 μm by base coating (ippen-ji), 20 μm by second coating (nihen-ji), 5 μm by rust lacquers (me-su-ri), and 40 μm by top coating A (uwa-nuri A), respectively.

After the painting of top coating A (uwa-nuri A), a second sound test was carried out, which will be indicated by ② hereafter.

The most difficult task for Wajima-nuri for the yidaki was to coat the inner surface. In addition to its length (1245 mm), the inner diameter was narrow, 28 mm only. Therefore, normal coating by hand could not be possible. In order to solve such a problem, a wooden square bar (500 mm long, 10 mm in diameter) was constructed. Around the wooden bar, tack cloth was wrapped (24 mm in diameter), over which lacquers were poured. Rotating both the bar and the yidaki, top coating of the lacquers was carried out on the inner surface of the yidaki. Refilling lacquers on the bar, the preparation of films on the inner surface was carried out repeatedly (top coating B). The central part of 200 mm length, however, could not be coated, because it was too narrow to rotate along with the bar. After

© 2020 The Japan Society of Applied Physics

Fig. 2. (Color online) Evaluation test of yidaki at anechoic chamber at IRII (the yidaki is being played by HA). This figure is reproduced from Ref. 4. Copyright © 2020 The Japan Society of Applied Physics.

top coating B, the yidaki was again placed inside the humid room (nushi-buro) to dry.

From the consumption of the lacquers used, the thickness of top coating B (uwa-nuri B) could be estimated to be not less than 70 μm—direct measurement was not possible due to the narrowness of the inside of the yidaki.

3.7. Final polishing (ro-iro)

The yidaki was painted with another kind of lacquer which did not include fat content. After drying, final polishing was carried out by charcoal. The yidaki was painted with raw lacquers, and polished with an abrasive (titanium powders) and oil.

The handiwork of Wajima-nuri was thus finished after more than half a year. A third sound test was carried out (hereafter indicated by ③).

4. Sound tests on the yidaki

As mentioned above, a sound test was carried out three times. The first test was done just before the coating (August 2, 2018). The results obtained by this sound test are indicated by ①.

The second test was carried out after top coating A on the outer surface (Nov. 13, 2018), the results of which are indicated by ②.

The third test was performed after top coating B on both the inner and outer surfaces of the yidaki (May 16, 2019). The results of these are indicated by ③.

All the sound tests were carried out at the IRII, located at Kanazawa City. The analysis and evaluation were done by a discrete frequency spectrum analysis, fast Fourier transform (FFT). Selected frequency spectra of the fundamental tone of the yidaki were investigated. Tests were carried out by using an FFT analyzer (Bruel & Kjaer, 3050-I-4/0), and a microphone (Bruel & Kjaer, 4189). The resolution of the frequency was less than 4 Hz.

Figure 2 shows a photograph of an evaluation test of the yidaki at an anechoic chamber at the IRII.

5. Frequency spectra

Figure 3 shows the superimposed overall frequency spectra of ①, ② and ③ in the whole frequency range of 50 Hz–10 kHz.[4] Since we used a high-pass filter with a

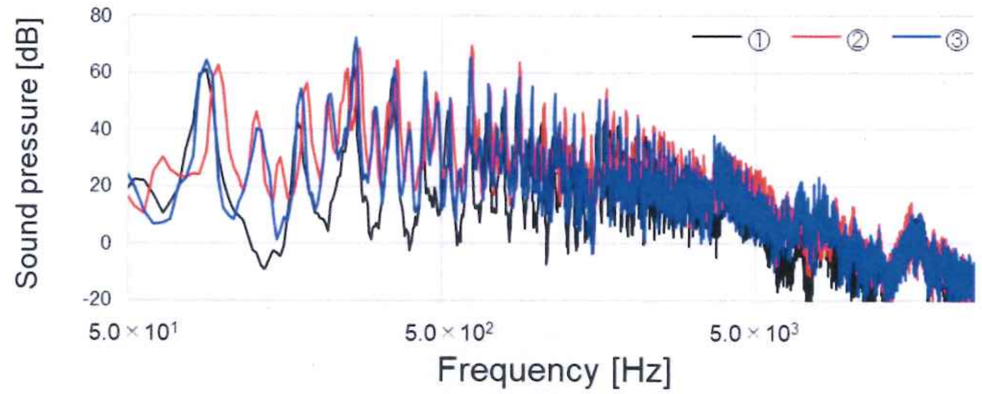

Fig. 3. (Color online) Comparison of the (superimposed) frequency spectra of ①, ② and ③ in the whole frequency range of 50 Hz–10 kHz.

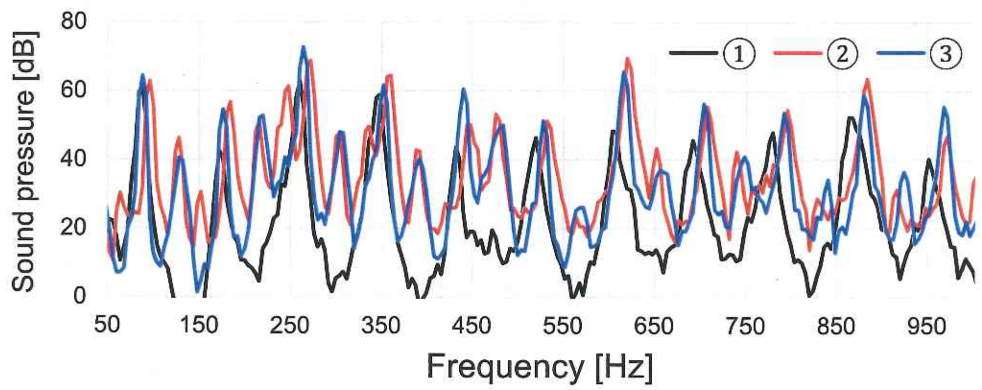

Fig. 4. (Color online) Comparison of the (superimposed) frequency spectra of ①, ②, and ③ in the low-frequency range of 50 Hz–1 kHz. This figure is reproduced from Ref. 4. Copyright © 2020 The Japan Society of Applied Physics.

© 2020 The Japan Society of Applied Physics

Table I. Changes of the peaks before and after coating by Wajima-nuri in the low-frequency range of 0–1 kHz. This table is reproduced from Ref. 4. Copyright © 2020 The Japan Society of Applied Physics.

Before Wajima-nuri			After Wajima-nuri		
Peaks	Frequency (Hz)	Sound pressure (dB)	Peaks	Frequency (Hz)	Sound pressure (dB)
①	172	42.57	②	176	56.82
			③	176	54.70
①	260	63.11	②	264	68.95
			③	264	72.78
①	348	58.87	②	352	64.58
			③	352	61.70
①	432	43.67	②	440	50.20
			③	440	60.57
①	520	46.36	②	524	46.36
			③	528	51.24
①	604	48.31	②	612	69.95
			③	616	65.59
①	692	45.68	②	700	55.49
			③	704	56.36
①	780	47.98	②	788	54.66
			③	792	53.70
①	952	40.19	②	964	46.98
			③	968	55.46

cut-off frequency of 22.4 Hz, we plotted spectra for more than 50 Hz. From Fig. 3, it is found that, in the whole frequency range, the sound pressure of ① was the lowest, and that the sound pressure was strongly enhanced by ② and ③.

In the following, other FFT data will be presented in narrower frequency ranges.

Figure 4 shows the superimposed frequency spectra of ①, ② and ③ in the frequency range of 50 Hz–1 kHz.[4] It can be seen that new peaks, which could not be observed for ①, appeared for ② and ③. In particular, very strong peaks around 120 Hz, 240 Hz, 304 Hz, 380 Hz, 392 Hz, and 484 Hz appeared for ② and ③, which could not be seen for ①. It is noted that the sound pressure in the low-frequency region was strongly enhanced, and that the spectrum for ③ was sharp compared with that for ② in the frequency range of 600–900 Hz. Furthermore, a peak at 144 Hz cannot be found for ①, appearing only for ② (see Table I).

Furthermore, it has been found by the coating that the peaks of sound pressure were shifted toward the higher-frequency range. In the low-frequency region, the peaks of both ② and ③ were located at the same frequency. In the high-frequency region, however, the peaks of ② and ③ began to separate, and the peaks of ③ were always higher than those of ②. Such changes are summarized in Table I. From Table I, it is evident that sound pressure was always enhanced significantly after coating by Wajima-nuri. In addition, the peaks of the sound were shifted toward higher frequencies. The percentage of the upper shift from ① was estimated as 1.2% for ②, and 1.7% for ③.

Figure 5 shows the superimposed frequency spectra of ①, ② and ③ in the midrange frequency of 1–2 kHz.[4] In this range, we see some components were enhanced for ② and ③, whereas they were very weak for ①. Specifically, the signals were strongly enhanced around 1052 Hz, 1056 Hz, 1140 Hz, 1144 Hz, 1242 Hz, 1320 Hz, 1400 Hz, 1488 Hz, 1584 Hz, 1664 Hz, 1672 Hz, 1752 Hz, 1848 Hz, and 1928 Hz (see Table II). In particular, it is noted that a significant enhancement appeared at 1584 Hz for ③.

Figure 6 shows the superimposed frequency spectra of ①, ②, and ③ in the high-frequency range of 3–10 kHz.[4] In the frequency ranges of 3.75–4.1 kHz, 4.6–4.9 kHz, 5.0–5.9 kHz, 6.0–6.7 kHz, 7.1–7.5 kHz, and 8.5–9.5 kHz, the sound pressures of ② and ③ were strongly enhanced as compared to those of ①.

Figure 7 shows the superimposed frequency spectra of ①, ②, and ③ in the high/ultrahigh-frequency range of 18–24 kHz. It is clear that the sound pressures of ② and ③ were strongly enhanced as compared to those of ① in the ranges of 19.0–19.2 kHz, 20.0–21.2 kHz, 21.8–22.2 kHz, 22.8–23.0 kHz, and 23.7–24.0 kHz. Furthermore, the bandwidth was extended up to a higher-frequency range.

6. Discussion

To study further the differences of the sound pressures of ①, ②, and ③, we investigated the characteristics in the high-frequency region.[4]

Figure 8 shows the superimposed frequency spectra of ①, ②, and ③ in the high-frequency range of 3.7–5.5 kHz. In this range, the component of ① was rapidly damped in the high-frequency region. The sound pressures of ② and ③, on the other hand, decayed gently toward the high-frequency region. Furthermore, the sound pressure of ② expanded more widely than that of ③. The sound pressure of ③ was stronger than that of ② in the low-frequency region, but tended to damp rapidly

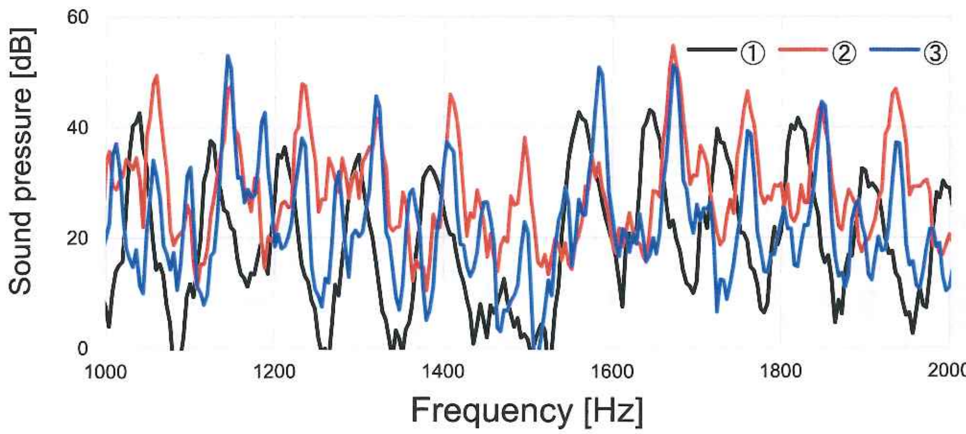

Fig. 5. (Color online) Comparison of the (superimposed) frequency spectra of ①, ②, and ③ in the midrange frequency of 1–2 kHz. This figure is reproduced from Ref. 4. Copyright © 2020 The Japan Society of Applied Physics.

© 2020 The Japan Society of Applied Physics

Table II. Peaks for ①, ②, and ③ in the midrange frequency of 1–2 kHz.

f [Hz]	p [dB]		f [Hz]	p [dB]		f [Hz]	p [dB]		f [Hz]	p [dB]	
1012	37.12	③	1256	34.43	②	1512	16.99	②	1752	46.51	②
1016	34.28	②	1272	34.43	②	1516	4.37	①	1760	39.30	③
1028	34.58	②	1276	31.95	③	1524	19.92	②	1792	21.83	①
1036	17.91	③	1296	21.39	③	1536	19.03	②	1792	29.80	②
1040	42.65	①	1300	35.03	①	1544	29.17	③	1804	25.32	③
1052	49.49	②	1312	41.71	②	1560	42.71	①	1816	29.49	②
1056	34.13	③	1320	45.65	③	1560	26.95	③	1820	41.60	①
1080	17.39	③	1344	3.24	①	1568	34.83	②	1840	44.56	②
1088	25.98	②	1344	28.28	②	1584	50.84	③	1848	44.60	③
1100	32.84	③	1364	28.76	③	1600	21.71	②	1872	28.67	②
1124	37.62	①	1380	24.22	②	1612	24.52	②	1892	26.85	③
1140	47.52	②	1384	32.82	①	1612	21.58	③	1896	32.49	①
1144	53.02	③	1400	45.93	②	1632	24.29	③	1916	20.12	③
1168	30.82	②	1404	37.33	③	1640	28.48	②	1928	46.96	②
1184	19.18	①	1432	28.59	②	1644	43.07	①	1936	37.21	③
1184	20.20	②	1444	7.97	①	1664	54.72	②	1964	11.07	①
1188	42.66	③	1452	26.40	③	1672	51.21	③	1964	30.48	②
1204	26.59	②	1472	12.51	①	1696	36.68	②	1980	21.53	③
1212	36.44	①	1472	27.52	②	1700	25.98	③	1992	30.24	①
1224	47.85	②	1488	38.14	②	1716	26.36	③	1992	20.56	②
1232	38.03	③	1496	22.84	③	1724	39.70	①			

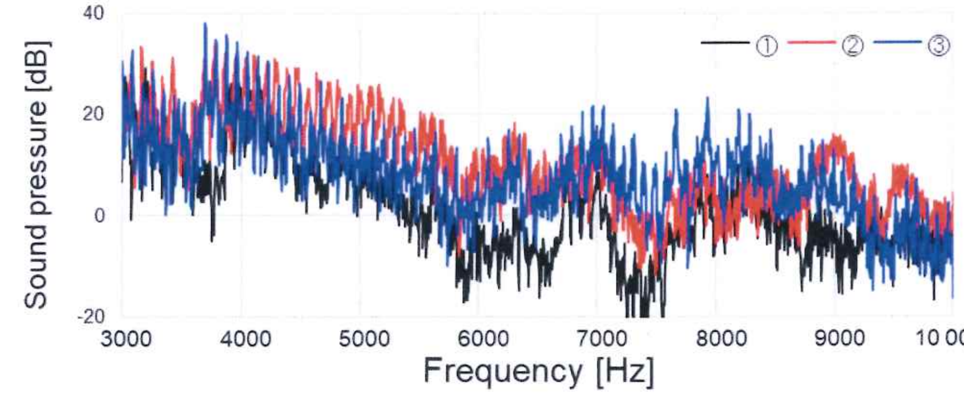

Fig. 6. (Color online) Comparison of the (superimposed) frequency spectra of ①, ②, and ③ in the high-frequency range of 3–10 kHz. This figure is reproduced from Ref. 4. Copyright © 2020 The Japan Society of Applied Physics.

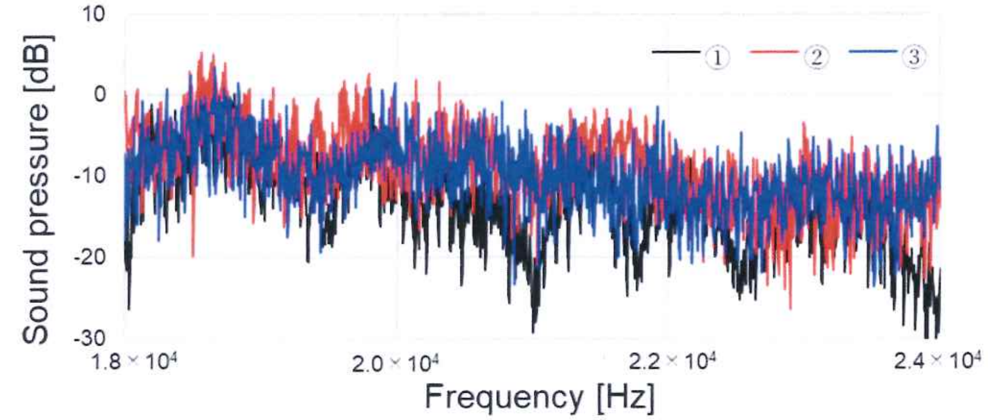

Fig. 7. (Color online) Comparison of the (superimposed) frequency spectra of ①, ② and ③ in the high/ultrahigh-frequency range of 18–24 kHz.

in the high-frequency region. In Fig. 8, envelopes of ② and ③ are shown for comparison, and fitting lines are also indicated.

Table III shows the parameters of the fitting lines in Fig. 8. The intercept of ② was clearly lower than that of ③. The bandwidth of ② was wider than that of ③, and expanded up to a higher frequency. In contrast, the intercept of ③ was higher than that of ②, the incline grew large, and damping occurred in the high-frequency region. The fitting line for ③ was close to a straight line, where the coefficient of determination was much closer to 1.

7. Concluding remarks

The sound characteristics of the yidaki were studied before and after it was coated with thick films of Wajima-nuri.

© 2020 The Japan Society of Applied Physics

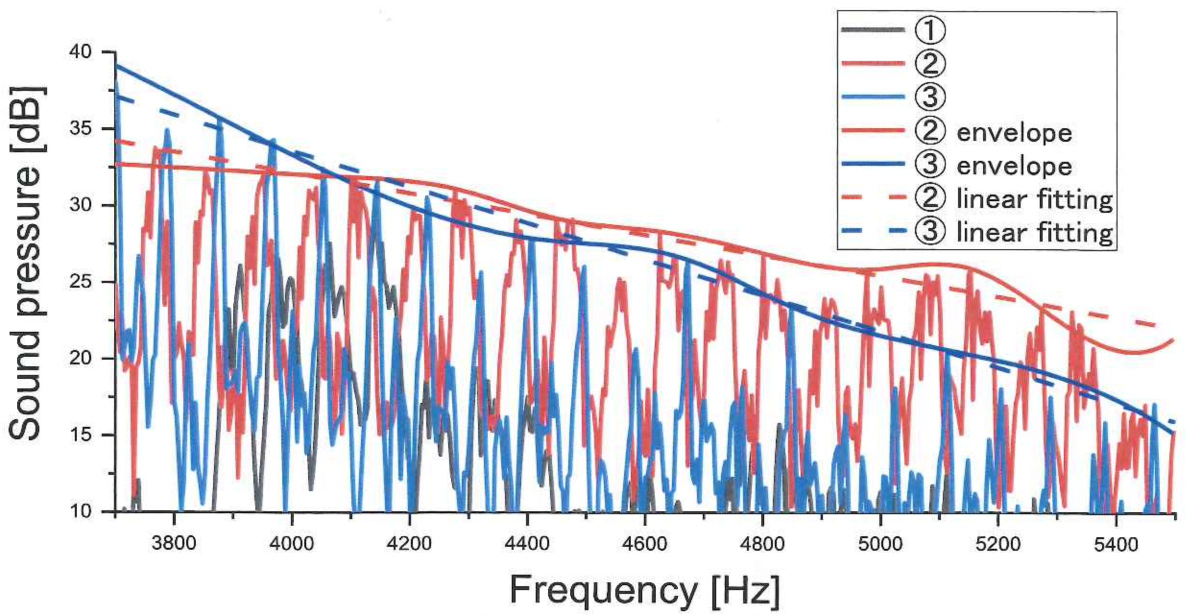

Fig. 8. (Color online) Comparison of the (superimposed) frequency spectra of ①, ② and ③ in the frequency range of 3.7–5.5 kHz. This figure is reproduced from Ref. 4. Copyright © 2020 The Japan Society of Applied Physics.

Table III. Fitting parameters in Fig. 8.

	Intercept		Slope		Statistics
	Value	Standard deviation	Value	Standard deviation	Coefficient of determination
② linear fitting (red broken line)	59.171	0.360	−0.006 74	7.78×10^{-5}	0.943 46
③ linear fitting (blue broken line)	80.662	0.329	−0.011 77	7.10×10^{-5}	0.983 88

Significant enhancement of sound pressure was achieved by the coating particularly in the low-frequency range of 500 Hz–1 kHz. The peaks of the sound pressures were shifted to higher frequencies by the coating. The shift was more remarkable for ③ than for ②. Sounds by ③ were strongly damped in the high-frequency region, yielding sharper sounds than those in ②. In summary, the yidaki by ③, where lacquers were coated not only outside, but also inside, gave the best sounds. It is expected that these results could be useful for other musical instruments.

When Wajima-nuri was initially developed, the main purpose could have been development for use as robust, durable, and practical thermal insulation. Later, a decorative aspect was added by sprinkling gold (makie) and inlaying gold in lacquerware engraved by knives (chinkin). Now, a new field of application has been opened up in musical sound.

Acknowledgments

This work was carried out with the collaboration of many craftsmen and craftswomen in Wajima. A lot of enthusiastic and devoted work was performed by Kazuhiko Miyakoshi (shita-ji), Sumie Tsunomura (ji-togi), Kazuaki Isogami (naka-nuri), Keijiro Hira (uwa-nuri), and Kenshuh Makisuna (ro-iro); without their support this work would never have been carried out. According to Hira, final coating B (uwa-nuri B) inside the yidaki was the most daunting task. Fukuko Yatsui, the manager of Tohka-doh, smoothly conducted the division of labor on the Wajima-nuri.

ORCID iDs

Kiyoshi Yatsui https://orcid.org/0000-0001-7664-6551
Takashi Yatsui https://orcid.org/0000-0001-7295-4514

1) For example, "Guidebook on Wajima Nuri," Wajima-nuri Industrial Office, Wajima City (2004).
2) N. Fletcher, Acoust. Aust. **24**, 11 (1996).
3) A. Tarnopolsky, N. Fletcher, L. Hollenberg, B. Lange, J. Smith, and J. Wolfe, Nature **436**, 39 (2005).
4) K. Yatsui, H. Asaoka, Y. Yoshida, and T. Yatsui, Oyo Buturi **89**, 109 (2020) [in Japanese].
5) Y. Shimotori, M. Yokoyama, S. Harada, K. Masugata, and K. Yatsui, Jpn. J. Appl. Phys. **28**, 468 (1989).
6) K. Yatsui and W. Jiang, Oyo Buturi **67**, 648 (1998) [in Japanese].

© 2020 The Japan Society of Applied Physics