Japanese Flutes and Their Musical Acoustic Peculiarities

Shigeru Yoshikawa

Abstract Representative Japanese bamboo flutes, the *shakuhachi*, *nohkan*, and *shinobue* are investigated from musical acoustic viewpoint. The end-blown longitudinal flute, shakuhachi has only five tone holes, and several cross fingerings causes pitch sharpening (called *intonation anomaly*) as well as characteristic timbre, particularly in the second and third registers. Also, acoustical differences between classical and modern shakuhachis are made clear. The nohkan has a special tube device, "throat" (called *nodo* in Japanese), which is inserted between the embouchure hole and the top tone hole to narrow the bore. This throat significantly upsets the expected octave relation between the first and second registers. The octave is enlarged for low-pitched fingerings, while it is strongly shrunk for high-pitched fingerings. The nohkan is compared with the piccolo concerning an interesting fingering with two extremely distant open tone holes. The upper tone hole functions as an octave hole. The shinobue has another special device, a membrane hole over which the inner skin of the bamboo node (called *chikushi* in Japanese) is glued. The membrane vibration driven by the bore resonance pressure produces brilliant and distinctive sounds due to the resulting high-frequency emphasis. These unique structural properties of Japanese flutes bring about their musical and acoustical peculiarities not usually observed in Western flutes.

1 Introduction

Traditional lip-driven brass instruments do not exist in Japan as well as in Asia in contrast with many brass instruments in the West. On the other hand, a variety of woodwind instruments made of bamboo have been played in Japan, Korea, and China. Particularly, there are flute-type instruments in wide varieties in Japan. Generally, they are called *fue* (as a suffix, *-bue*, e.g. *yokobue*, which is general term

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for transverse flutes) including the end-blown longitudinal bamboo flute, *shakuhachi*.

The objective of this chapter is to explore the musical acoustics of Japanese flutes (*fue*) while considering distinctive characteristics in Asian music. It will be demonstrated that structural peculiarities of Japanese flutes bring about their musical peculiarities. We should pay our attention onto the embouchure edge, mouth-hole geometry, finger-hole geometry, etc., which have deep relation with their sounds.

The origin of *fue* might be considered as *iwabue* (stone whistle). Typical stone whistles excavated from several remains in the *Johmon* period (around BC 3000) are made of natural stone with the Y-shaped open holes (stone shape and size are various, 10 cm × 6 cm in rough average). If the branched Y-shaped holes are closed/opened by fingers when it is blown from the bottom hole, very vivid, clear, and powerful tones (with nearly sinusoidal waveforms of pitches around C_7, D_7, and E_7) are generated [1, 2]. These iwabue tones seem to have created tonal sensations toward *fue* for the Japanese from the ancient to the modern.

In this chapter the *shakuhachi*, *nohkan*, and *shinobue* are considered from the viewpoint of musical acoustics. The roots of these flue instruments were imported from China in its classic period of *Tang* dynasty (618–690, 705–907) and in Japanese periods of *Asuka* (538–710) and *Nara* (710–794). However, these three instruments as well as others are completely changed to Japanese instruments based on their tonal sensations mentioned above. The shakuhachi was fue for the *komuso* (wandering monks) in the *Edo* period (1603–1867), the nohkan was fue for the *samurai* (faithful warriors) in the *Muromachi* period (1334–1573), and the shinobue was fue for the common people in the Edo period. Their tones have taken on unique characteristics born from their histories and relations with the society.

2 The Shakuhachi

According to Malm [3], “One of the easiest ways to approach the music of another culture is through its flute literature. There seems to be something in the tone of the flute that has a universal appeal. This catholic quality is amply illustrated by the example of the *shakuhachi*.”

2.1 Brief History

The shakuhachi was originally introduced to Japan from China in the Tang dynasty around 750. Since this ancient shakuhachi has been preserved in the *Shosoin* warehouse of the *Tohdaiji* temple, it is called the *Shosoin shakuhachi* (its musicological term is the *gagaku shakuhachi*). This shakuhachi, which had six tone holes to play a Chinese diatonic scale (e.g. D-E-Gb-G-A-B-D), was adapted to play a Japanese pentatonic scale (D-E-G-A-B-D) by removing the second (counted from the bottom) tone hole (Gb) around early 16th century. Moreover, the positions of five tone holes were modified to make effective use of pitch bending (e.g. Eb and A#) by the *meri/kari* blowing (by pulling down/up player's jaw) and by half-covering the tone hole(s) around the 17th century, and thus a scale pattern D-F-G-A-C-D was established when playing the shakuhachi with the standard length of *ichi* (one) *shaku* and *hachi* (eight) *sun* (54.5 cm) [4–6].

Since this shakuhachi (made from the root end of bamboo) was played exclusively by a group of wandering priests (called *komuso* having faith in *Fukeshu*, a sect of Buddism), it is called the *komuso* (or *Fuke*) *shakuhachi* and regarded as the origin of the modern shakuhachi [3, 5, 6]. The history of changes from the Shosoin shakuhachi to the komuso shakuhachi is very complicated and indefinite [3–5]. The former was probably played in court chamber music (*gagaku*); the latter was played in solo.

In 1871 (the 4th year of *Meiji*) Fukeshu was abolished from various reasons under the Meiji Restoration which executed strong national policy of the westernization. The Western-oriented music was eagerly promoted; the Japanese traditional music was coldly shunned. In this early Meiji period the shakuhachi became open to common people and was used in ensemble music with string instruments such as the *soh* (*koto*) and the *shamisen* (three-stringed instruments). In the late 20th century non-Japanese performers and makers of the shakuhachi appeared in the West as well as in Japan. Nowadays the International Shakuhachi Festival has been held every a few years. The shakuhachi is an international musical instrument with its contemporary vitality.

2.2 Unique Structural Properties

As properly pointed out by Malm [3], the characteristic properties of the shakuhachi are (1) the oblique blowing edge, (2) only five tone holes (four on the front and one on the back), and (3) the inner bore geometry from the edge to the root bottom. In this section acoustical effects of these properties will be demonstrated. Before that, unique these properties are to be explained in more detail.

Embouchure edge: Using his Fig. 23, Malm [3] described the evolution of the edge shape of the end-blown instruments as follows: The original pipe was merely blown across the top end just as children do a hollow bottle. The Chinese end-blown instrument *dungxiao* (in Japanese, *dohsho*), which has been considered as the origin of the shakuhachi, has the edge obliquely cut inward. However, the shakuhachi is unique in the way in which its embouchure is constructed [3]. It is cut outward, the exact opposite of the Chinese manner. This should be a Japanese innovation.

Two examples of the shakuhachi edge are shown in Fig. 1. A shallow edge with a short cut is depicted in Fig. 1a; a deep edge with a long cut in Fig. 1b. The edge shape and geometry are very essential to the players because the embouchure edge is the point joining the instrument and player. The starting transient of a tone largely depends on the embouchure edge. The shape of back side, on which player's lower lip is placed, is also important when the meri/kari blowing is applied. It is different from each other as shown in Fig. 1a, b.

The edge shape and geometry decisively determine the harmonic generation of the shakuhachi sound [7–9]. The blowing edge forms the source spectrum through the interaction with the air flow from the player. The source spectrum is then modified by the resonance characteristics of the bore and by the radiation characteristics of end openings at the embouchure and finger holes (or the bore end) as illustrated in Fig. 2. Of course, the conditions for sound production should have been satisfied [9]. If so, the air jet operates as a growing wave affected by the bore resonance [10]. Although the essential importance of the edge is well understood by

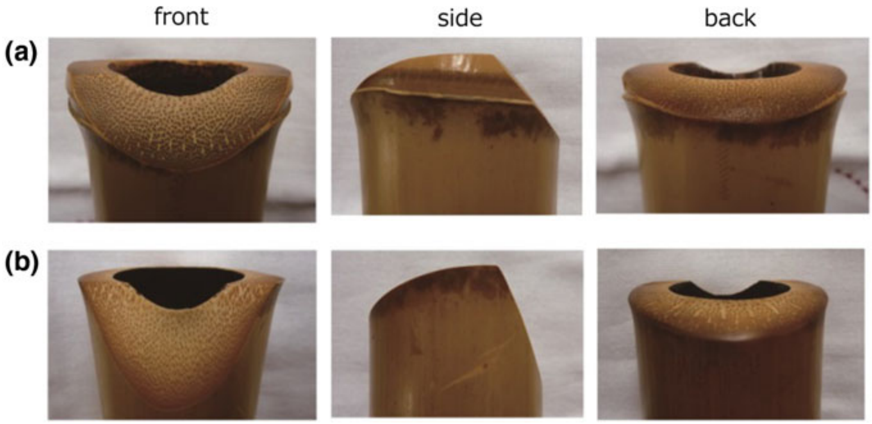


Fig. 1 Two examples of the shakuhachi embouchure edge. **a** A shallow edge with a short cut; **b** a deep edge with a long cut. Also, the construction of the back side is different between them

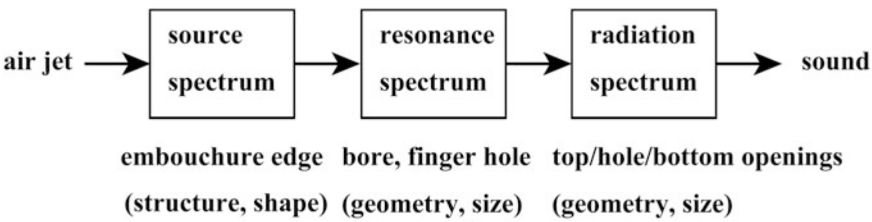


Fig. 2 Harmonic generation in the shakuhachi. The source spectrum formed by the interaction between the air jet and the edge is modified by resonance and radiation characteristics of the bore and finger holes

the player and the maker, scientific research on the flow acoustics around the real shakuhachi edge is still a future work [11].

Tone holes: In contrast with modern Western instruments with many tone holes (e.g. the clarinet, oboe, and flute has 24, 23, and 13 tone holes, respectively), the shakuhachi has only five tone holes traditionally. This means a decisive importance of cross (or fork) fingerings in the playing of it. A Japanese physicist, Torahiko Terada (1878–1935), first carried out an accurate measurement of its intonation [12]. He carefully measured pitch frequencies in the first and second registers for 32 fingerings, and directed attention to the octave balance.

If his intonation table is extensively examined, it is known that there are many cases where cross fingerings cause pitch sharpening instead of usual pitch flattening. Because the pitch sharpening due to cross fingerings is the reverse of conventional pitch flattening [9, 13–15], it may be called an *intonation anomaly* [16]. The acoustics of this intonation anomaly will be described later.

Inner bore: Yoshinori Ando (1928–2013) actively and accurately investigated the interrelation between the shakuhachi bore geometry and the resulting tones. He measured and calculated the input admittance of normal fingerings based on X-ray photography of the inner bore [17–20]. According to his research, there are four fundamental types of the bore geometry (the inner radius distribution along the bore) and major differences between classical (komuso) and modern shakuhachis.

Modern shakuhachis are often used in ensemble music and their exact tuning is required. As a result, diaphragms inside a bamboo pipe are completely removed, and then the inner pipe wall is shaved a little and pasted with a kind of clay consisting of polishing powder, *urushi* (Japanese lacquer), and water. The pasted surface in dried and solid condition is carefully polished up. This series of works may be called *ground-paste finish*. Also, the culm is divided between the third (counted from the bottom) and fourth tone holes in advance for the convenience of this ground-paste finish. Thus it has become easy to adjust the inner bore geometry, whose acoustical effects will be described later.

On the other hand, the original construction method of the shakuhachi had no ground-paste finish applied. The diaphragms were not completely removed and small ridges were retained on the inside nodes [21, 22]. These remaining portions of the diaphragms subtly affect the intonation and produce natural tones, which cannot be heard in modern ground-pasted shakuhachis. Most classical shakuhachis are *ground-paste free*.

It should be also noted that the bore is not divided and finger holes are undercut in classical shakuhachis. The length of the shakuhachi varies, although the standard length is 54.5 cm (pitched in D_4) as mentioned above. Recently, a ground-paste-free shakuhachi longer than *two-shaku and five-sun* (75.8 cm, ${A^b}_3$) has been preferred for personal deeper introspection.

2.3 Sound Examples

A few sound examples from a ground-paste-free shakuhachi [length: two-shaku and three-sun (69.5 cm); top bore diameter: 28 mm; bottom bore diameter: 23 mm; pitch: $B^b{}_3$] are shown in Fig. 3. This shakuhachi was made by Johzan Iso who made the one whose bore geometry was depicted in Fig. 4b. Its bore geometry is similar to Fig. 4b except for wider and smoother finish near the bottom. Also, its total view and the edge structure are given in Fig. 1.6 of Ref. [22] and Fig. 1a, respectively. All of these sound examples are played in the first register by the

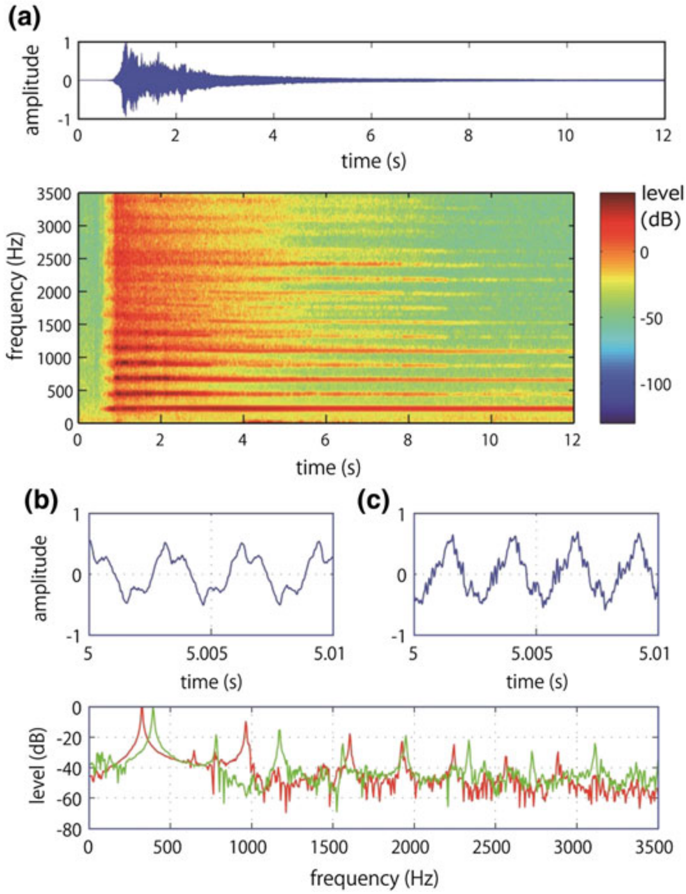


Fig. 3 Tone examples of the two-shaku three sun shakuhachi. **a** *Ro* (all tone holes closed) blown with *muraiki* during the starting four seconds; **b** *Wu* (the first and third tone holes opened half) with *meri* blowing; **c** *Ri* (the third and fourth tone holes opened) with normal blowing. The corresponding spectrum of the *Wu* and *Ri* tones is shown in the bottom frame by the *red* and *green lines*, respectively

author. Fingerings of (a) all holes closed, (b) the first and third holes opened half, and (c) the third and fourth holes opened completely are used in Figs. 3a–c, respectively.

Generally called *muraiki* (a rough and strong blow) is applied to the all-hole-closed fingering (called *ro*) during about four seconds from the starting transient in Fig. 3a. The spectrogram of the lower frame indicates the temporal change of the relative strength (in dB) of tonal components by color. The fundamental frequency varies from 224 Hz at the transient to 219 Hz of *pianissimo* playing near 10 s, and the pitch is closer to A_3 rather than $B^b{}_3$. This is due to a thick bore and the player's blowing way. The muraiki brings about very strong harmonics (from the second to the fifth) and a few inharmonic spectra above the seventh harmonic. Also, strong wind noise is involved from above 1.3 kHz to about 2.7 kHz. After the blowing becomes normal, even harmonics are very weak and odd harmonics (the fundamental, the third, and the fifth) are predominant. The harmonic structure with stronger odd harmonics is a distinguished character of the classical ground-paste-free (komuso) shakuhachi [17, 20].

The *meri* (or down) blowing given by pulling down the jaw is applied to the fingering *wu* (the first and third tone holes are half opened) in Fig. 3b. The fundamental frequency of a steady tone is 319 Hz, and the pitch is close to $E^b{}_4$. As shown in the spectrum diagram of the lower frame, this tone (drawn by the red line) almost lacks the second and fourth harmonics. The normal blowing is applied to the fingering *ri* (the third and fourth tone holes are opened) in Fig. 3c. The fundamental frequency of a steady tone is 389 Hz, and the pitch is close to G_4. This tone (drawn by the green line in the spectrum diagram) contains rich harmonics, while the third and fifth harmonics are slightly predominant. Tone *wu* brings a blue, melancholic feeling; tone *ri* a cheerful, fine feeling.

2.4 Acoustical Differences Between Classical and Modern Shakuhachis

Ando [19] investigated bore geometries and dimensions of about 70 shakuhachis and classified them into four types. Furthermore, he intensively measured and calculated input admittances (i.e., resonance characteristics) of six shakuhachis typical of four types [17, 18]. Essential results of his research are summarized below.

Bore shape patterns observed in modern and classical shakuhachis are depicted in Fig. 4a, b, respectively. These were classified as "type 1" and "type 4" by Ando [17, 18], respectively. The "type 2" is a significant enlargement near the bottom of "type 1"; the "type 3" seems to be a relaxation of "type 4" around the bamboo nodes. Major differences between Figs. 4a, b are (1) small/large bore diameter, (2) convergent/divergent bore from the embouchure (the 1st node) to the 2nd node (located near 190 mm from the edge), and (3) without/with abrupt changes at the

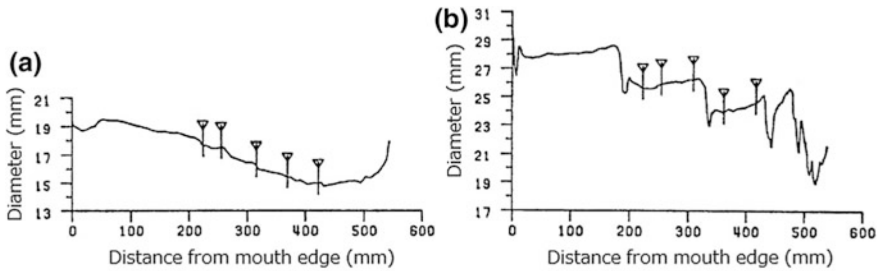


Fig. 4 Inner bore shape patterns of a modern shakuhachi (**a**) and a classical (*komuso*) shakuhachi (**b**) [17, 19]. Also, five tone-hole positions are indicated by the *vertical line*

nodes. Roughly speaking, modern shakuhachi of "type 1" has continuous convergent bore like the recorder and the baroque flute except for the portion near the bottom, while classical shakuhachi of "type 4" has an distinctive bore shape consisting of a few cylindrical pipes with stepwise decrease in diameter. Some important comments are given by Simura [21] from his long research experience.

The calculated input admittances of these modern and classical shakuhachis are shown in Fig. 5, respectively. Cases of two common fingerings *chi* (the first to third tone holes are open; A_4) and *ri* (the third and fourth tone holes are open; C_5) are exemplified, although Ando [17] calculated for six basic fingerings. The bore shape

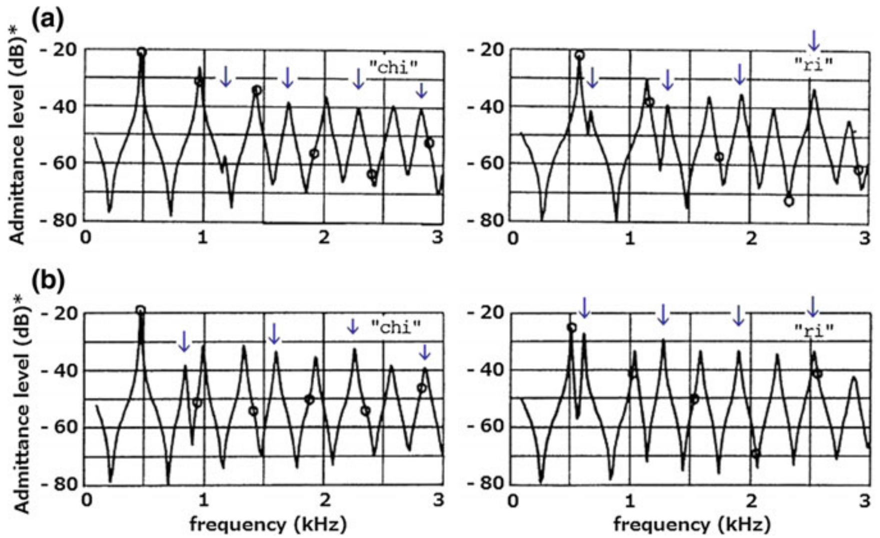


Fig. 5 The calculated input admittances of a modern shakuhachi (**a**) and a classical shakuhachi (**b**) [17]. Fingerings are basic ones, *chi* and *ri*. The symbol *open circle* indicates the harmonics of the fundamental frequency that is given by the first admittance peak. The *vertical arrows* suggest the upper-bore intermediate modes or the lower-bore modes. The symbol *asterisk* attached to "Admittance level" indicates the level relative to 1 SI unit (1 m^2 s/kg)

was approximated by many cylindrical segments in order to apply the transmission line theory [18, 23] and the lumped T circuit representations of the open/closed tone holes [18, 24, 25]. The numbers of cylindrical segments, which were determined based on the criteria of the calculation precision [18], were 67 and 168 of the above modern and classical shakuhachis, respectively [17].

The input admittance curves of Fig. 5 are rather complicated. This is probably due to the contribution of the lower bore below the top open tone hole (cf. next subsection). Although Ando [17, 18] suggested such a contribution, the present author would like to add more suggestive comments below based on the research of cross fingerings in the shakuhachi [16].

The fundamental frequency of basic fingerings is given by the first peak of the input admittance curve [17]. Harmonics are indicated by the symbol ○ marked on the curve in Fig. 5. As shown in Fig. 5a, the second and third harmonics of fingering *chi* are located near the tops of the second and third peaks, though the fourth, fifth, and sixth harmonics deviate from the curve peaks. It should be noted that another series of peaks appears between the peaks that give harmonics as indicated by the vertical arrow. These peak frequencies might be caused by the resonance of the intermediate mode of the upper bore (i.e. the pipe above the top open tone hole) (cf. f_{34} in Fig. 10a) or by the resonance of the lower bore (i.e. the pipe below the top open tone hole) (cf. f'_{2-} in Fig. 10a). It is confirmed that Fig. 5a agrees with Fig. 10a very well.

The third tone hole is the top open tone hole in the case of normal fingering *chi*. The length of the upper and lower bores is about 320 and 220 mm, respectively. Because the end corrections at the embouchure and the open top tone hole (roughly estimated as 30 mm in total) should be added, the fundamental frequency is calculated as 345,000/(350 × 2) = 493 Hz. Because the lower bore seems to generate no radiation, the end correction should be negligible, then its fundamental frequency is calculated as 345,000/(220 × 2) = 784 Hz if the first and second tone holes operate as the closed ones. Although this frequency is not observed in Fig. 5a, it might be observed in Fig. 5b. The difference between two figures around 1 kHz might suggest the difference in the acoustic coupling between the upper and lower bores occurring at the third open tone hole. Particularly, Fig. 5b on fingering *chi* suggests that the mutual repelling might be occurred between the second mode of the upper bore and the first mode of the lower bore because of the raised frequency of the second mode of the upper bore in comparison with Fig. 5a. However, a very small peak near 1.2 kHz in Fig. 5a should be the lower second mode of the lower bore (see f'_{2-} in Fig. 10a).

Such a modal repelling may be seen between the first modes of the upper and lower bores in Fig. 5b on fingering *ri* whose top open tone hole is the forth. The length of the upper and lower bores is 260 and 280 mm, respectively. Assuming the end corrections, the fundamental frequencies are 345,000/(290 × 2) = 594 Hz and 345,000/(280 × 2) = 616 Hz, respectively. The fundamental frequency of the classical shakuhachi might be reduced a little by the modal repelling. Since fingering *ri* gives tone holes closed below the third one, the effect of the lower bore on the admittance curve is more significant.

The admittance curve of the shakuhachi (exactly its upper bore) is apparently *inharmonic* due to (1) the bore-shape perturbation and (2) frequency characteristics of energy dissipation along the wall boundary and energy radiation from the open ends. This inharmonic series of the peaks determines the harmonic content of the tone generated if the effect of acoustic inertance lumped at the embouchure end can be considered properly [8, 17, 26].

According to Ando [20, 27], a significant tonal difference between modern and classical shakuhachis can be expressed as $L_e - L_o$, where L_e denotes the averaged level of even (2nd, 4th, and 6th) harmonics and L_o the averaged level of odd (3rd, 5th, and 7th) harmonics. For basic six fingerings, the classical shakuhachi indicates the dominance of odd harmonics and gives around null $L_e - L_o$ values, while the modern shakuhachi indicates the dominance of even harmonics and gives apparently positive $L_e - L_o$ values. Sound examples *ro* (after 8 s) and *ri* shown in Fig. 3a, c give an apparently negative $L_e - L_o$ value and a slightly negative $L_e - L_o$ value, respectively. The down blowing strongly emphasizes this tendency by almost removing even harmonics as shown in Fig. 3b for the cross fingering *wu*. Moreover he [20] demonstrated that the difference in the $L_e - L_o$ value substantially depends on the bore shape from the embouchure end to a point 110 mm down. A generally decreasing diameter (a convergent bore) as shown in Fig. 4a yields apparently positive $L_e - L_o$ values; a generally increasing diameter (a divergent bore) as shown in Fig. 4b yields around null $L_e - L_o$ values.

The effects of small ridges remaining on the inside nodes upon shakuhachi tones is a very interesting topic [12]. However, it is rather difficult to separate them from the effects of overall bore shape. The effects of small ridges, which can be estimated by Rayleigh's perturbation theory [9, 28], seems to be insignificant compared with the effects of overall bore shape (cf. Fig. 4b). Anyway, this problem should be solved in the near future.

2.5 Intonation Anomaly Due to Cross Fingerings

A decisive importance of cross fingerings in the playing of the shakuhachi is easily understood from its only five tone holes. As briefly mentioned in Sect. 2.2, cross fingerings often cause pitch sharpening instead of usual pitch flattening. This *intonation anomaly* due to cross fingerings, which is observed in the recorder and Baroque flute too, usually appears in the second register. The acoustics of the intonation anomaly [16] is described below.

Terada [12] investigated tonal octave balance on 32 fingerings including 26 cross fingerings, and Yoshikawa and Kajiwara [16] intensively studied 7 fingerings including 5 cross fingerings on the basis of the pressure standing wave along the bore and the input admittance. It is important to identify and discriminate the input-admittance spectra between the upper and lower bores from the standing-wave patterns. In this subsection, the results on three fingerings (*chi*, *wu*, and *wu3*) whose top open tone-hole is the third one (see Fig. 6) are illustrated. Also,

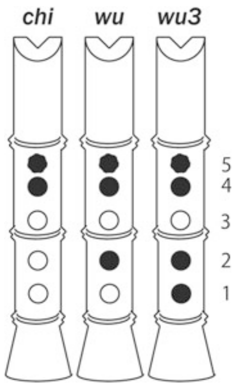


Fig. 6 Three fingerings of the shakuhachi treated in this section

the bore shape of a standard shakuhachi used for the experiment and numerical calculation is depicted in Fig. 7.

At first, the playing experiment is effective. The playing frequencies of each fingering are easily measured. In the first register three fingerings (*chi*, *wu*, and *wu3*) gave 444 Hz (A_4), 433 Hz ($A^b{}_4$), and 426 Hz ($A^b{}_4$), respectively (room temperature was about 23 °C). In the second register the three fingerings gave 898 Hz (A_5), 853 Hz ($A^b{}_5$), and <u>920 Hz ($A^\#{}_5$)</u>, respectively. Furthermore, in the third register the three fingerings gave 1322 Hz (E_6), <u>1475 Hz ($G^b{}_6$)</u>, and <u>1472 Hz ($G^b{}_6$)</u> [plus 1273 Hz ($E^b{}_6$)], respectively [16]. The underlined frequencies denote intonation anomalies. Other examples from different fingerings are shown in Ref. [16].

Secondly, the external blowing experiment is effective, too. The measurement of the internal pressure distributions (standing-wave patterns) can be carried out by moving a probe microphone (Brüel and Kjær type 4182) with a long probe tube (e.g. 570 mm in length and 1.25 mm in inner diameter) when the external drive is successfully done by using an exponential horn attached in front of the loudspeaker diaphragm (see Fig. 8). Resonance frequencies of a fingering are measured prior to

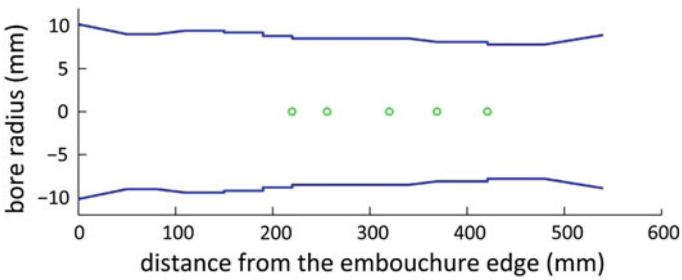


Fig. 7 Bore geometry of a modern shakuhachi treated in this section. The tone-hole positions are also indicated by the *circle*. The bore is approximated by ten cylindrical, two divergent conical, and two convergent conical tubes for numerical calculation

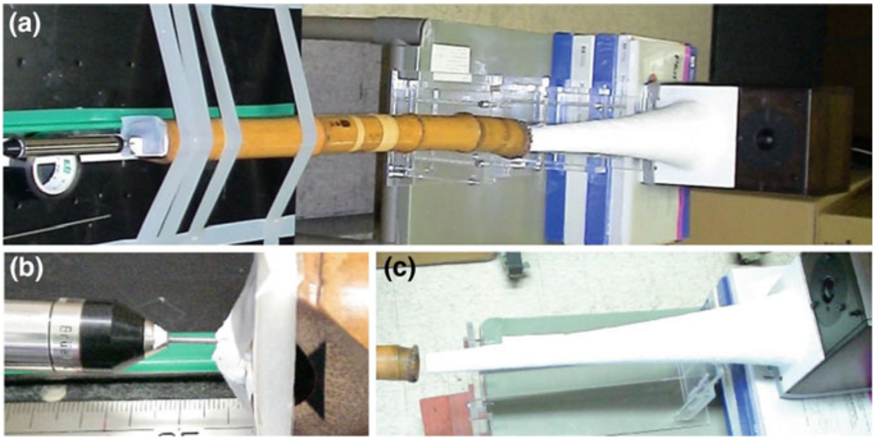


Fig. 8 Setup of the blowing experiment for measuring the pressure standing waves along the air column of the shakuhachi. **a** Total view; **b** close-up of a probe microphone and the embouchure; **c** close-up of the shakuhachi bottom and an exponential horn whose shape was designed to have the cutoff frequency at about 200 Hz

the standing-wave measurement. The details of measurement method and result are given in Ref. [16].

Thirdly, the calculation of the input admittance is also very effective as mentioned in Sect. 2.4. The conventional transmission matrix (T-matrix) method has been applied to the bores of woodwinds [17, 18, 23] and brasses [29–31]. Also, see the fifth chapter on the "acoustical modeling of mutes for brass instruments" involved in this book for the T-matrix formulation. On the other hand, the tone or finger hole is not simple as the bore, and we have a long and extensive history on acoustical tone-hole research [9, 14, 24, 25, 32, 33]. In this section and Ref. [16] new results given by Lefebvre and Scavone [33] are applied to the input-impedance calculation. The tone-hole position is indicated in Fig. 7, the tone-hole diameter is about 10 mm, and the tone-hole length is about 7.5 mm [16]. Moreover, the calculation of the internal pressure distribution along the bore can be carried out on the basis of the T-matrix formulation with the tone-hole matrix representation. This internal pressure calculation was first explicitly formulated by Ebihara and Yoshikawa [31] on brass instruments.

The results of the external driving experiment and the numerical calculation based on the T-matrix method are shown in Fig. 9. Fingerings *chi*, *wu*, and *wu3* are used. Note that the calculation is done at the same frequency as the measured one by adjusting the embouchure end correction except for f_4 (1903 Hz) and f_4 (1880 Hz) in Figs. 9a, c, respectively. The upper-bore modes are illustrated, where the upper-bore mode is usually defined as the standing wave indicating larger amplitude in the upper bore and satisfying the resonance conditions (the pressure minima) at both ends of the upper bore above the third tone hole. Also, $f_n \approx nf_1$ for

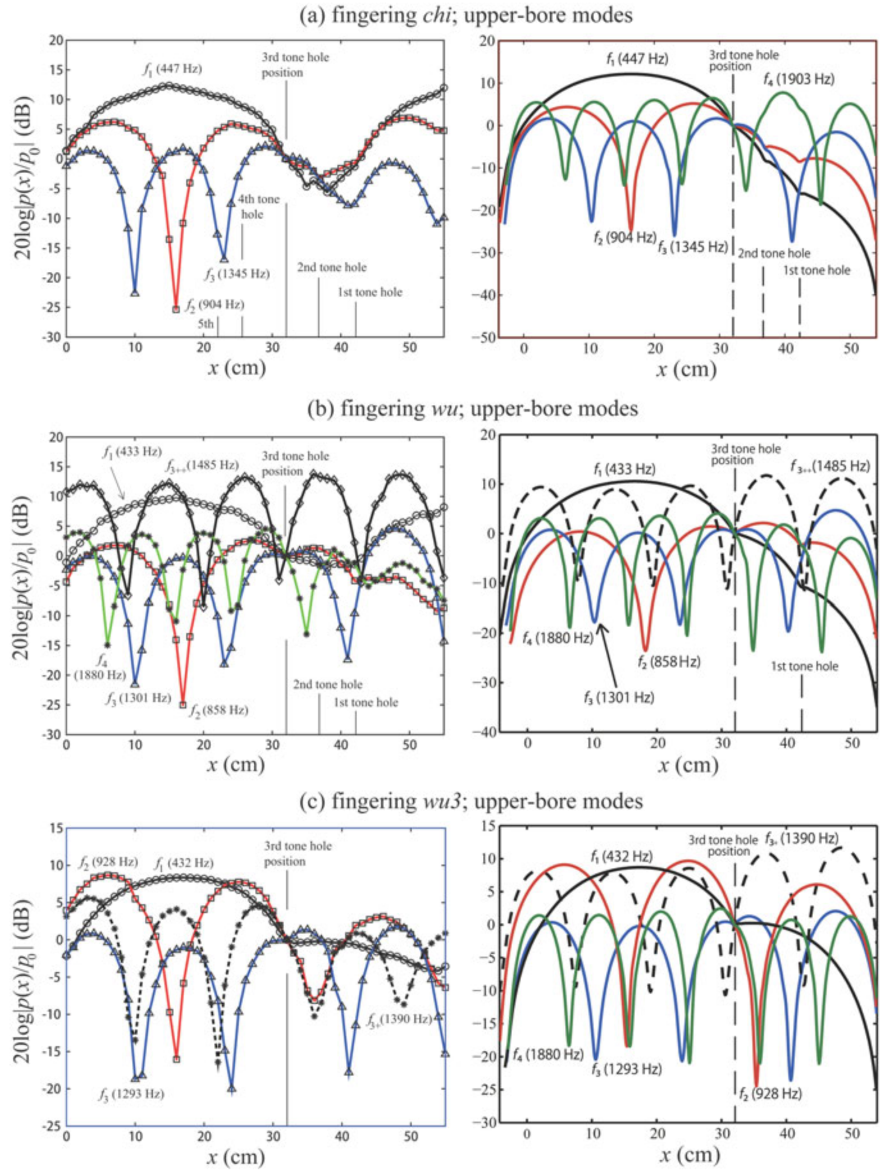


Fig. 9 Results of the measurement (*left column*) and numerical calculation (*right column*) on the internal standing-wave patterns [16, 34]. The distributions of the upper-bore modes are depicted. **a** Normal fingering *chi* (the first to third tone holes are open); **b** cross fingering *wu* (the first and third tone holes are open); **c** cross fingering *wu3* (only the third tone hole is open). Note that the acoustic pressure $p(x)$ is normalized by the pressure p_0 at the third tone hole

the mode order $n = 1, 2, 3$, and 4. Subscripts such as "+" and "++" are used to discriminate multiple modes in the same mode, such as f_3 and f_{3+} ($f_{3+} > f_3$).

However, there are a few exceptions: (1) the f_{3++} mode (1485 Hz) in fingering *wu*, (2) the f_3 mode (1293 Hz) in fingering *wu3*, and (3) the f_{3+} (1390 Hz) in fingering *wu3*. The first two modes do not satisfy the resonance condition at the open third tone hole, but they satisfy the resonance condition at the bore bottom. Therefore, they should be regarded as the *whole-bore mode* instead of the upper-bore or lower-bore mode. It should be noted that these two modes are actually played as tones with frequencies 1475 Hz (G^b_6) and 1273 Hz (E^b_6) respectively as mentioned above. Although the third one f_{3+} (1390 Hz) satisfies the resonance condition at the open third tone hole in the blowing experiment, it does not satisfy the resonance condition at the bore bottom. It seems that such a mode can be measured due to the external drive near the bore bottom. On the other hand, numerical calculation indicates that this f_{3+} (1390 Hz) violates the resonance condition at the third tone hole if it is considered as the upper-bore mode. However, if it is considered as the lower-bore mode, it satisfies the resonance conditions both at the bore bottom and the third tone hole. Only this f_{3+} (1390 Hz) mode brings about the major discrepancy between the experiment and the calculation. Except this mode and the distributions along the lower bore, the agreement between the experimental and calculated results shown in Fig. 9 is very high.

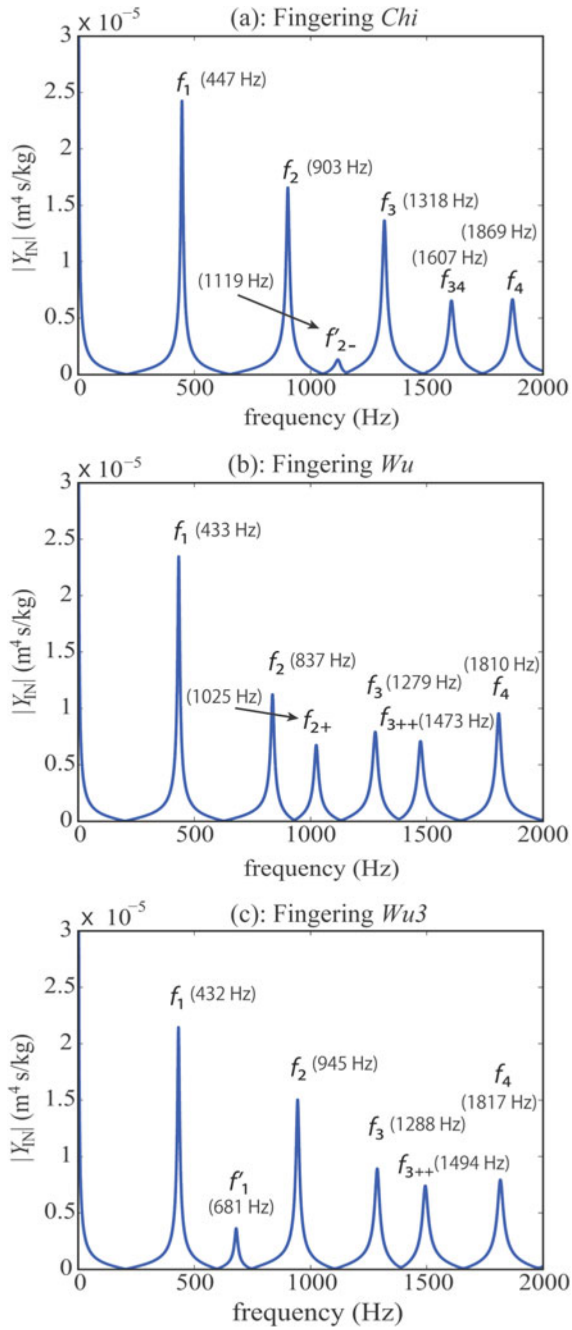
The calculated result of the input admittance $|Y_{IN}|$ is given in Fig. 10. It should be noted that small peaks f'_{2-} and f'_1 appear in Figs. 10a, c, respectively. These two peaks with the prime possibly indicate the lower-bore modes. Because the third tone hole is located at 220 mm from the bore bottom, the upper-bore physical length is 320 mm. Then, the first mode of the upper and lower bores is given as f_1 (432 Hz) and f'_1 (681 Hz), respectively (see Fig. 10c). Since the f'_{2-} seems to be quite lower than the assumed second mode of the lower bore, subscript "−" is added in Fig. 10a.

Although the f_2 (837 Hz) in cross fingering *wu* is lower than the f_2 (903 Hz) in normal fingering *chi*, the f_2 (945 Hz) in cross fingering *wu3* is appreciably higher than that in normal fingering. Thus the f_2 (945 Hz) indicates the intonation anomaly. Also, the f_{3++} (1473 Hz) and f_{3++} (1494 Hz) in Figs. 10b, c may be regarded as the intonation anomaly compared with f_3 (1318 Hz) in Fig. 10a.

In order to demonstrate the intonation anomaly in clearer fashion, the calculated standing-wave patterns for three fingerings in Fig. 9 are re-drawn for the respective mode in Fig. 11 [16, 34]. Figure 11a is on the first mode, where the pressure along the lower bore below the open third tone hole becomes higher as the second and first tone holes are closed in succession in fingering *wu* and *wu3*. Also, a weak kink of the pressure amplitude, which indicates the phase change due to the partial reflection, is seen at the open tone hole. These patterns well illustrate the typical (or conventional) effect of cross fingerings, which yields the descent of the resonance frequency.

On the other hand, cross fingering *wu3* produces a very deep trough near the closed second tone hole, as shown in Fig. 11b for the second mode. Also, the kink at the open third tone hole is inappreciable for this second mode. As a result, the

Fig. 10 The calculated absolute value of the input admittance $|Y_{IN}|$ for three fingerings [16]. **a** Normal fingering *chi*; **b** cross fingering *wu*; **c** cross fingering *wu3*



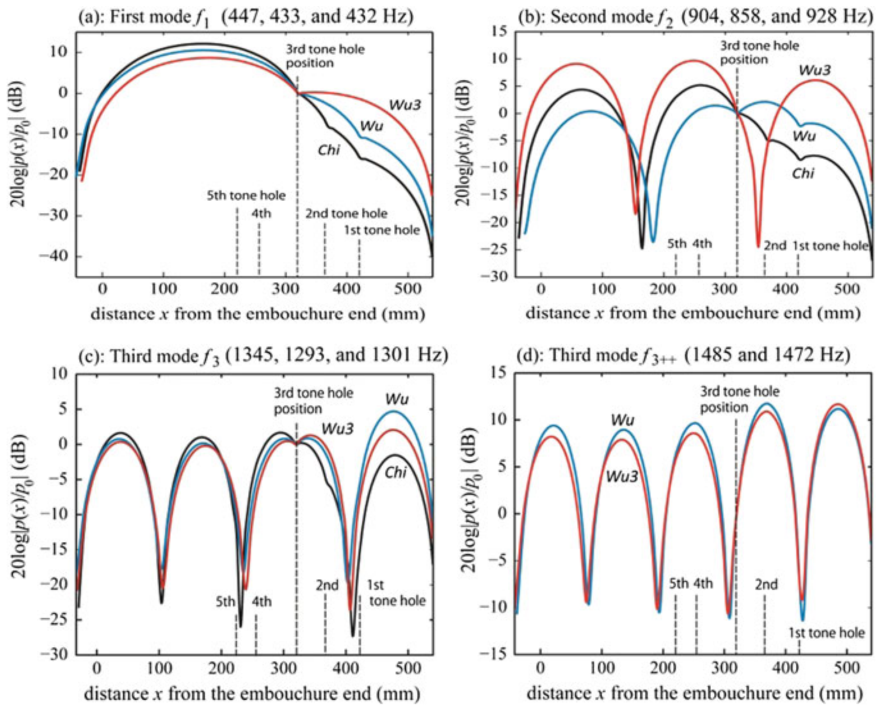


Fig. 11 Standing-wave patterns for the respective mode given by the three fingerings [16, 34]. The mode frequencies noted in each frame are in order of fingering *chi*, *wu*, and *wu3*

wavelength of this mode by *wu3* is significantly shorter than those by *chi* and *wu*. At this time, the clear third mode is formed along the whole bore and the intonation anomaly is induced. It may then be understood that the lower bore is almost completely coupled with the upper bore instead of being separated at the top open tone hole. The whole-bore mode is thus formed.

Although each third mode f_3 seemingly forms the fourth mode along the whole bore as shown in Fig. 11c, the kink (phase change) at the open top tone hole is stronger than that of the first mode shown in Fig. 11a. Then, the complete coupling at the top open tone hole is obstructed, and the intonation anomaly does not occur, as noted in the measurement and playing results.

However, cross fingerings *wu* and *wu3* easily yield the higher third mode f_{3++}, as shown in Fig. 11d. It should be noted that this higher third mode was really played by the player. Therefore, this mode may be regarded as an upper-bore mode, but it violates the resonance condition at the top open tone hole for the upper-bore mode. Moreover, the pressure amplitude along the lower bore is larger than that along the upper bore. Hence, this f_{3++} might be a lower-bore mode. In either case, it is essential that the whole-bore mode (the fifth mode) due to the complete coupling between the upper and lower bores is formed through the continuity (no phase change) at the top open tone hole and then the intonation anomaly is induced.

The intonation anomaly is derived from the complete coupling between the upper and lower bores through an open top tone hole. At this time, the discrimination of the upper-bore mode from the lower-bore mode is rather difficult as indicated in Fig. 11d. This may be because the third mode frequency of the upper-bore resonance is very close to the second mode frequency of the lower-bore resonance. In general, the intonation anomaly may be deduced when one of the resonance frequencies of the upper bore (from the embouchure end to the outer end of the top open tone hole) is very close to one of the resonance frequencies of the lower bore (from the bore bottom to the outer end of the top open tone hole). This strongly depends on the position of the top open tone hole [16]. Under such a situation, the modal interaction or mutual repelling (supposed in the explanation of Fig. 5b) in a coupled resonance system might be occurred.

Also, since the top open tone hole functions like a closed tone hole (cf. Fig. 11b, d) when the intonation anomaly occurs, the cutoff frequency of the open-tone-hole lattice [9, 15, 32] might be involved. The calculated cutoff frequency was about 1270 Hz when averaged geometrical values on the bore and tone holes are applied [16]. The modes penetrating into the lower bore such as f_3, f_{3+}, and f_{3++} might be related with the cutoff frequency. More detailed discussion on the physical mechanism causing the intonation anomaly and its modeling leading to our adequate understanding will be an important issue from the viewpoint of musical acoustics.

3 The Nohkan

The transverse bamboo flute, *nohkan* with seven finger holes is usually performed in ensemble with two-head drums (larger one is called *ohtsuzumi*; smaller one *kotsuzumi*) in Japanese traditional musical drama, *noh*. Its unique acoustical properties are described in this section.

3.1 Brief History

Four transverse flutes have been preserved in the *Shosoin* warehouse. They have seven tone holes, while the transverse flute *dizi* in China and *taegum* in Korea have six tone holes. Some varieties of the Indian flute *bansuri*, which dates in India from the first century AD at the latest, have six or seven tone holes [35]. According to Hayashi [4], flutes with seven tone holes were played in the secular music during the *Han* dynasty (206 BC–220 AD) of China, and they were introduced to Japan. Although the transverse flute first appeared in the *Han* period in China, its origin could be found in India [4, 36].

These Shosoin flutes were linked with the *ryuteki* played in the court music (*gagaku*), and furthermore were brought into the nohkan. Moreover, similar flutes were propagated from the Korean peninsula in the middle age. At last, the form of Japanese transverse flutes was decisively fixed [36]. Nevertheless, the origin of

Japanese transverse flutes (*fue*) still has many mysterious aspects [36]. A close relation between the nohkan altissimo tone (called *hishigi*) and the iwabue tone was mentioned in Introduction. The role of the iwabue seemed to lay down the god or ghost to the earth or this world. Most of noh dramas almost always have stories connecting this world with that world. The role of the nohkan seems to let the audience feel a premonition of this connection through its very high pitch and very solid timbre. On the other hand, there is another opinion that the nohkan altissimo tone is just only a signal to give the main players the timing for the entrance onto the stage [3, 36].

3.2 Unique Structural Properties

The external views of a nohkan are shown in Fig. 12. The top and side views are given in Fig. 12a, b, respectively. The total length of the nohkan is 410 mm, but the bore for the resonance is only 312 mm long as shown in Fig. 12b. The tube from the left edge of the embouchure (or mouth) hole to the left closed end is filled with bees-wax in which lead or iron bar is embedded. The bore diameter at the left edge of the embouchure hole is about 18 mm. However, it should be noted that the nohkan is different from one to the other. This is because the nohkan has no definite tuning pitch and it never be played with other nohkans in ensemble.

The embouchure hole is oval and large (the diameter is 19 mm long and 16 mm wide) as shown in Fig. 12c. Its edge against which the player's breath is blown is rather shallow so that the player can apply very strong blowing pressure in the second and third registers [37, 38]. The resulting forceful attack generates a great deal of wind noise. This is definitely different from Western flutes. Also, finger holes are not flat but curved against the external surface of the instrument as shown in Fig. 12b. This is because the tone holes of the nohkan (and the ryuteki) are covered by the middle joints of the fingers and because the half-hole and partly-raising-finger techniques for subtle pitch and timbre adjustments [3, 39] are often used. The diameter of tone holes is 12–13 mm.

Although the nohkan resembles the ryuteki, the nohkan has a thin tube inserted between the embouchure hole and the first (counted from the top) tone hole as illustrated in Fig. 12d. This inserted tube is called *nodo* (throat), which constricts the bore and makes the notes of the second octave increasingly flat to the lower octave as the scale is ascent [27, 35, 37, 38]. In other words, there is no concept of "octave" in playing the nohkan. The origin of this unique device is still obscure. Possibly one of nohkan makers found incidentally its interesting effects on the pitch and timbre during the repairing process [36]. Anyway, this nodo should be the Japanese invention probably carried out in the *Muromachi* period (1334–1573) during which the noh play was largely developed. Note that a tube section around the nodo is cut in half near the middle of the nodo so that the nodo is smoothly inserted. The narrowed bore shape of the nodo is approximately depicted by the dashed line in Fig. 12d, but there are some different bore shapes, one of which is almost straight except for both ends.

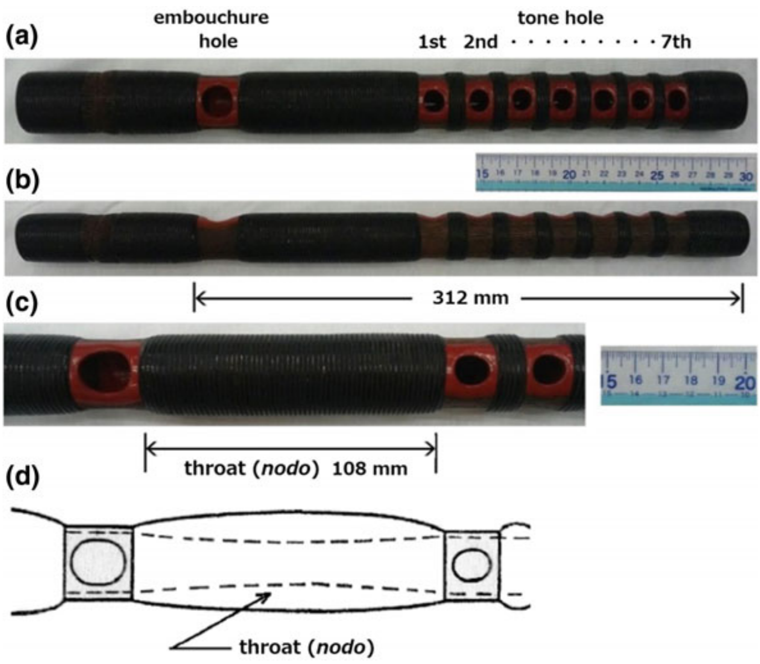


Fig. 12 External views of a nohkan (offered by professional player DenshoTosha). **a** Top view; **b** side view; **c** close-up from the embouchure hole to the second tone hole; **d** illustration of the throat (*nodo*) inserted between the embouchure hole and the first tone hole. This illustration is based on Fig. 3 in Ref. [37]. This nohkan is quite longer than the averaged one

Especially on this flute, a note is characteristically attacked from well below, strongly and breathily [35]. Malm [3] described the uniqueness of the nohkan: "the indefinite quality of its tone and its music are eminently suitable for supporting the drama without interfering with the declamation of the poetry". This declamation is called *ji-utai* in Japanese and it is completely different from the Western singing but rather close to narrating or recitative chanting. Since the nohkan has no consistent pitch and no octave balance, there can be no deliberate relation between the pitches of the instrument and those of the vocal line [3]. On the basis of essentially indefinite characteristics of the nohkan and the ji-utai, the noh is played freely between this world and that world [40].

3.3 Sound Examples

Some tonal examples are given in Fig. 13. These tones were played by professional player Densho Tosha and recorded in a large studio of the Osaka University of Arts by Prof. S. Simura. Tones in the first and second registers when all tone holes are closed are shown in Fig. 13a, b, respectively. The upper frame shows the temporal

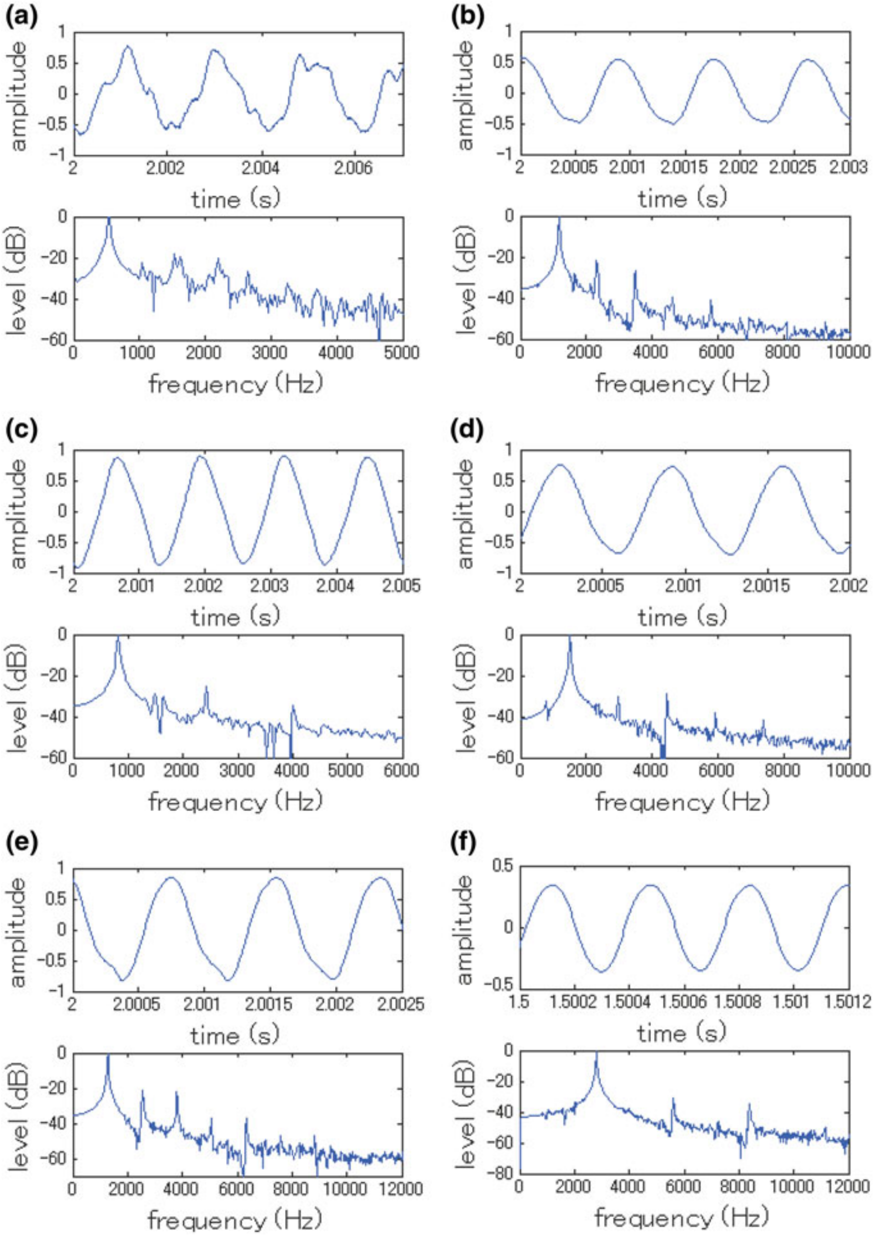


Fig. 13 Examples of steady-state tones by the nohkan. The spectral level is relative (normalized by the pressure amplitude of the fundamental). The details are given in the text

waveform and the lower frame the corresponding frequency spectrum. The fundamental frequency of the first register is 503 Hz (a little higher than B_4), and the overblown frequency in the second register is 1157 Hz (a little lower than D_6). This clearly indicates the octave enlargement. Also, the spectrum of the first-register tone shows indefinite harmonic structure. The lower harmonics are seemingly masked by wind noise from about 1–2.5 kHz. On the other hand, the second to fifth harmonics can be recognized in the second-register tone.

A cross fingering that opens the fourth to sixth tone holes produces the first-register and second-register tones shown in Fig. 13c, d, respectively. The respective tonal pitch is 794 Hz (G_5) and 1472 Hz (${G^b}_6$). The octave is considerably shrunk. The second and fourth harmonics of the first-register tone cannot be clearly detected. Although the lower harmonics are observed in the second-register tone, the second harmonic is quite weak. Also, a small peak at 792 Hz is recognized. This peak probably reflects the first-mode resonance of the fingering.

A peculiar cross fingering that opens two extreme (the top and the bottom) tone holes produces the first-register tone shown in Fig. 13e. The tonal pitch is 1257 Hz (${E^b}_6$). Since the pitch of the second-register tone (not shown here) is 2327 Hz (D_7), the octave shrink occurs. The sounding frequency of Fig. 13e gives the half-wavelength 137 mm, which corresponds to the resonating bore length. Therefore, this tone reflects the resonance of the throat itself, which brings unexpectedly quite rich harmonics (up to the seventh harmonic). Also, it can be understood that the total end corrections at both openings are estimated as about 29 and 40 mm for the first and second registers, respectively.

Another cross fingering that opens the second, fifth, and sixth tone holes produces the third-register tone as shown in Fig. 13f. This tone is called the *hishigi*, which means "to crush" or "to squash". This powerful piercing tone has an uncanny atmosphere. The tone frequency is 2775 Hz (F_7). The second and third harmonics are very weak, and the waveform is close to pure sinusoid. Also, we may observe small level changes from about 1 to about 2 kHz. These components might be related with the first and second modes of the resonance given by the fingering as noticed in Fig. 13d.

The octave balance between the first and second registers is depicted in Fig. 14, where the "octave" curve (connected by the square symbol) corresponds to twice the frequency of the first-register tone. The abscissa indicates the position of the top open tone hole given by the fingering. The octave enlargement occurs when all tone holes are closed (shown as "CL" on the abscissa) and when the top open tone hole is the seventh and the sixth. However, the octave shrink occurs when the top open tone hole is the fifth to the first. Like this, the throat makes the second-register tones increasingly flat as the scale is ascent and upsets the pure octave. As a result, the playing in the second register with subtle tone intervals becomes possible. The result of actually playing the nohkan shown in Fig. 14 well agrees with the measurement result of Ando [37, 38].

It is essentially important that the nohkan has been always pursued very solid and hard timbre. This tendency might be reverse the modern shakuhachi, while it

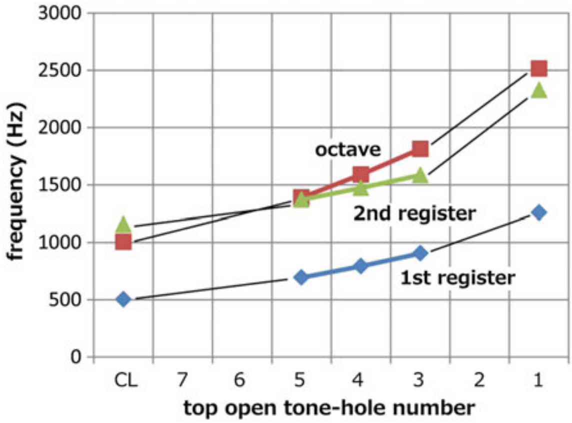


Fig. 14 Octave relation between the first and second registers based on the actually played tones. The "octave" curve gives the pure octave of the first-register tone

might be partially common to the old (*komuso*) shakuhachi, which however attaches importance to the first register. The inner wall of the nohkan is undercoated by the *urushi* lacquer 10–20 times, moreover the cinnabar urushi is coated over it 5–10 times [1]. This urushi coating seems to have deep relation with the hard timbre of the nohkan. The quality and the layer of the urushi lacquer seem to considerably affect the timbre of the nohkan and old shakuhachi [22].

3.4 Numerical Calculation on the Effects of Nodo

In order to understand the effects of the throat (*nodo*) more quantitatively, numerical calculation based on the *T*-matrix method was carried out on the throat shapes depicted in Fig. 15 [41]. A normal model of the throat, which is drawn by

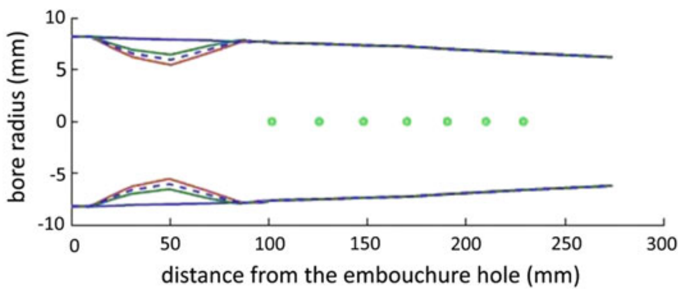


Fig. 15 Throat shape models for numerical calculation [41]. The *dashed line* is supposed to be a normal model seen in common nohkans. The *blue solid line* indicates no throat; the *green solid line* the throat widening the normal throat by 2 mm; the *red solid line* the throat narrowing the normal throat by 2 mm. The nohkan bore without the throat is convergent conical just as the piccolo. Also, the finger hole position is marked by the *green circle*

the dashed line, has a total length of 80 mm, and its center is located at 50 mm from the embouchure hole. If there is no throat, the overall bore (the blue line) is close to reverse (convergent) conical. The throat diameter at the center is varied from 14 mm (for a widened model depicted by the green line) to 10 mm (for a narrowed model depicted by the red line) through 12 mm (for the normal model).

At first the comparison between the nohkans with and without the throat (drawn by the dashed line and the blue solid line, respectively) is carried out. Four kinds of fingerings are used: fingerings A (all tone holes are closed), B (the fourth, fifth, and sixth tone holes are open), C (the first and seventh tone holes are open), and D (the second, fifth, and sixth tone holes are open). These fingerings were used in our playing experiment described in Sect. 3.3.

Results of numerical calculation are depicted in Figs. 16, 17, 18 and 19 for each fingering [41]. The dashed blue line is on the nohkan without the nodo (throat); the solid red line is on the nohkan with the nodo (throat).

The result of fingering A in Fig. 16a shows a definite frequency shift of the second mode resonance. The frequency raised by inserting the throat is 62 Hz. As a result, the octave enlargement occurs. It should be also noted that the reverse conical bore (without the throat) yields the octave enlargement (from 538 to 1100 Hz). This conical bore characteristic was applied to the Baroque flute to improve the octave shrink brought by the Renaissance cylindrical bore. Although Japanese transverse flutes have no headjoint, Western flutes always have it. Particularly its effect on the octave balance was well known historically. A good explanation of it is given by Benade [13] using his Fig. 22.11. The fact that the Japanese flutes have no such headjoints probably implies no concept of the octave in Japanese traditional flute music, particularly in the nohkan music.

The peak amplitudes of the first and third modes (f_1 and f_3) are larger than that of the second mode (f_2) when the throat is inserted. Also, the peak amplitudes of the modes above the fourth are quite low. These characteristics and the octave enlargement mentioned above of $|Y_{in}|$ probably produce the tonal spectrum shown in Fig. 13a, although the third harmonic might be masked by the wind noise.

Interestingly enough, the half-wavelength at the embouchure-hole side is increased by inserting the throat as indicated in Fig. 16c. However, since the second resonance frequency is clearly ascent, the shorter half-wavelength at the bore-bottom side should be responsible for the pitch ascent. The inner pressure distributions of the first and third modes are not appreciably changed by inserting the throat except for the amplitude increase along the throat as shown in Fig. 16d, which causes the amplitude increase in the third mode of $|Y_{in}|$.

On the other hand, fingering B gives the second mode which is not affected by the throat, but the first mode is increased by 38 Hz when the throat is inserted as shown in Fig. 17a. As a result, the octave shrink occurs. This result agrees with the playing experiment shown in Fig. 14. The peak amplitude of f_1 is decreased by the throat as suggested from the decrease in $p(x)$ shown in Fig. 17b. However, the peak amplitude of f_2 is significantly increased by the throat as suggested from the quite increase in $p(x)$ along the throat shown in Fig. 17c. The strength of the bore resonance seems to be affected by the throat from the results on fingerings A and B,

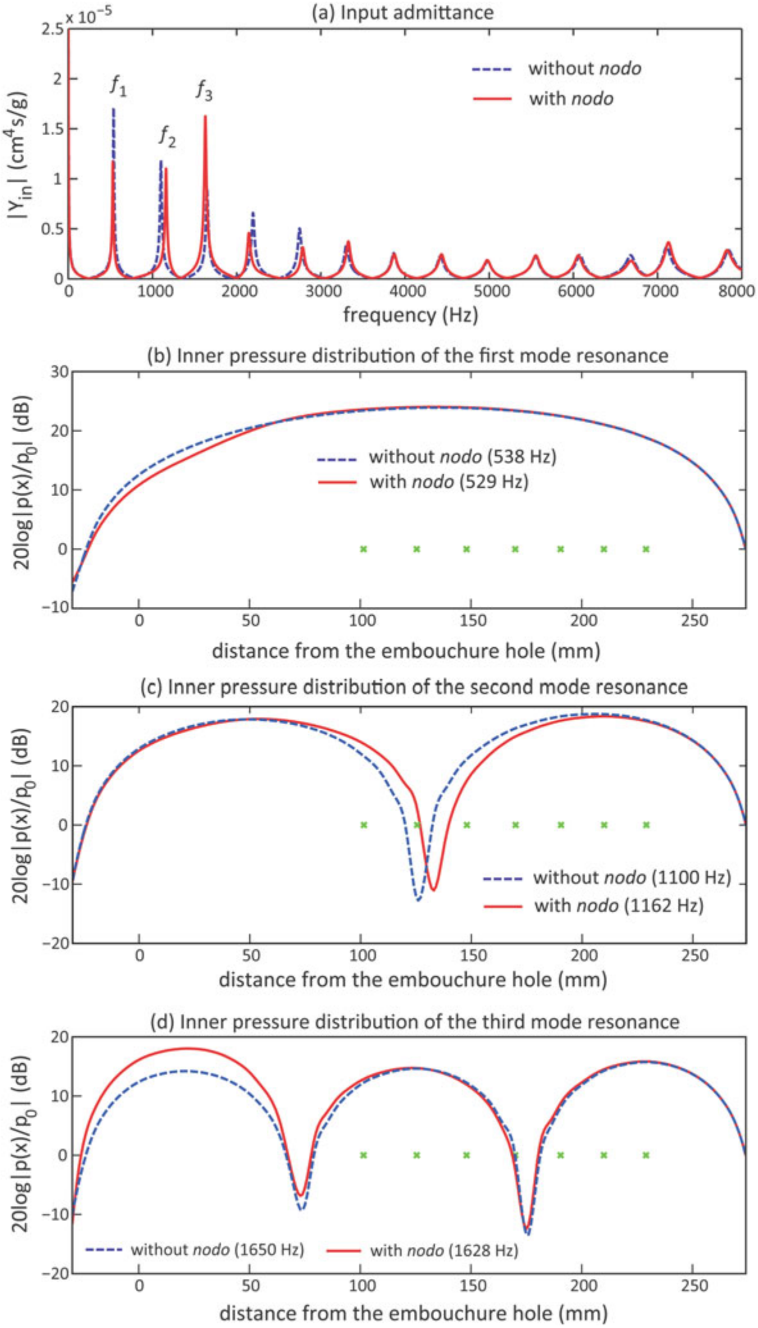


Fig. 16 Results of numerical calculation on fingering A [41]. **a** Input admittance; **b**–**d** inner pressure distribution along the bore in the first to third mode resonance, respectively. The pressure $p(x)$ at the position x from the right edge of the embouchure hole (x = 0) is normalized by that at the bore bottom. The symbol "×" indicates the closed tone hole

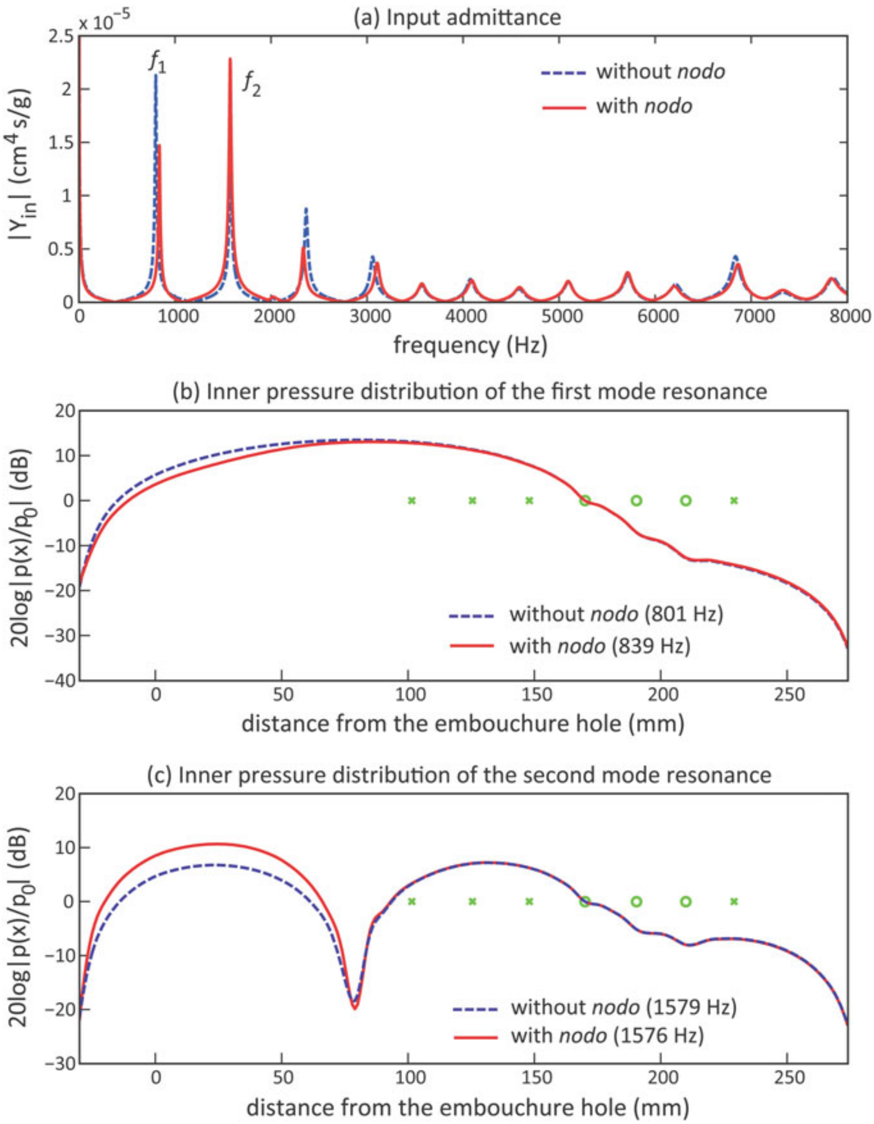


Fig. 17 Results of numerical calculation on fingering B [41]. **a** Input admittance; **b** and **c** inner pressure distributions along the bore in the first and second mode resonances, respectively. The pressure $p(x)$ is normalized by that at the top (fourth) open tone hole. The symbol "×" indicates the closed tone hole; the symbol "*open circle*" the open tone hole

particularly the frequency range of around 1600 Hz tends to be strengthened. The half-wavelength of 1600 Hz is 108 mm, which corresponds to the acoustical throat length with the embouchure-hole end correction. Also, it should be noted that the

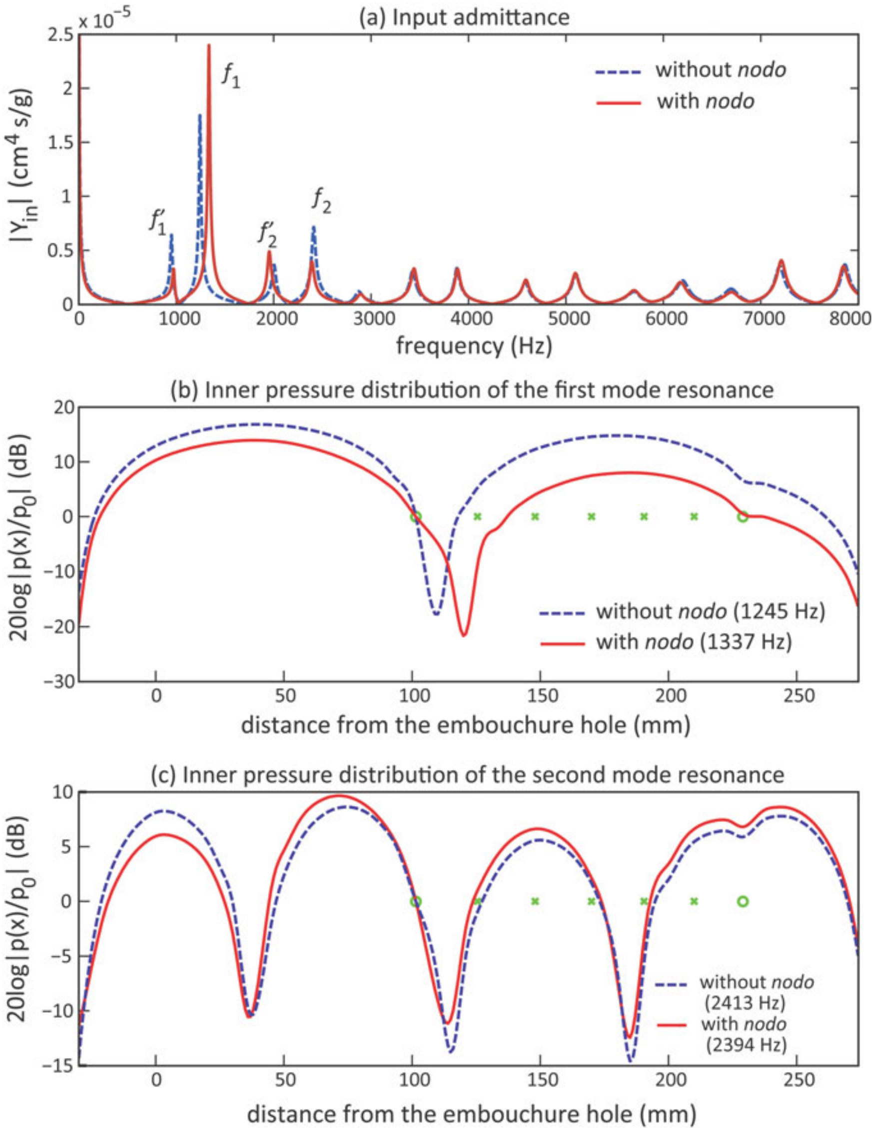


Fig. 18 Results on fingering C [41]. **a** Input admittance; **b** and **c** inner pressure distributions along the bore in the first and second mode resonances, respectively

phase shift (the amplitude kink) is observed at the open tone hole just as in the case of the shakuhachi (cf. Figs. 9 and 11).

A peculiar cross fingering C gives a complicated input admittance as depicted in Fig. 18a. The peaks of f_1 and f_2 should be the resonances of the upper bore above the first open tone hole, but the peaks of f'_1 and f'_2 should be the resonances of the

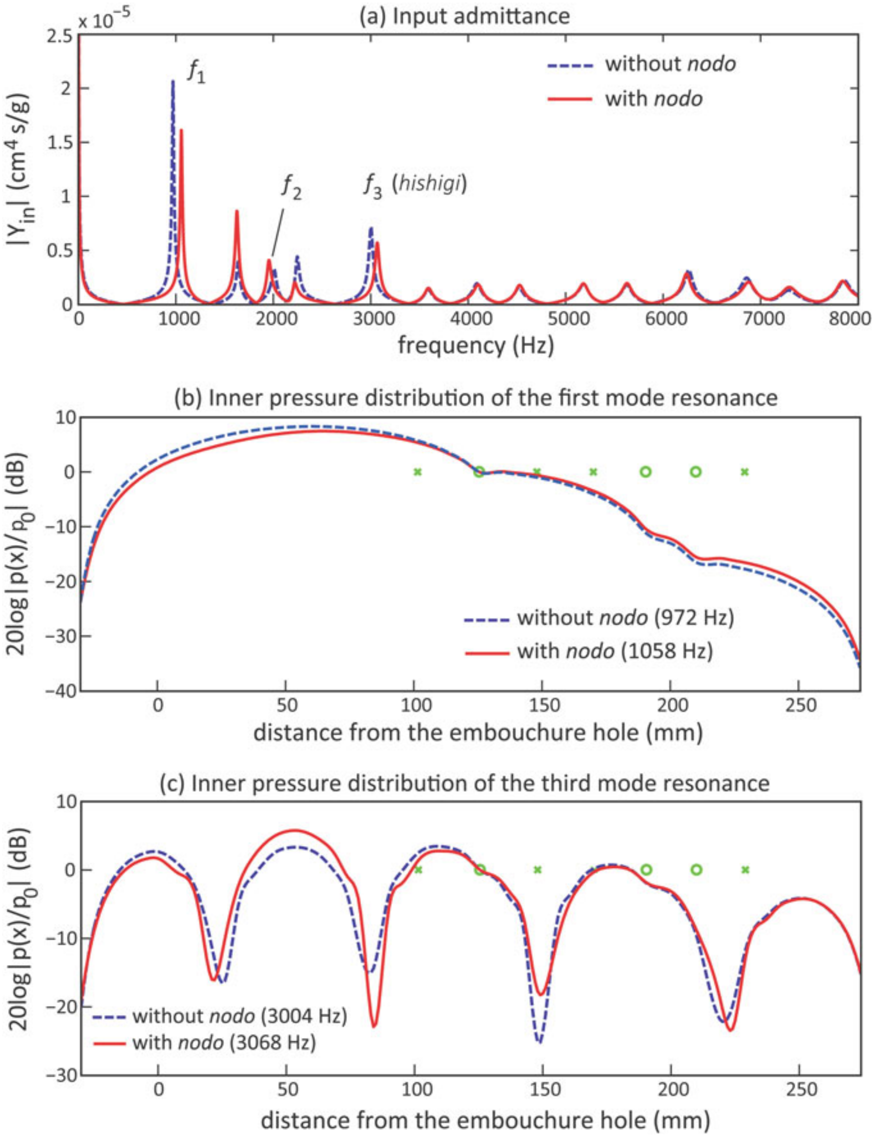


Fig. 19 Results on fingering D [41]. **a** Input admittance; **b** and **c** inner pressure distributions along the bore in the first and second mode resonances, respectively

lower bore below the first open tone hole. The frequency of f_1 is largely ascent by the throat (by 92 Hz). Moreover, f_2 is descent by 19 Hz, and then the octave is definitely shrunk. The inner pressure distribution of the first mode shown in Fig. 18b indicates that similar to Fig. 16c on fingering A. The lower bore is responsible for the pitch sharpening. The dominance of the lower bore is also seen in Fig. 18c where the longer half-wavelength along the lower bore is observed for the pitch flattening by the throat (from 2413 to 2394 Hz).

As in the case of fingering C, fingering D gives a strong octave shrink by inserting the throat as the result of the ascent in f_1 and the descent in f_2 as shown in Fig. 19a. The admittance peak between f_1 and f_2 might be the first resonance of the lower bore below the second open tone hole, but that between f_2 and f_3 might not be the second resonance of the lower bore. The complicated fingering might cause the bore resonance between the open second and fifth tone holes.

The third mode f_3 of cross fingering D produces the *hishigi* tone. There was a conventional explanation that the throat was inserted to make the hishigi tone be played easily. However, the peak of f_3 is a little lowered by the throat as indicated in Fig. 19a. Therefore, the above explanation seems to be inadequate. Nevertheless, we may recognize a larger half-wavelength pressure around x = 50 mm when the throat is inserted (also, this half wavelength is made longer in spite of the pitch ascent) as depicted in Fig. 19c. The third-mode distribution pattern is made more complicated by the throat.

3.5 Numerical Calculation on the Effects of Nodo *Shape*

Numerical calculation of the resonance frequency was moreover carried out concerning four patterns of the throat shape depicted in Fig. 15 and its result was compared with the measurement results [20, 38]. The four patterns were referred to as “no throat” (the blue solid line), “normal throat” (the blue dashed line), “widened throat” (the green solid line), and “narrowed throat” (the red solid line). Eight common fingerings depicted in Fig. 20 were used for our calculation [41, 42], where the end correction at the embouchure hole was fixed to 30 mm for the simplicity. These fingerings were selected from 15 fingerings given in Fig. 5 of Ref. [39]. Each fingering is shown below the staff notation of the resulting tones, which

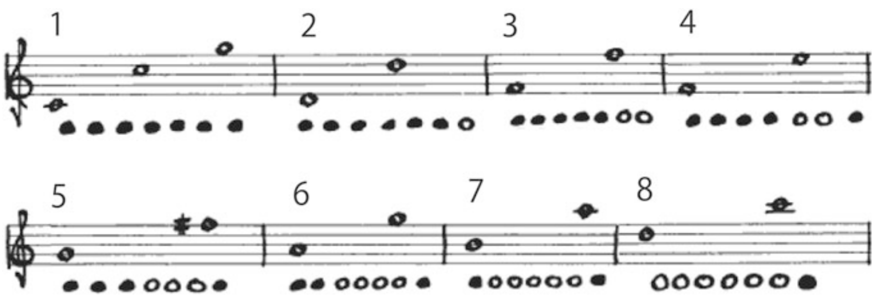


Fig. 20 Eight common fingerings of the nohkan and the resulting approximate tones. The tone hole is opened from the bore bottom in sequence and the tonal pitch is correspondingly ascent. This figure is based on Ref. [39]

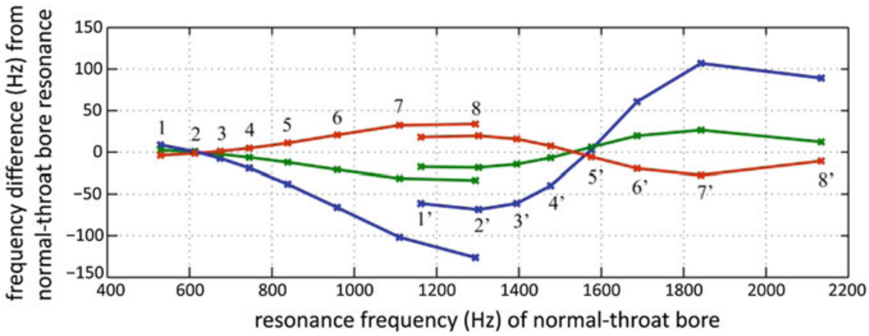


Fig. 21 The resonance frequency differences from the normal-throat resonance frequency [41]. The *red line* a narrowed throat; the *green line* a widened throat; the *blue line* no throat. The *numeral on the curve* denotes the first-mode resonance of each fingering; the *numeral with the apostrophe on the curve* the second-mode resonance of each fingering

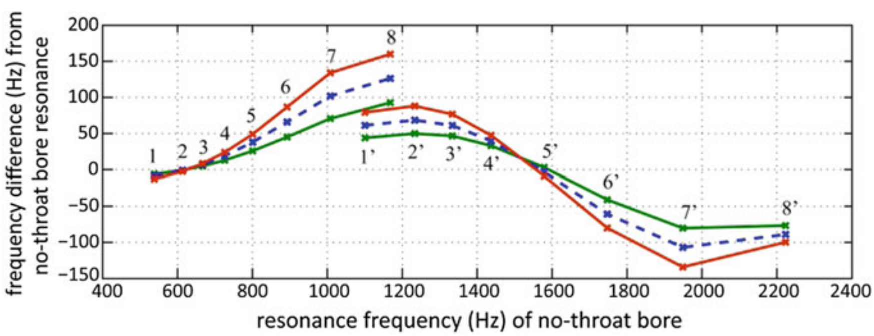


Fig. 22 The resonance frequency differences from the no-throat resonance frequency [41]. The *red line* a narrowed throat; the *green line* a widened throat; the *blue dashed line* normal throat. The *numeral* indicates the fingering; *the apostrophe* the second-mode resonance

only indicate approximate tones. The filled circle denotes a closed tone hole while the open circle denotes an open tone hole.

The calculated result is illustrated in two ways [41]: The abscissa in Fig. 21 is the resonance frequencies in the normal throat case; the abscissa in Fig. 22 is the resonance frequencies in the no-throat case. As shown in Fig. 21, the resonance frequencies of the narrowed-throat and widened-throat bores indicate symmetrical frequency differences from the resonance frequency of the normal-throat bore. In other words, the positive and negative of their frequency differences are reverse each other. The cross-over occurs at fingering 2 in the first register, and it occurs at fingering 5 in the second register. The degree of frequency difference is strengthened as the fingering changes from 2 to 8 in the first register. The measurement [38] gave the cross-over at fingering 4 (near 700 Hz) in the first register, and the cross-over at fingering 7 (near 1900 Hz) in the second register. These disagreements are probably

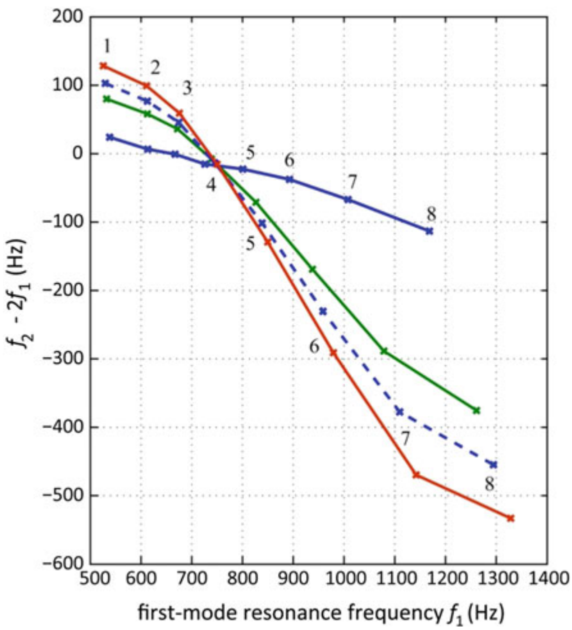


Fig. 23 The octave relation between the first-mode and second-mode resonances [41]. The f_1 denotes the first-mode resonance frequency; f_2 the second-mode one. The *blue solid line* no throat; the *blue dashed line* normal throat; the *green solid line* widened throat; the *red solid line* narrowed throat. The *numeral on the curve* denotes the fingering in Fig. 20

due to the difference between the actual nohkan used for the measurement and the modeled nohkan used for the calculation. The no-throat bore strongly exaggerates the resonance frequencies of the widened-throat bore.

The difference in resonance frequency for each throat model from that for the no-throat bore is depicted in Fig. 22. Except for fingerings 1 and 2, the resonance frequency is raised more and more as the upper tone hole is opened in the first register. The cross-over occurs at fingering 5 in the second register. It should be noted that the resonance frequency is appreciably raised by the throat from about 600–1600 Hz (between the cross-over in the first register and that in the second register) in comparison with the no-throat bore.

The deviation from the octave relation between the first-mode resonance frequency f_1 and the second-mode resonance frequency f_2 is shown in Fig. 23. The abscissa is f_1; the ordinate is $f_2 - 2f_1$. The numeral on the curve denotes the fingering given in Fig. 20. Fingering 1 indicates positive $f_2 - 2f_1$ for all throat shapes, and the positive degree becomes weak as more tone holes are opened in fingerings 2 and 3. Fingering 4 then brings negative $f_2 - 2f_1$ and the negative degree is strengthened as more tone holes are opened in fingerings 5, 6, 7, and 8. The octave relation $f_2 - 2f_1$ mentioned above occurs in the no-throat nohkan due to the reverse conical bore. However, the throat causes much stronger effect to this octave relation. It is well known that the octave shrink is brought as more tone holes are opened in fingerings 4, 5, 6, 7, and 8. This tendency is recognized in Fig. 14 on many cross fingerings, too. Also, our calculation result generally agrees with the measurement result by Ando [20, 38], but the cross-over occurred near 800 Hz or fingering 5.

3.6 Perturbation Theory Applied to the Nohkan

Since the throat can be recognized as a perturbation to the bore, the resonance frequency shift due to the throat may be calculated from the perturbation theory developed by Rayleigh [9, 28]. The following definitions are made: The bore length from the embouchure hole is denoted as x; the pressure distribution along the bore with no throat as $p_0(x)$; the sound speed in the bore as c; the widening of the bore at $x = x_0$ as Δ; the resonance angular frequency of the bore with no throat as ω_0; the bore cross section with no perturbation as $S_0(x)$; the integral of $S_0(x)p_0^2(x)$ along the bore as N. Then, the deviation of the resonance angular frequency $\delta\omega$ due to the positive bore perturbation $\Delta(>0)$ concentrated at $x = x_0$ is given as

$$\delta\omega = \frac{c^2\Delta}{2\omega_0 N}\left[\frac{d}{dx}\left(p_0\frac{dp_0}{dx}\right)\right] \quad at \quad x = x_0 \tag{1}$$

according to Eq. (8.72) in Ref. [9].

If the pressure with no perturbation $p_0 = \sin(2\pi x/\lambda)$ (λ denotes the wavelength and x involves the end correction at the embouchure hole) is inserted in Eq. (1), the quantity in the angular parenthesis is $(2\pi/\lambda)^2 \cos(4\pi x_0/\lambda)$. The value of x_0 may be represented by the middle position (50 mm in Fig. 15) at which the throat is most narrowed and by the assumed end correction at the embouchure hole (30 mm). Hence, $x_0 = 80$ mm is supposed. Since λ, c, ω_0, and N are positive, but Δ is negative for the nohkan throat, the value of the index

$$W = -\cos(4\pi x_0/\lambda) \tag{2}$$

determines the sign of the perturbed frequency $\delta\omega$ of Eq. (1). If λ is converted by c/f ($c = 344$ m/s), Eq. (2) is plotted as Fig. 24 against the resonance frequency f of the nohkan without the throat.

The frequency f_{0n} satisfying $W = 0$ is given by

$$f_{0n} = (2n-1)c/8x_0 (n = 1, 2, 3, \ldots), \tag{3}$$

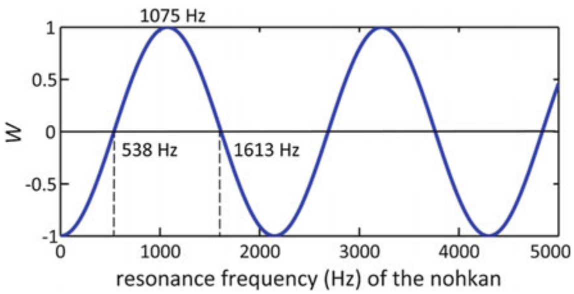


Fig. 24 The deviation of the nohkan resonance frequency expressed by the index W [42]. The bore perturbation Δ given by the normal throat is represented at a point $x = x_0 = 80$ mm including the assumed embouchure end correction 30 mm (cf. Fig. 15)

where n denotes the mode number of the resonance. The values of f_{01} and f_{02} are calculated as 538 and 1613 Hz, respectively. These values match well those given from Fig. 22 which illustrates the resonance frequency difference of the nohkan with the throat from the no-throat nohkan resonance frequency. The dependence of the throat effect on the resonance frequency can be estimated by the perturbation method. Also, as the middle position of the throat is closer to the embouchure hole, the f_{0n} value for each mode n is increased as known from Eq. (3). In other words, the intonation and octave relation in the nohkan can be adjusted not only by the throat shape but also by the throat position [41, 42].

3.7 A Comparison of the Nohkan with the Piccolo

Both the piccolo and the nohkan have a reverse conical bore as shown in Fig. 25 and have a very similar playing range [D_5 (587 Hz) to C_8 (4186 Hz) and C_5 (523 Hz) to F_7 (2794 Hz), respectively]. However, the throat breaks down the octave balance in the nohkan as discussed so far, while the cylindrical headjoint serves to hold the octave balance in the piccolo. The frequency characteristic of the reverse conical bore (without the throat) was already shown in Fig. 16a on fingering A (all tone holes are closed). In this subsection, a cross fingering with two extremely distant open tone holes just like cross fingering C of the nohkan will be discussed between the nohkan and the piccolo. Numerical data on the two tone holes are indicated in Table 1 [41].

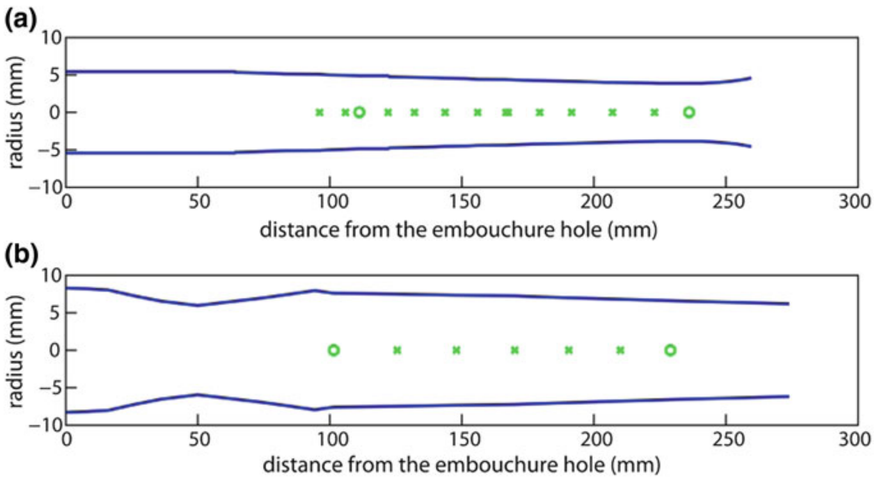


Fig. 25 A cross fingering with two extremely distant open tone holes in a modern piccolo (**a**) and a nohkan (**b**) [41]. The bore radius of (**a**) is based on Ref. [14]

Table 1 The position and diameter of the upper and lower tone holes in a modern piccolo [14] and a nohkan [41]

	Upper tone hole position (mm)	Upper tone hole diameter (mm)	Lower tone hole position (mm)	Lower tone hole diameter (mm)
Piccolo	111.2	4.2	236.1	8.0
Nohkan	101.5	9.2	229.0	8.2

Prior to our comparison between a piccolo and a nohkan, the input admittance $|Y_{in}|$ and the inner pressure distribution $p(x)$ along the bore, which is normalized p_0 at the upper open tone hole, are calculated on Fig. 25a and depicted in Fig. 26. Since this fingering usually gives $D^{\#}_6$ (1245 Hz), the second peak in Fig. 26a corresponds to this tonal pitch and the pressure minimum is observed at the upper open tone hole in Fig. 26b on the first mode resonance. Also, it should be noted that a similar but a little different half-wavelength distribution is observed between the two tone holes. Probably the first peak in Fig. 26a is on the first mode resonance f'_1 of the bore below the upper open tone hole as indicated in Fig. 18a. As a result, the piccolo as well as the nohkan can bring about a pair of f_n and f'_n (n = 1, 2, 3, …).

For the simplicity, a common cylindrical pipe instead of actual bores depicted in Fig. 25 is used for our calculation to estimate the acoustical role of the two distinct tone holes. This pipe is 265 mm long and 12 mm in diameter. The two tone holes are located at 100 and 230 mm distant from the embouchure hole respectively, and

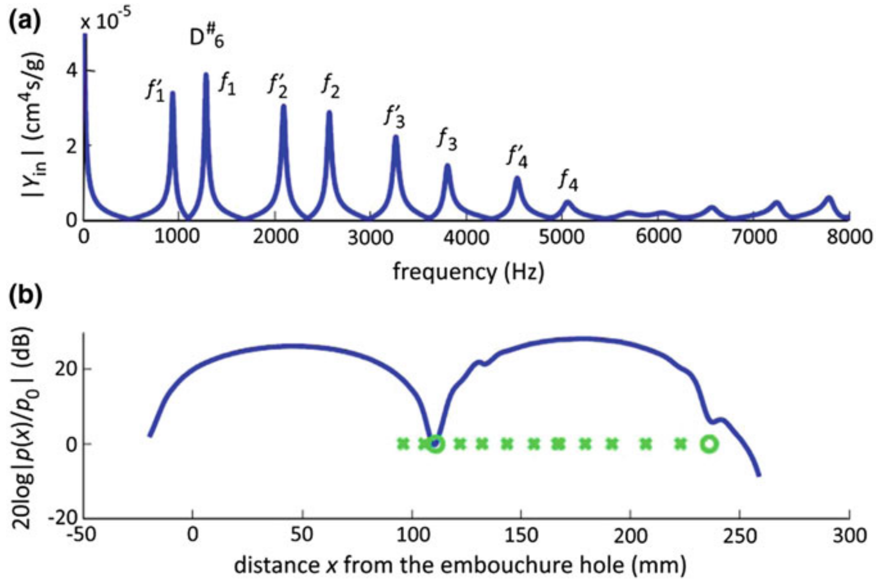


Fig. 26 The calculated input admittance (**a**) and internal pressure distribution along the bore (**b**) of the piccolo on the fingering for $D^{\#}_6$ (cf. Fig. 25a) [41]

they are commonly 8 mm in diameter and 3 mm long. The end correction at the embouchure hole is assumed to be 30 mm. On this reference pipe model the input admittance $|Y_{in}|$ and the inner pressure distribution $p(x)$ along the pipe are shown in Fig. 27, respectively [41]. Although six (or three pairing) peaks are shown in frame (a), the pressure distributions of the third modes (f) and (g) are not shown. The lower first mode frequency (1021 Hz) gives the acoustical pipe length 168 mm (for c = 344 m/s), which is very close to the physical length 165 mm of the pipe below the upper open tone hole. Since this mode seems to radiate no sound, this agreement confirms that the lower first mode corresponds to f'_1 (the first mode of the lower bore below the upper open tone hole) in Fig. 26a. On the other hand, the higher first mode (1247 Hz) gives the acoustical pipe length 138 mm, which probably consists of the physical length 100 mm of the upper pipe, the end correction 30 mm

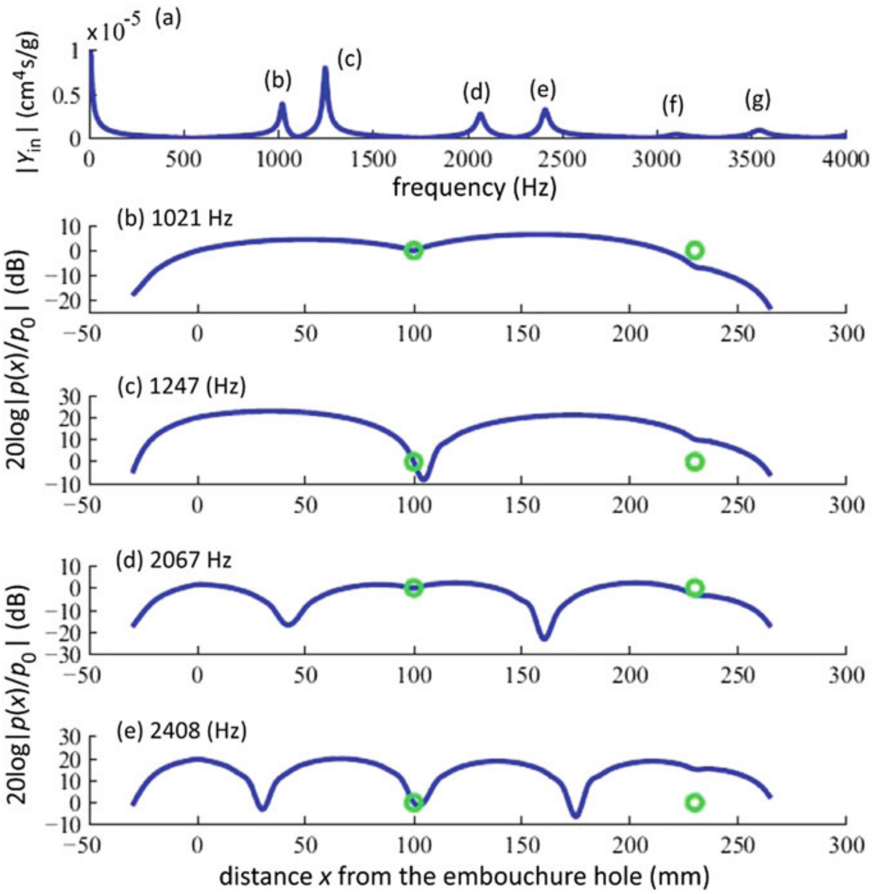


Fig. 27 Input admittance (**a**) and internal pressure distributions of the admittance peaks denoted as (**b**–**e**) in frame **a** concerning the reference cylindrical pipe of d = 8 mm [41]

assumed beforehand at the embouchure hole, and the end correction 8 mm anticipated at the upper open tone hole. This result confirms that the higher first mode corresponds to f_1 (the first mode of the upper bore) in Fig. 26a. The pressure distributions depicted in Figs. 27c, e well indicate the patterns of the first and second resonance modes of the upper pipe above the upper open tone hole, respectively.

Also, another interpretation seems to be possible: The upper open tone hole may operate as an octave hole for the fingering that only the lower hole is opened. Such an interpretation can be derived from much smaller diameter (4.2 mm) of the upper tone hole in the piccolo as shown in Table 1. Therefore, it seems to be worthy to calculate the models with smaller diameters of the upper tone hole. The diameter d is changed from 8 mm to 4, 2, and 0 mm. The corresponding results are shown in Figs. 28, 29 and 30, respectively [41].

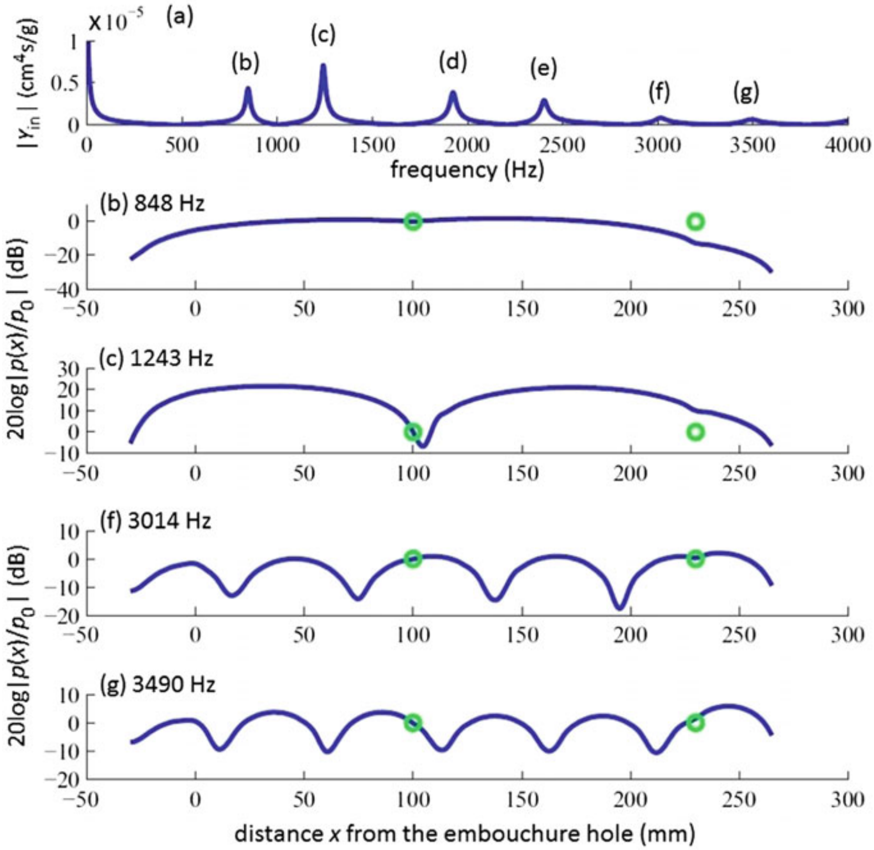


Fig. 28 Input admittance (**a**) and internal pressure distributions of the admittance peaks denoted as (**b**, **c**, **f**, and **g**) in frame **a** concerning the cylindrical pipe with an upper open tone hole of diameter d = 4 mm [41]

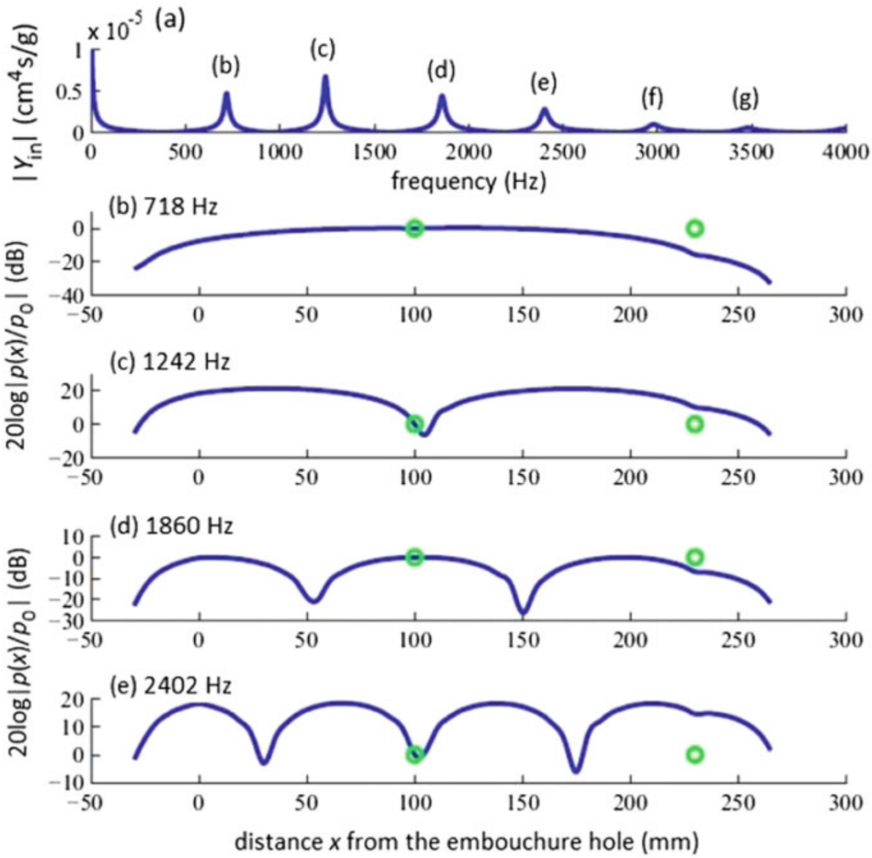


Fig. 29 Input admittance (**a**) and internal pressure distributions of the admittance peaks denoted as (**b–e**) in frame **a** concerning the cylindrical pipe with an upper open tone hole of diameter $d = 2$ mm [41]

It should be noted that the frequencies of admittance peaks (c) and (e) are almost unchanged in Figs. 27, 28, 29 and 30 [in Fig. 28 pressure distributions of (f) and (g) are depicted instead of (d) and (e)]: The frequency of peak (c) varies as 1247, 1243, 1242, and 1243 Hz corresponding to the sequential change in the diameter of the upper tone hole (8, 4, 2, and 0 mm); similarly the frequency of peak (e) varies as 2408, 2403, 2402, and 2405 Hz. If these results are considered based on Fig. 30 concerning the pipe without the upper tone hole, the frequency of peak (b) gradually increases and approaches peak (c) as the upper tone hole becomes larger. Also, at that time the amplitude of peak (b) gradually decreases. According to Fig. 30, peak (b) is understood as the first mode of the pipe when only the lowest tone hole is open. Since the upper tone hole at $x = 100$ mm is nearly located at the pressure loop of the above first mode, a kink appreciably appears there as the upper tone hole

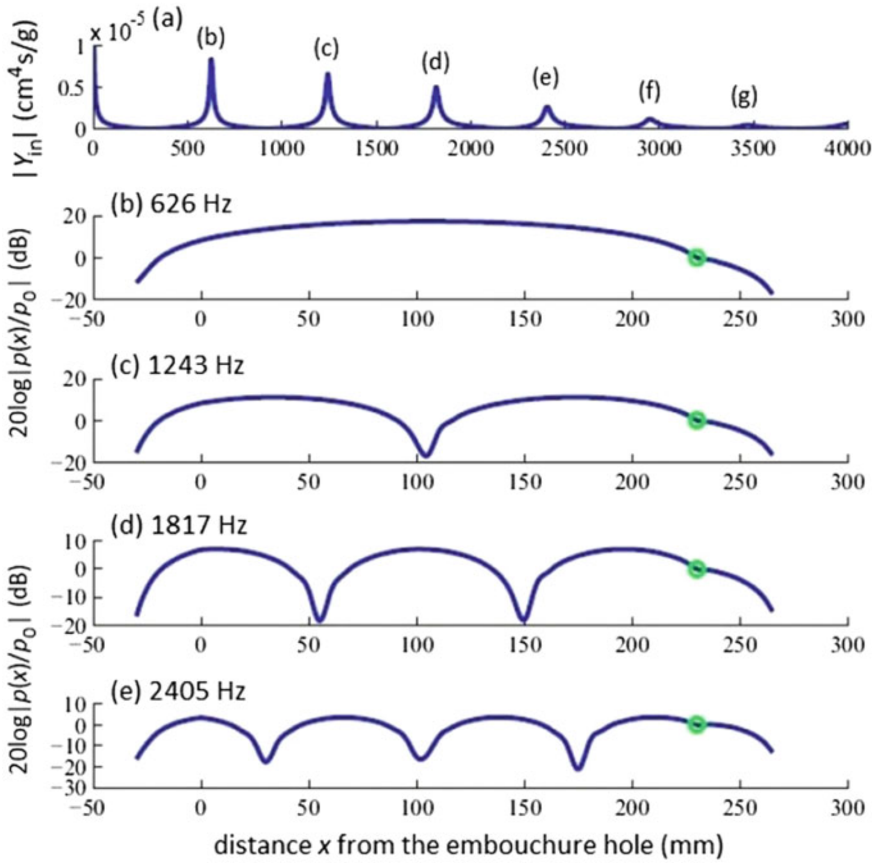


Fig. 30 Input admittance (**a**) and internal pressure distributions of the admittance peaks denoted as (**b**-**e**) in frame **a** concerning the cylindrical pipe with an upper open tone hole of diameter $d = 0$ mm [41]

is opened larger. Such a tendency is indicated by the pressure distributions on peaks (d) and (f) as shown in Figs. 27, 28 and 29.

Therefore, fingering $D^{\#}_6$ in the piccolo and fingering C in the nohkan, which give pairing admittance peaks, make the second mode of the bore with only the lowest open tone hole produce easier. However, in exchange for this octave-hole effect, the original odd modes [(b), (d), and (f) in the input admittance plot of Fig. 30] are made almost difficult to play because these modes are divided by the upper open tone hole [41]. Moreover, it is known that the original odd modes are completely disappeared when the diameter of the upper tone hole becomes 18 to 19 mm [41]. This calculated result suggests that an open tone hole with a diameter more than 1.5 times a pipe diameter (12 mm) can yield a pipe cut down at the tone-hole position.

4 The Shinobue

Another transverse bamboo flute, *shinobue*, is always used in *matsuri* (Japanese festival for celebrating the gods). Also, *matsuri* is the prayer of common people for their happiness, health, safe, prosperity, and so on. The *sinobue* sounds represent such prayer of common people.

4.1 Brief History

The Japanese *yokobue* is roughly categorized as *ryuteki* for the court ensemble, *nohkan* for the noh play, and *shinobue* for the events performed by common people. Although the shinobue has been exclusively used as a melody instrument for *matsuri* in ensemble with drums, it has been used for other cultural events such as *nagauta* and *kabuki* in ensemble with *shamisen* and singing after it was improved in tuning. Historically, the shinobue has six or seven tone holes, however, the seven tone-hole shinobue is generally used with singing. Since the shinobue is the flute for common people, a great variety of the shinobue with different length and structure are found throughout Japan. It is, therefore, very important to recognize that the shinobue strongly reflects the local color. Even its pitch and intonation are different between local customs [1].

The shinobue has been considered as a simplified version of the ryuteki after it became popular among common people around ninth century. However, there are two kinds of shinobue with six or seven tone holes. Also, the musical scale and the inner structure of the ryuteki and shinobue are different from each other. The unified view on the origin and transfiguration of Japanese *fue* has not been established yet as mentioned about the nohkan in Sect. 3.1.

4.2 Unique Structural Properties

The external view of a shinobue with six tone holes (pitched in around $C_5 = 523$ Hz) is shown in Fig. 31. Since the bore is stopped at the left edge of the embouchure hole, the physical length for the bore resonance of the lowest tone is about 313 mm. A small hole near the bore bottom is a kind of the ornament hole and it has almost no influence upon the bore resonance in normal playing range except for possible subtle adjustment of the intonation. The shinobue for the festival usually has tone holes with an equal size and with an equal hole-to-hole distance for the easiness in play and production. The hole-to-hole distance in the one shown in Fig. 31 is about 23 mm, but hole sizes are slightly different from each other (the diameter of the third and fourth holes is larger: 8.2 mm long and 7.2 mm wide).

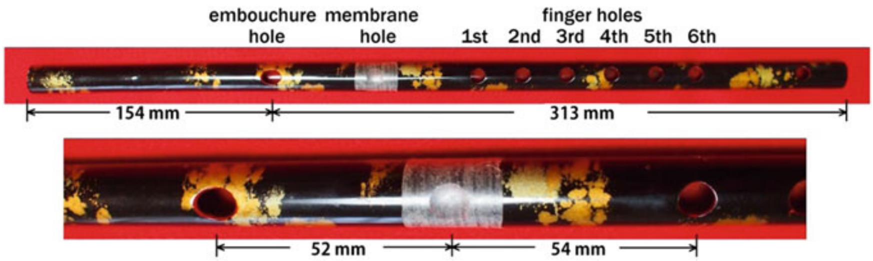


Fig. 31 External view of a shinobue (offered by Shiori Ide). The *upper* and *lower frames* show the total view and the close-up around the membrane hole halfway between the embouchure hole and the first tone hole, respectively

The embouchure hole and tone holes are simply opened and flat against the external surface of the instrument. This is significantly different from the nohkan shown in Fig. 12. Also, both holes are quite smaller and the tone-hole shape is rather close to the circle. These characteristics reflect the blowing and fingering ways different from those in the nohkan. Particularly, *uchiyubi* (the quick finger striking) on a closed tone hole is frequently used in the shinobue.

The bore of the shinobue shown in Fig. 31 is not reverse-cylindrical as in the ryuteki and nohkan. The diameter is 13.4 mm at the embouchure hole; about 12.3 mm at the membrane hole, the first, and second tone holes; 13.2 mm at the third and fourth tone holes; 12.9 mm at the fifth tone hole; about 12.6 mm at the sixth tone hole, the ornament hole and the bore bottom. A wider bore around the larger third and fourth tone holes is characteristic, and it might suggest the importance of these tone holes.

As shown in the lower figure of Fig. 31, this shinobue has a unique hole over which a piece of very thin membrane (traditionally prepared from the inner skin of the bamboo node, called *chikushi*, meaning “bamboo paper”) is glued. Although this kind of shinobue with a *membrane hole* is now very rare in Japan, it has been used in northern Kyushu districts. The shinobue in Fig. 31 is still used for the fork festivals called *Kunchi* (meaning *Ku no Hi,* special 9th day in September [43]) in Karatsu, Saga prefecture. This kind of folklore flute with a membrane hole in north Kyushu may be a living evidence of Chinese music influence [44].

The vibrating membrane glued over a hole just halfway between the embouchure hole and the first tone hole (as indicated in Fig. 31) has been used for the *di* (or *dizi*) in China and for the *taegum* in Korea [35, 44]. Transverse flutes with a membrane hole are also played in Mongolia [35]. Therefore, this vibrating membrane probably reflects the tonal taste in East Asia. In China most *di* players prefer a membrane taken from the inner side of a reed because of its even thickness, soft and high elastic quality that creates desired resonant sounds [44]. However, it should be noticed that there is a definite difference between the tonal tastes in the *di* and the *shinobue*: The *di* aims strong and bright reverberant sounds, while the *shinobue* aims beautiful and clear distinguished sounds. See Ref. [44] for the origin of the membrane hole and historical backgrounds of the *di*, *taegum*, and shinobue with a membrane hole.

The decisive effect of the membrane hole seems to be the high-frequency emphasis and the generation of inharmonic or noise frequencies due to the vibration of the membrane. This tonal effect is common to the effect due to the *sawari* (gentle touch with a string) device which was first applied to the Japanese stringed instruments, *biwa* and *shamisen* [20, 27, 45–47]. The tonal effects brought by the *sawari* and by the membrane hole (probably developed in China and Korea independently) seem to have strong interrelation with the performing environment such as an open-air theater, village square, and *matsuri* procession. In this section the distinctive effects of the membrane hole will be briefly discussed.

4.3 Sound Examples

The tonal difference of the shinobue with and without the membrane hole is shown by the waveforms in Fig. 32a, b, respectively. Tone (a) was played by closing the first and second tone holes in the first register; tone (b) was played by closing the membrane hole in addition to the first and second tone holes. The fundamental frequencies of (a) and (b) were 912.5 and 925.9 Hz, respectively. These tones were a little lower than $B^b{}_5$ (932 Hz).

Since the membrane hole approximately locates at the middle of the bore resonating between the embouchure hole (with the assumed end correction of about 20 mm) and the second tone hole, the pressure maximum of the first mode can be formed near the membrane hole, which brings positive perturbation (local

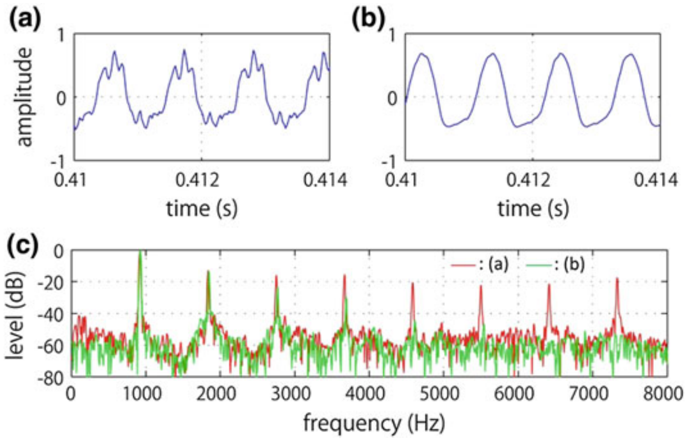


Fig. 32 Sound examples of the shinobue (closely pitched in C_5) played by closing the first and second tone holes in the first register. **a** The waveform when the membrane hole is covered by *chikushi*, the inner skin of the bamboo node; **b** the waveform when the membrane hole is closed; **c** frequency spectra of tones **a** and **b**

cross-sectional enlargement) to the bore. As a result, small frequency lowering occurs in the above tone of the shinobue with the membrane hole (cf. Sect. 3.6).

The waveform of (a) indicates that complicated corrugations are overlapped on a simple waveform of (b). Their frequency spectra are given in Fig. 32c. The harmonics of tone (b) without the membrane hole are poor and almost limited to the fourth harmonic. While all the harmonics of tone (a) maintain almost the same high level up to the eighth harmonic. This high-frequency emphasis seems to be derived from the membrane hole.

4.4 Acoustical Effects of a Membrane Hole

The effect of the membrane hole on the resonance frequency was already explained on the basis of the perturbation theory in the previous subsection. However, the tension, density, and quality of the membrane material as well as the size and location of the membrane hole will affect the instrument sounds. Therefore, an analytic model incorporating these parameters is desired. Samejima [48] and Ide [49, 50] proposed a vibro-acoustical model of the flute with a membrane hole. Their numerical method is based on the coupling between the membrane vibration and the surrounding sound field. Since its description is too complicated to the readers of this book, a brief explanation of the membrane tension effect on a modeled tube is given below.

A tube model is 250 mm long and 40 mm in diameter. Both ends are open. An open hole (18 mm in diameter) is perforated at the position of 140 mm from the top (left) open end. A piece of bamboo paper, whose aerial density is assumed to be 0.00374 (kg/m^2) from the measurement, is glued over this hole. This model tube was used in acoustical measurements [49, 50]. However, it was needed to setup the flat membrane surface for the calculation based on the finite element method, and then the model tube was approximated by a hexagonal column. Numerical calculation on this column with a membrane hole was carried out by changing the membrane tension from 15 to 50 (N/m) stepwise. It should be noted that this applied tension is very low compared with the timpani head to which the tension of 4000–5000 (N/m) is usually applied.

The calculated result is illustrated in Fig. 33, where the dashed line gives the result when the membrane is rigid or when the membrane hole is completely closed [48, 49]. The ordinate, relative SPL (sound pressure level), corresponds to the frequency response function (giving the resonance characteristics) defined by the ratio of the sound pressure at a receiving point (located at the center of the bottom end) to that at the sound-source point (located at the upper side of the top end). It is normalized by the value at the response peak.

Although the model tube with a rigid membrane hole indicates almost harmonic structure as shown by the dashed line (the peak frequencies are 628, 1268, 1892, 2546, 3180, 3808, and 4496 Hz in sequence), the model tube with a vibrating membrane causes appreciably inharmonic structure as shown by the solid line in

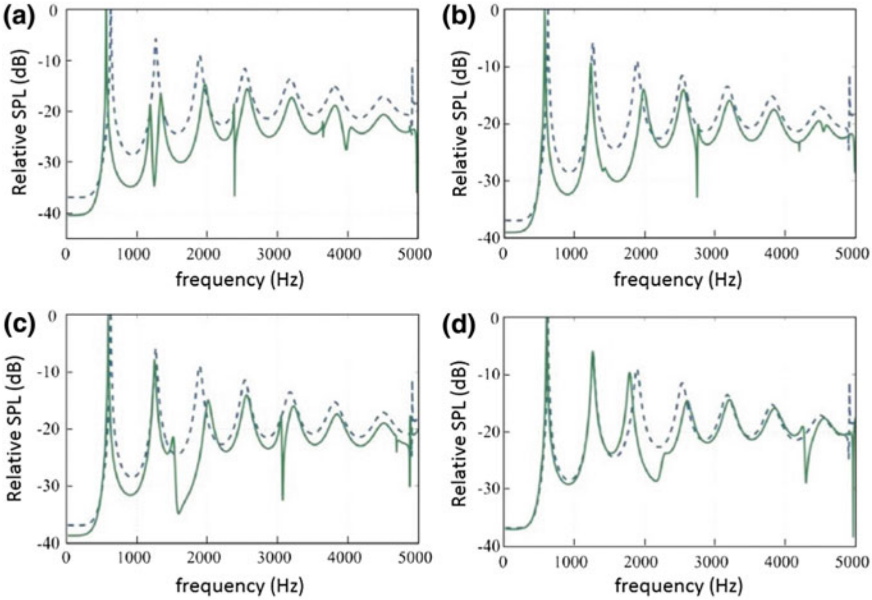


Fig. 33 Calculated effects of the membrane tension T on the frequency response function of a simplified model consisting of a hexagonal column with open ends and a membrane hole [48, 49]. **a** T = 15 N/m; **b** T = 20 N/m; **c** T = 25 N/m; **d** T = 50 N/m. The *dashed line* in each frame indicates the result when the membrane hole is completely closed

each frame of Fig. 33. However, this inharmonicity seems to be diminished as the membrane tension T is increased. Frame (d) for T = 50 N/m shows the harmonic second mode.

The fundamental frequency f_1 in each frame of Fig. 33 approaches to that when the membrane hole is completely closed. The f_1 for T = 15 and 25 N/m is 564 and 592 Hz, respectively; f_1 for $T = \infty$ is 628 Hz. This result qualitatively corresponds to the sound example shown in Fig. 32, where f_1 for the finite T is 912.5 Hz and f_1 for the infinite T is 925.9 Hz. Probably it may be assumed that the tension of 15–25 N/m is a little too weak in comparison with the actual case.

It is interesting that the resonance peaks on the dashed line split into two due to the membrane vibration. It is very appreciable in Fig. 33a, where the second, fourth, and sixth resonance peaks on the dashed line split into two. This peak splitting might be interpreted as follows: If the membrane tension is quite weak, the membrane hole can be like an open hole. As a result, the resonance peaks of the upper tube (140 mm long) above the membrane hole and the lower tube (110 mm long) below the membrane hole might be produced. The second peak frequency on the dashed line is 1268 Hz; the corresponding splitting two peak frequencies in Fig. 33a are 1188 and 1440 Hz, respectively. If the end correction is assumed to be 10 mm, the first-mode resonance frequency of the upper and lower tubes is calculated as 1147 and 1433 Hz, respectively. On the other hand, another interpretation might be allowed:

One of two splitting peaks might be derived from the modal frequency of the circular membrane that is considerably lowered by the surrounding air loading [49]. For example, the small third peak (1516 Hz) on the solid line in Fig. 33c is considered as an original (0, 1) mode (4477 Hz) of the membrane vibration in Ref. [49]. More detailed calculation and experiment are necessary to judge which hypothesis is valid.

Also, the variation of the third peak in Fig. 33 should be paid attention. The frequency of the third peak appreciably higher than that on the dashed line and ascents (from 1968 to 2012 Hz) as the membrane tension increases from 15 to 25 N/m. However, that frequency for $T = 50$ N/m is significantly lower than that on the dashed line as shown in Fig. 33d. The reasonable cause of this inversion is unknown. The interaction between the air-column resonance and the membrane vibration, particularly in actual shinobue with tone holes, is an intricate and intriguing topic in musical acoustics, which is hopefully solved in the near future by incorporating the blowing mechanism.

5 Conclusions

Distinctive characteristics of Japanese (or Asian) flutes (*fue*) and their music are recognized in (1) wind noise as an essential part of the instrument tone, (2) timbre-oriented music rather than octave-oriented or harmonic-oriented music, and (3) high-frequency emphasis suitable for the performing environment (particularly, for the outdoors). If there is no wind noise, the shakuhachi and nohkan cannot create their own sounds. The nohkan has been pursuing very solid and hard timbre and has definitely upset the octave expected when overblown by inserting a kind of obstacle, the throat (called *nodo*) between the embouchure hole and the top tone hole. The classical (*komuso*) shakuhachi traditionally prefers personal deeper introspection to musical performance itself. The nohkan used to be played in outdoors and produce very high and penetrating sounds. In *matsuri* (Japanese folk festival) procession, the shinobue with a membrane hole perforated between the embouchure hole and the top tone hole can create the decisive effect of the high-frequency emphasis due to the membrane vibration.

The classical (*komuso*) shakuhachi has been played in religious environments and appreciated natural bamboo structure. Its original construction had no *ground-paste finish* as seen in the modern shakuhachi but had very thin *urushi* coating over the inner bore surface. The diaphragms were not completely removed and small ridges were retained on the inside bamboo nodes. These remaining diaphragms might affect the intonation and timbre, although their effects are not satisfactorily elucidated yet. The essential difference between classical and modern shakuhachis is in the difference of the inner bore shape with or without the remaining diaphragms. The calculation of the input admittance is very effective to make the difference clear.

The wind noise is dominant between about 1.5–3 kHz when the classical shakuhachi is blown by *muraiki* (a rough and strong blow) during the starting transient.

The definite contrast between noisy, rough sound by *muraiki* and clear, almost noiseless sound by smooth blowing is the essence in shakuhachi sounds.

Also, cross fingerings in the shakuhachi playing, which yield subtle timbre taste, are investigated through the measurement and calculation of the internal standing-wave patterns and the calculation of the input admittance. Cross fingerings in the shakuhachi often causes pitch sharpening (called *intonation anomaly* in this chapter) instead of conventional pitch flattening. This is mainly due to only five tone holes in the shakuhachi. The intonation anomaly is generated if the resonance in the upper bore above the top open tone hole or in the lower bore below the top open tone hole leads the resonance of the whole bore. In other words, the complete coupling between the upper and lower bores through an open top open tone hole is derived when both bores give very close resonance frequencies in the fundamental or higher harmonic modes. The intonation anomaly strongly depends on the position of the top open tone hole. This intonation anomaly has been first quantitatively described through the shakuhachi acoustics.

A special tube device (about 80 mm long), the throat (*nodo*), is intentionally inserted between the embouchure hole and the top tone hole in the nohkan. As a result, the nohkan bore becomes narrowest near the middle of the throat, and then the octave relation between the first and second registers is upset. This throat shape in the nohkan is a great contrast to the cylindrical headjoint in the piccolo that yields the correct octave, although the both have a reverse (convergent) conical bore below the throat and the headjoint, respectively. Acoustical effects of the throat are investigated on the bore with or without the throat and on the bores with different throat shapes through the calculations of the input admittance and the internal pressure distribution for several fingerings. The throat makes the notes of the second octave increasingly flat to the lower octave as the scale is ascent. This octave shrink is generally carried out by the major increase in the first-mode resonance frequency and the minor decrease in the second-mode resonance frequency. The calculated result shows good agreement with the conventional measured result if the fact that the nohkan has no standard length and no consistent pitch is considered. Also, the admittance suggests that the throat does not operate to play easier the *hishigi* tone, the powerful piecing altissimo tone. Moreover, a comparison between the nohkan and the piccolo on a cross fingering with two extremely distant open tone holes reveals that the upper tone hole operates as an octave hole.

The spectra of the first-register tones in the nohkan usually show indefinite harmonic structure. The lower harmonics are seemingly masked by wind noise from about 1 to 2.5 kHz (a little lower than that in the shakuhachi). However, higher harmonics can be usually recognized in the second-register tones of the low-pitched fingerings. On the other hand, the second-register and third-register tones (above 2 kHz) of the high-pitched cross fingerings produce almost sinusoidal waveforms. These tonal differences in the registers and fingerings are very characteristic in the nohkan. Through this tonal tendency and construction method based on the *urushi* coating, the nohkan has been always pursued very solid and hard timbre for the high-pitched tones.

The shinobue has been played by common people in various occasions, particularly in local festivals, *matsuri*. The pitch, intonation, and tone itself of the shinobue largely depend on the locality. The shinobue played in the north Kyushu has been kept the original one traditionally played in China and Korea. It has a membrane hole just halfway between the embouchure hole and the top tone hole. The membrane vibration, which is affected by the hole position, membrane material, membrane tension, and so on, produces characteristic high-frequency emphasis, which should be very effective in *matsuri* procession. This phenomenon is common to the stringed instruments with the *sawari* (gentle touch) mechanism against the string vibration. Therefore, the high-frequency emphasis seems to be the tonal taste common to musical instruments in East Asia.

Bibliography

1. Shibata, M.: Listening to Japanese Sounds. Seidosha, Tokyo, pp. 10–17, 258 (in Japanese) (1987)
2. Shibata, M.: Musical History and Musical Theory. Iwanami, Tokyo, pp. 30–34 (in Japanese) (2014)
3. Malm, W.P.: Traditional Japanese Music and Musical Instruments. Kodansha International, Tokyo Chaps. 4 and 6 (2000) (originally published in 1959 by Charles E. Tuttle Company under the title *Japanese Music and Musical Instruments*)
4. Hayashi, K.: Study of the Shosoin musical instruments. Kazama-Shobo, Tokyo, pp. 164–173 (in Japanese) (1964)
5. Tsukitani, T.: Diffusion and interchange of the Fuke shakuhachi. In Japanese music and Asian music Vol. 3, Propagation and Transfiguration, Iwanami, Tokyo, pp. 37–42 (in Japanese) (1988)
6. Yoshikawa, S.: Changes in acoustical design from ancient shakuhachi to modern shakuhachi. Proceedings of Acoustics 2012 Hong Kong, 2aMU4. Hong Kong (2012)
7. Fletcher, N.H., Douglas, L.M.: Harmonic generation in organ pipes, recorders, and flutes. J. Acoust. Soc. Am. **68**, 767–771 (1980)
8. Yoshikawa, S.: Harmonic generation mechanism in organ pipes. J. Acoust. Soc. Jpn. (E) **5**, 17–29 (1984)
9. Fletcher, N.H., Rossing, T.D.: The Physics of Musical Instruments, 2nd edn. Springer, New York, Chaps. 4, 8, 16 and 17 (1998).
10. Yoshikawa, S.: Jet-wave amplification in organ pipes. J. Acoust. Soc. Am. **103**, 2706–2717 (1998)
11. Yoshikawa, S., Tashiro, H., Sakamoto, Y.: Experimental examination of vortex-sound generation in an organ pipe: a proposal of jet vortex-layer formation model. J. Sound Vib. **331**, 2558–2577 (2012)
12. Terada, T.: Acoustical investigation of the Japanese bamboo pipe, syakuhati. J. Coll. Sci. Tokyo **21**, 1–34 (1907)
13. Benade, A.H.: Fundamentals of musical acoustics. Oxford University Press, New York, Chap. 21 (1976).
14. Nederveen, C.J.: Acoustical aspects of woodwind instruments, 2nd edn. Northern Illinois University Press, DeKalb, USA, pp. 50–53, 132–133 (1998)
15. Wolfe, J., Smith, J.: Cutoff frequencies and cross fingerings in baroque, classical, and modern flutes. J. Acoust. Soc. Am. **114**, 2263–2272 (2003)

16. Yoshikawa, S., Kajiwara, K.: Cross fingerings and associated intonation anomaly in the shakuhachi. Acoust. Sci. Tech. **36**, 314–325 (2015)
17. Ando, Y.: Input admittance of shakuhachis and their resonance characteristics in the playing state. J. Acoust. Soc. Jpn. (E) **7**, 99–111 (1986)
18. Ando, Y., Ohyagi, Y.: "Measuring and calculating methods of shakuhachi input admittance. J. Acoust. Soc. Jpn. (E) **6**, 89–101 (1985)
19. Ando, Y., Tsukitani, T., Maeda, M.: On the shakuhachi structure. In: Sumikura, I., Takano, N., Tohkawa, S., Watanabe, K. (ed.) Music and musicology, Ongaku-No-Tomo-Sha, Tokyo, pp. 39–70 (in Japanese) (1986)
20. Ando, Y.: Acoustics of musical instruments, 2nd edn., Ongaku-No-Tomo-Sha, Tokyo, pp. 79–90, 193–203 (in Japanese) (1996)
21. Simura, S.: An Organology of Kokan Syakuhati (Old Pipe Syakuhati). Shuppan-Gejutsu-Sha, Tokyo (in Japanese) (2002)
22. Waltham, C., Yoshikawa, S.: Construction of wooden musical instruments. In: Bader, R. (ed.) Springer Handbook for Systematic Musicology, pp. 2–16. Springer, New York (to be published)
23. Plitnik, G.R., Strong, W.J.: Numerical method for calculating input impedance of the oboe. J. Acoust. Soc. Am. **65**, 816–825 (1979)
24. Keefe, D.H.: Theory of the single woodwind tone hole. J. Acoust. Soc. Am. **72**, 676–687 (1982)
25. Keefe, D.H.: Experiments on the single woodwind tone hole. J. Acoust. Soc. Am. **72**, 688–699 (1982)
26. Yoshikawa, S., Saneyoshi, J.: Feedback excitation mechanism in organ pipes. J. Acoust. Soc. Jpn. (E) **1**, 175–191 (1980)
27. Ando, Y.: Several peculiar structural devices of Japanese musical instruments and some aspects of timbre taste in Japanese music common with western ones. J. Acoust. Soc. Jpn. (E) **14**, 377–382 (1993)
28. Rayleigh, L.: The theory of sound, vol. 2. Macmillan, London, reprinted 1945, Dover, New York (1894)
29. Caussé, R., Kergomard, J., Lurton, X.: Input impedance of brass musical instruments: Comparison between experimental and numerical models. J. Acoust. Soc. Am. **75**, 241–254 (1984)
30. Mapes-Riordan, D.: Horn modeling with conical and cylindrical transmission-line elements. J. Audio Eng. Soc. **41**, 471–484 (1993)
31. Ebihara, T., Yoshikawa, S.: Nonlinear effects contributing to hand-stopping tones in a horn. J. Acoust. Soc. Am. **133**, 3094–3106 (2013)
32. Benade, A.H.: On the mathematical theory of woodwind finger holes. J. Acoust. Soc. Am. **32**, 1591–1608 (1960)
33. Lefebvre, A., Scavone, G.P.: Characterization of woodwind instrument toneholes with the finite element method. J. Acoust. Soc. Am. **131**, 3153–3163 (2012)
34. Kajiwara, K., Yoshikawa, S.: Discussion on the internal sound pressure distributions when cross fingerings are used in the shakuhachi. Proc. Autumn Meet. Acoust. Soc. Jpn., 903–906 (in Japanese) (2013)
35. Baines, A.: The Oxford companion to musical instruments, Oxford University Press, New York, pp. 21, 58, 90, and 122 (1992)
36. National Museum of Japanese History (ed.), The origin of Japanese musical instruments. Daiichishobo, Tokyo. Chap. III *Fue* (in Japanese) (1995)
37. Ando, Y.: An acoustical study of "Nokan", Ongakugaku (J. Jpn. Musicol. Soc.) **12**, 143–158 (in Japanese) (1966)
38. Ando, Y.: An acoustical study of Japanese transverse flutes. NHK Tech. Res. **22**, 63–78 (in Japanese) (1970)
39. Berger, D.P.: The nohkan: its construction and music. Ethnomusicology **9**, 221–239 (1965)
40. Yoshikawa, S., Kajiwara, K.: Acoustics of the Japanese noh flute, nohkan. Organological Congress 2014, Braga (2014)

41. Kajiwara, K.: Numerical Calculation Method of Sound Pressure Distributions Along the Bore and its Applications to Woodwind Instruments. Master Thesis, Graduate School of Design, Kyushu University (in Japanese) (2014)
42. Kajiwara, K., Yoshikawa, S.: Numerical calculation on acoustical characteristics of the nohkan. Rep. Musical Acoust. Res. Group, MA2013-66, pp. 59–64 (in Japanese) (2013)
43. Yanagida, K.: Japanese Festivals. Kadokawa, Tokyo, originally published in 1932, p. 54 (in Japanese) (1969)
44. Odaka, A.: The resonance hole with membrane; A distinctive feature of East Asian transverse flutes. Proceedings of Acoustics 2012 Hong Kong, 2aMU1. Hong Kong (2012)
45. Yoshikawa, S.: Acoustical classification of woods for string instruments. J. Acoust. Soc. Am. **122**, 568–573 (2007)
46. Yoshikawa, S., Shinoduka, M., Senda, T.: A comparison of string instruments based on wood properties: Biwa vs. cello. Acoust. Sci. Tech. **29**, 41–50 (2008)
47. Yoshikawa, S.: Chapter 11 "Plucked string instruments in Asia. In: Rossing, T.D. (edn.) The Science of String Instruments. Springer, New York (2010)
48. Samejima, T.,Ide, S., Araki, Y.: Vibro-acoustic analysis of wind instruments with membranes on resonance holes. Proceedings of Acoustics 2012 Hong Kong, 2aMU2. Hong Kong (2012)
49. Ide, S.: Acoustic Characteristics of Wind Instruments with Membrane on Resonance Hole. Master Thesis, Graduate School of Design, Kyushu University (in Japanese) (2011)
50. Ide, S., Samejima, T., Araki, Y.: Numerical coupled analysis and measurement of wind instruments with membranes on resonance holes. Proceedings of Autumn Meet. Acoust. Soc. Jpn., pp. 961–962 (in Japanese) (2011)

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