Current Research in Systematic Musicology

Albrecht Schneider *Editor*

Studies in Musical Acoustics and Psychoacoustics

Springer

Current Research in Systematic Musicology

Volume 4

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Studies in Musical Acoustics and Psychoacoustics

Springer

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ISSN 2196-6966 ISSN 2196-6974 (electronic)
Current Research in Systematic Musicology
ISBN 978-3-319-47291-1 ISBN 978-3-319-47292-8 (eBook)
DOI 10.1007/978-3-319-47292-8

Library of Congress Control Number: 2016953316

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Introduction

In the volume at hand, topics in musical acoustics and perception of sound are treated from a range of perspectives and with various methods. In general, the scientific field of musical acoustics is structured into several areas, some of which are close to physics, while others relate to music and musicology as well as to disciplines engaged in the study of sensation and perception. Musical instruments and the voice (of both humans and other species) are studied in regard to sound production and radiation of sound from a source into the environment. Sound production mechanisms often account also for pitch structures and timbral qualities available from individual instruments or from 'families' of instruments. Room acoustics is needed to understand the radiation processes including reflection and refraction of sound waves at boundaries as well as dissipation of sound energy within specific geometries.

Musical sound is produced, by musicians as well as singers, with the aim of communicating with a (real or virtual) listener. Of course, the player of an instrument or a singer acts himself or herself as a listener and makes use of his or her analytical listening capability to control, first of all, the parts (muscles, tendons, etc.) of his or her body involved, as effectors, in the production of sound. Playing an instrument or singing thus is based on feedback loops which control sound production, pitches and intonation as well as timbre and dynamic parameters in a musical performance.

Ideally, music as performed in a live event like a concert addresses an audience of appreciative subjects, meaning subjects capable of perceiving music as textures of sound from which the structure of a composition or improvisation may be gathered. Musical appreciation, however, can be viewed as the terminal point of a process that starts with sensation of sounds at the ears as the relevant peripheral sense organs (there are indications that also the vestibular system may be excited by very loud sounds). Taking the peripheral auditory system as a first stage of 'information pickup' and signal analysis, further analysis of sound in regard to salient features and pattern recognition is conducted along the auditory pathway and, finally, in cortical areas of the brain. Though there seems to be a hierarchy from initial sensation (which must be fast to allow for real-time processing

of complex sounds as well as efferent feedback activation within the auditory system) to perception directed to salient features and pattern recognition, followed by an evaluation of sensory input in cortical networks that might yield 'auditory objects', it is in fact the structure of the sound signal and the anatomical and physiological organization of the inner ear and the auditory pathway that determine perception of pitch, timbre and loudness. In this respect, a bottom-up approach to sound and music perception based on musical acoustics and psychoacoustics seems necessary notwithstanding the obvious role of musical training and sociocultural factors which can shape perception and cognition of music in individuals.

From what has been sketched in the preceding paragraph, one may view musical acoustics as centred on musical instruments in regard to mechanisms of sound production and radiation, but also including properties governing pitch, timbre and dynamic structures that in turn are relevant for sensation and perception of musical sound. Furthermore, studying actual playing and singing techniques can give insight into functional aspects of sound production and musical expression. However, musical acoustics includes also the formation of tone systems as well as scales, tunings and intonation patterns. Furthermore, while physical acoustics (traditionally a part of mechanics) may be conceived as a fundamental science treating the theory of vibration and sound with little regard to actual sensation and perception, musical acoustics relates to sensation and perception as well as to the production of sound in mammalian or other species in many ways. It is from such an integrative perspective that perceptual aspects and results from experiments involving musicians and/or listeners will be considered within the broader area of musical acoustics.

Several articles in this volume deal with the acoustics and organology of peculiar instruments as well as with certain types of instruments. Shigeru Yoshikawa offers a comprehensive study on Japanese flutes with a focus on their construction and acoustic properties as well as on playing techniques (such as cross-fingerings needed to produce a variety of pitches) as a factor that conditions intonation and timbral qualities. His article includes the classical and the modern shakuhachi, the nohkan (a transverse bamboo flute) and the shinobue (another transverse bamboo flute). Starting from the structural properties of each instrument (such as the shape of the embouchure and the bore), Yoshikawa has calculated admittance and resonance conditions in relation to fingerings. Also, he discusses the data obtained from a number of experiments including measurements as well as sound analyses. Taken together, the empirical evidence shows that the Japanese flute types studied in this article differ from European flutes in several respects, among them construction and materials, but most significantly sound properties which feature wind noise from blowing as an essential component of the sound. As Yoshikawa concludes, Japanese flutes are constructed for producing distinct timbral qualities with an emphasis on spectral energy in higher-frequency bands.

The study of the Chinese Qin carried out by Chris Waltham, Kimi Coaldrake, Evert Koster and Yang Lan provides fresh information from current research on the acoustics of an instrument that has a long history and is highly regarded in Chinese music tradition. The Qin is one of several plucked zither types of East Asia which

are of interest in regard to their construction, materials and sound properties. The acoustics of the Qin (of which little was known so far) is investigated, by Waltham and coworkers, by vibroacoustical measurement as well as a FEM modelling approach. The article offers empirical data in regard to materials, vibroacoustics, sound analysis and the FEM model chosen for this study.

Florian Pfeifle and Malte Münster have studied sound generation in two instruments widely used in rock and pop music genres, the Wurlitzer E-piano, and the Fender-Rhodes E-piano. While the Rhodes employs an electromechanical set-up for the generation and pickup of sound, the Wurlitzer uses electrostatical effects. Pfeifle and Münster have measured the vibrational patterns of sound generating elements (tine, bar, reed) with a high-speed camera and have made analyses of the electrical properties of the pickup systems as well as of the actual sound produced so that the mechanical and the electronic data form the basis, as intermediate results, for a finite-element modelling (FEM) and finite difference calculation approach to finding characteristics of sound generation in the two instruments. The article shows that the peculiar timbre in both instruments is largely due to the specific set-up and geometry of their respective pickup systems.

Jost Leonhardt Fischer investigates the feedback of different room geometries on the sound radiated from an organ pipe. Previous studies have demonstrated that pipes being placed on the same wind chest can influence each other because of acoustic coupling. In addition, one needs to consider sound radiation from individual pipes being hampered by the presence of several or even many pipes in their immediate surrounding as well as by structural parts of the organ (such as beams or brackets). Applying numerical simulation methodology, Fischer shows that sound waves radiated from an organ pipe undergo significant variation in regard to frequencies and amplitudes depending on the geometry of the reflecting surface. The effect is particularly visible if a pipe is located inside a closed swell chamber.

Shigeru Yoshikawa and Yu Nobara address acoustical problems associated with mutes as are used in playing brass instruments such as the French horn and the trumpet. In particular, they consider the stopping and straight mutes for the horn and the straight, cup and wah-wah mutes for the trumpet. From modelling the horn and the trumpet on the basis of branching theory and from extensive numerical calculation including transmission matrix (T-matrix) representation of the horn system as well as from data obtained in their own measurements, Yoshikawa and Nobara discuss acoustical parameters such as input impedance and admittance, internal pressure distribution in the bore and transmission function. Among their explanations of the effects mutes have for changes in resonance frequencies, modes and spectral energy distribution is that hand-stopping, in the French horn, causes a *descent* in pitch (while mutes in general sharpen pitches).

Malte Kob surveys a number of factors relevant for damping in musical instruments as well as parameters and methods suited to measuring damping in a vibrating system. Among the approaches that have been taken in experiments on musical instruments, one finds measurement of the loss factor, of the reverberation time (T_{60}), or of the −3dB bandwidth, respectively. In this article, results obtained from the measurement of vibrational patterns of a metal tongue are presented in a

comparative perspective. The study was undertaken using the reverberation time method in the time domain and the −3dB method in the frequency domain.

James Beauchamp bases his comparative study of vocal and violin vibrato viewed in regard to the source/filter model (prominent in phonetics but also in instrument acoustics) on signal processing methodology. In particular, he uses a range of tools available from the sndan package developed by Beauchamp and Maher. Applying the source/filter model to the analysis of complex sounds means one needs to separate the source waveform and spectrum from the filter defined by its transfer function. In complex sounds such as musical tones sung with vibrato in bel canto operatic style or played on a violin with vibrato (a nearly periodic change of the length of a vibrating string affected by finger movements), partial frequencies and amplitudes are modulated more or less sinusoidally, causing time-variant spectra. One method to track partials undergoing such modulation is the McAulay–Quatieri peak-picking algorithm (implemented as part of sndan). With detailed signal analyses, Beauchamp demonstrates how to separate the source spectrum for sung vibrato tones and for glides in violin tones (even though the source spectrum for such violin glides itself varies considerably with time).

Robert Mores proposes vowel quality (VQ) as a descriptor for the timbre of sounds recorded from Italian masterpieces (mostly Stradivari and Guarneri violins). VQ describes a vowel as produced by the human vocal tract by two key parameters, tongue backness and tongue height. The methodology outlined and discussed in this study is based on voice analysis and signal processing. Taking similarities in the sound structure of vowels and violin sounds as a starting point, formants are extracted and VQ parameters are calculated from recordings of violin tones in an automated process. Results are matched to the IPA chart of vowels and are validated by behavioural experiments in which subjects had to select voice sounds of different VQ so as to match violin sounds in terms of the VQ. Mores' study shows that VQ is an appropriate descriptor of violin timbre suited to be used in a comparative analysis of sounds recorded from a range of historic or contemporary violins.

Albrecht Schneider and Marc Leman investigate sound characteristics and the tuning of a historic carillon, founded by Joris Dumery for the city of Bruges (Flanders), in the eighteenth century. This carillon today comprises 47 bells, of which 26 are from Dumery. The bells were recorded on the belfry before a restoration took place lately. Though the daily use of the carillon might affect material and acoustical properties of its bells to some degree, the carillon could still be investigated for its original tuning. Since the spectra from bell sounds contain components which conform to segments of a harmonic series as well as numerous inharmonic components, pitch perception from bell sounds often is ambiguous. The article discusses the phenomenon of the so-called strike note in bell sounds and concepts of virtual pitch in regard to pitch perception of inharmonic sounds. Data from some recent behavioural experiments on pitch ambiguity employing the sounds from the Dumery carillon as stimuli are also included into this study.

Tim Ziemer's article on source width in music production (recording, mixing, mastering) comprises both theoretical modelling and experimental work. As is

known from acoustical measurements, the actual sound radiation patterns of individual instruments relate to their geometry as well as to the register and the dynamic level on which tones are played. Hence, the physical sound source can vary on several parameters. In addition, room acoustics can influence the perception listeners may have of a source in regard to spatial attributes. Different recording and mixing techniques either may preserve spatial characteristics of sound sources (e.g. natural voices or instruments), or may deliberately change the apparent source width for listeners (e.g. by applying stereophonic effects to monaural signals). After providing the fundamental concepts of room acoustics, Ziemer discusses source width in music production and recording with respect to stereo and surround set-ups as well as in ambisonics and in wave field synthesis. Finally, he reports an experiment in which sounds recorded from various instruments with a microphone array were projected to a large number of virtual listening positions with the aim of finding relations between sound field parameters and apparent source width.

Christiane Neuhaus reviews methods in neuromusicology (aka cognitive neuroscience of music) such as transcranial magnetic stimulation (TMS), functional magnetic resonance imaging (fMRI), positron-emission tomography (PET), electroencephalography (EEG) and measurement of event-related potentials (ERPs). Studies of neural processes and functions in the brain in regard to sensation and perception of sound and music were begun decades ago with EEG methodology but gained new impetus when imaging techniques such as PET and fMRI became available. Though research on 'the musical brain' employing the aforenamed technologies has largely expanded the scope of topics and methods known from 'classical' psychoacoustics and music psychology, there are also constraints that must be taken into account. In effect, each method needs to be evaluated, on theoretical grounds as well as with respect to results obtained from experiments or simulations.

Jonas Braasch, Selmer Bringsjord, Nikhil Deshpande, Pauline Oliveros and Doug Van Nort report on the current state of an ongoing project labelled *Creative Artificially-Intuitive and Reasoning Agent*, CAIRA, an intelligent music system capable to be used in performances of music from various genres, among them traditional and free jazz. The system has a dual architecture and combines signal-driven bottom-up analysis with tools from computational auditory scene analysis (CASA) and logic-based top-down reasoning. The bottom-up analysis is directed to psychoacoustic parameters and uses auditory models for pitch, timbre and loudness, while modules in addition extract parameters relating to sonic textures and gestures. The concept of an intelligent agent such as in CAIRA is that it needs to 'understand' the essential features of the genres and the style that is played by a musician (with whom the agent interacts in a live situation, that is, in real time). This implies the system needs to incorporate modules comprising algorithms for machine learning (as in this system).

The article on keyboard temperaments from Albrecht Schneider and the late Andreas Beurmann offers a historical review of sources from music theory and organology relating to tone systems, tunings and temperaments as well as empirical data from measurements and behavioural experiments. Since just intervals form the

basis of most tone systems and scale types (for acoustic and psychoacoustic reasons), the number of pitches (m) extends to $m > 12$ if chords in various major and minor keys shall be played in just intonation. Regarding technical limitations that existed for mechanical keyboard instruments as well as for musical performance practice, temperaments and actual tunings had to reduce the large number of tones and pitches resulting from modal and chordal structures conceived in just intervals to a much smaller number $n = 12$ of keys available in a conventional keyboard. Temperaments calculated and proposed by Werckmeister or Vallotti can be viewed as a compromise in regard to tuning scales and intervals so that with only 12 tones/pitches to the octave, modulation through a range of keys is possible, while beats and roughness are kept within certain limits. The article presents data for Werckmeister III and Vallotti tuned on a historical Kirckman harpsichord. Also included are data from behavioural experiments where subjects had to rate musical excerpts presented in various tunings.

Hamburg Albrecht Schneider
July 2016

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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A. Schneider (ed.), *Studies in Musical Acoustics and Psychoacoustics*,
Current Research in Systematic Musicology 4,
DOI 10.1007/978-3-319-47292-8_1

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

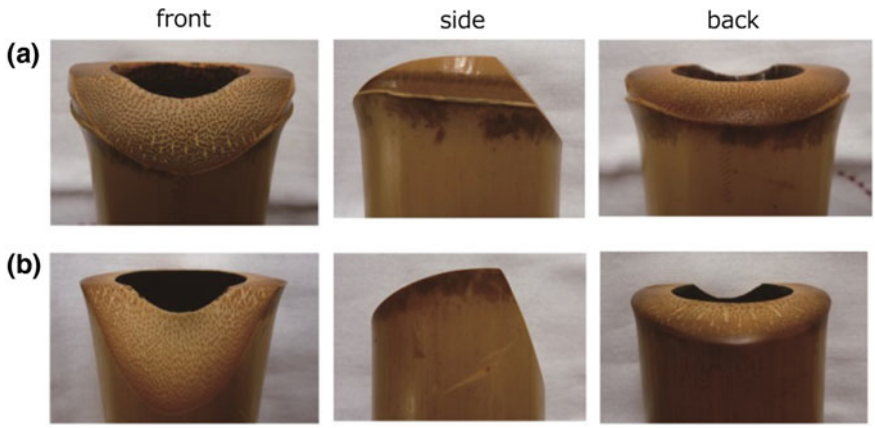

Fig. 1 Two examples of the shakuhachi embouchure edge. **a** A shallow edge with a short cut; **b** a deep edge with a long cut. Also, the construction of the back side is different between them

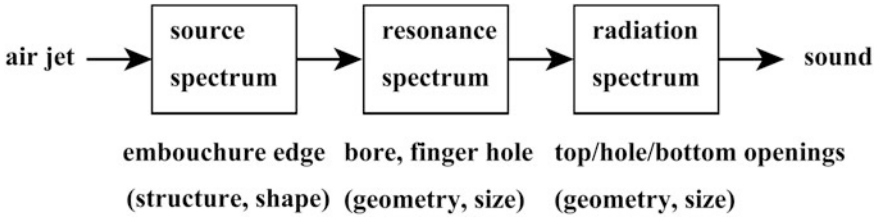

Fig. 2 Harmonic generation in the shakuhachi. The source spectrum formed by the interaction between the air jet and the edge is modified by resonance and radiation characteristics of the bore and finger holes

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

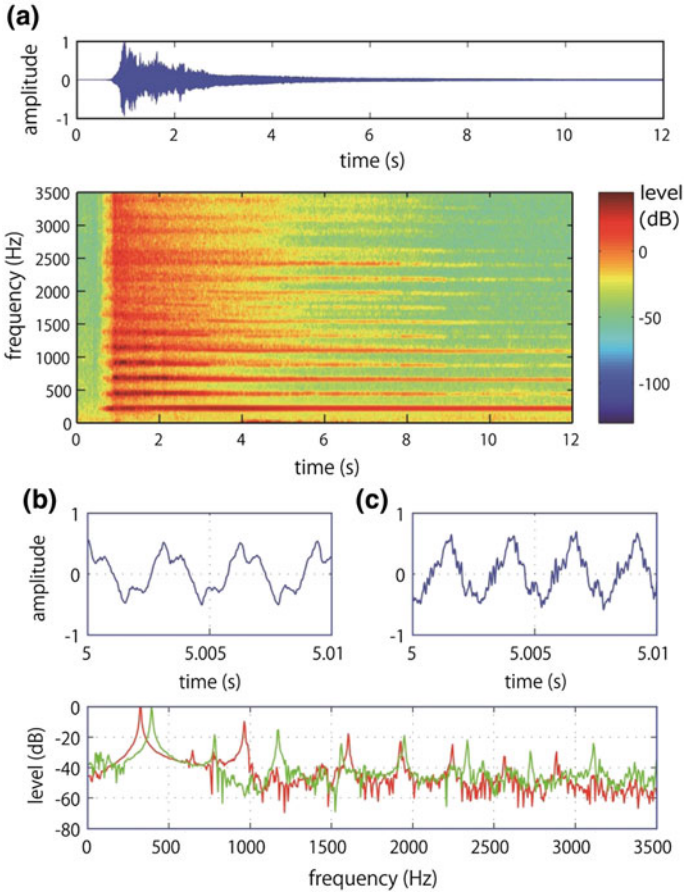

Fig. 3 Tone examples of the two-shaku three sun shakuhachi. **a** *Ro* (all tone holes closed) blown with *muraiki* during the starting four seconds; **b** *Wu* (the first and third tone holes opened half) with *meri* blowing; **c** *Ri* (the third and fourth tone holes opened) with normal blowing. The 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

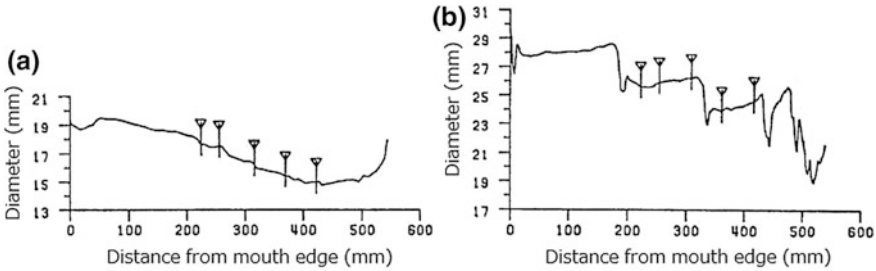

Fig. 4 Inner bore shape patterns of a modern shakuhachi (**a**) and a classical (*komuso*) shakuhachi (**b**) [17, 19]. Also, five tone-hole positions are indicated by the *vertical line*

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

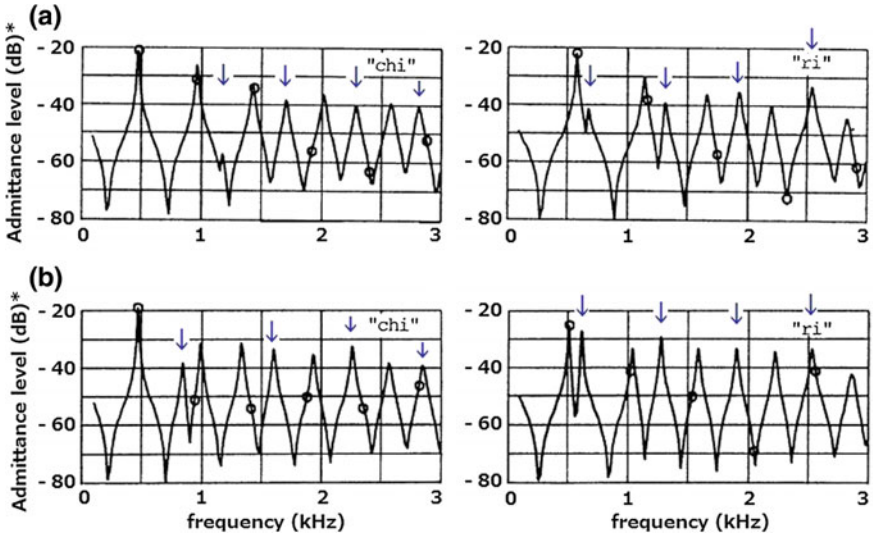

Fig. 5 The calculated input admittances of a modern shakuhachi (**a**) and a classical shakuhachi (**b**) [17]. Fingerings are basic ones, *chi* and *ri*. The symbol *open circle* indicates the harmonics of the fundamental frequency that is given by the first admittance peak. The *vertical arrows* suggest 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,

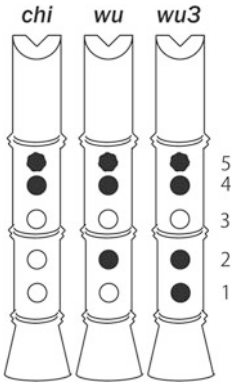

Fig. 6 Three fingerings of the shakuhachi treated in this section

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 920 Hz ($A^\#{}_5$), respectively. Furthermore, in the third register the three fingerings gave 1322 Hz (E_6), 1475 Hz ($G^b{}_6$), and 1472 Hz ($G^b{}_6$) [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

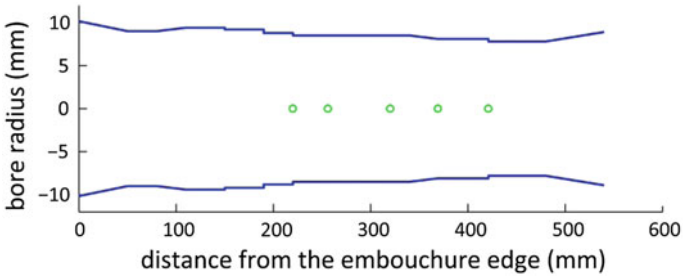

Fig. 7 Bore geometry of a modern shakuhachi treated in this section. The tone-hole positions are also indicated by the *circle*. The bore is approximated by ten cylindrical, two divergent conical, and two convergent conical tubes for numerical calculation

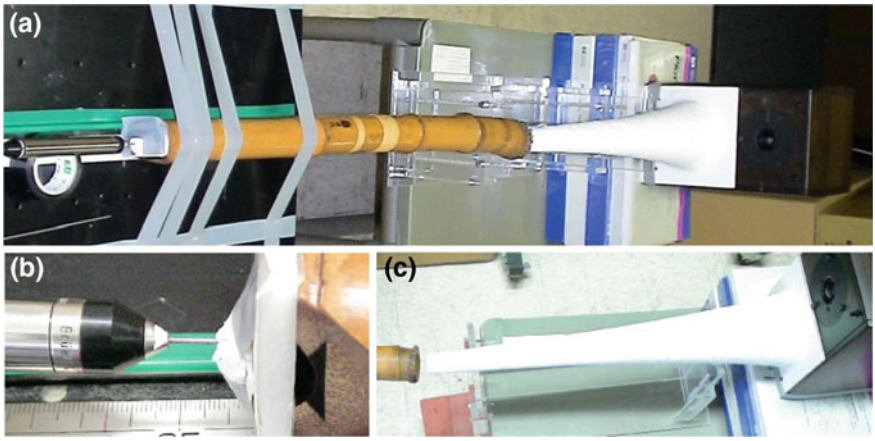

Fig. 8 Setup of the blowing experiment for measuring the pressure standing waves along the air column of the shakuhachi. **a** Total view; **b** close-up of a probe microphone and the embouchure; **c** close-up of the shakuhachi bottom and an exponential horn whose shape was designed to have the cutoff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

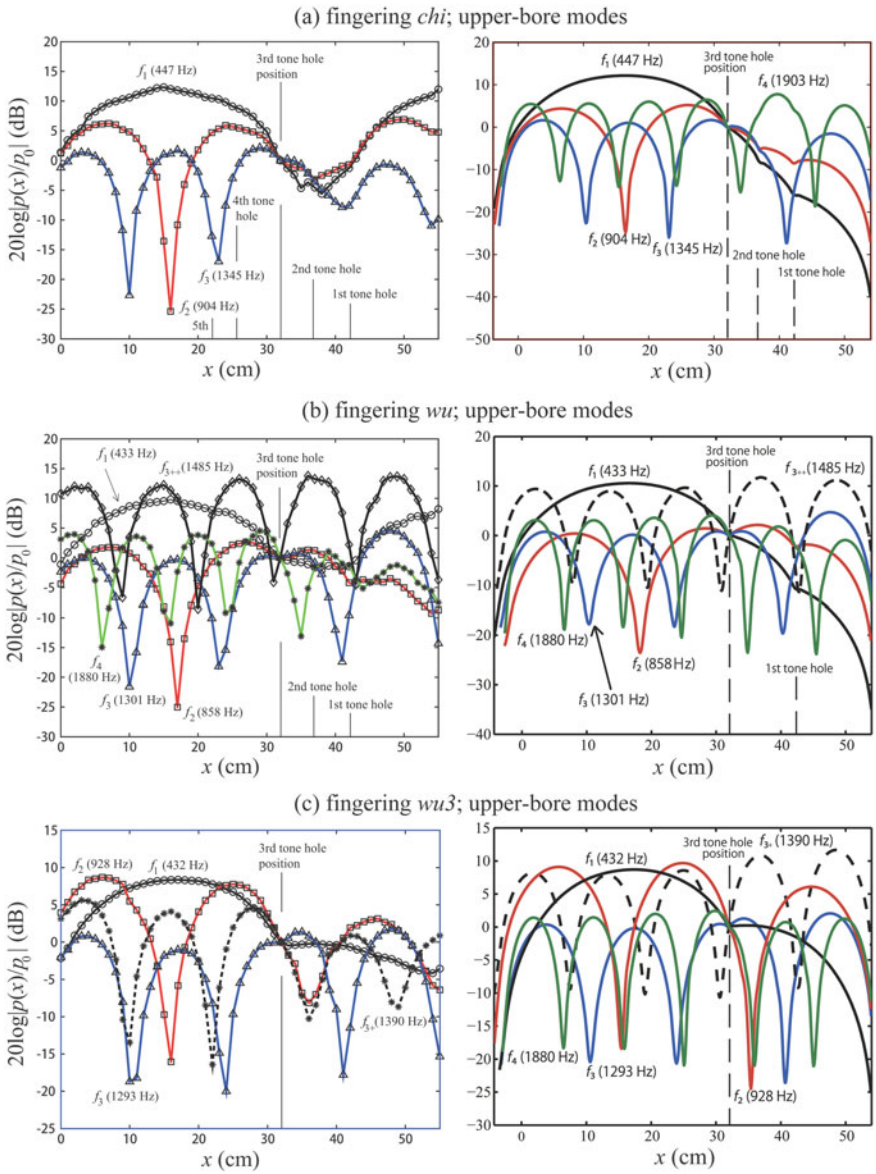

Fig. 9 Results of the measurement (*left column*) and numerical calculation (*right column*) on the internal standing-wave patterns [16, 34]. The distributions of the upper-bore modes are depicted. **a** Normal fingering *chi* (the first to third tone holes are open); **b** cross fingering *wu* (the 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

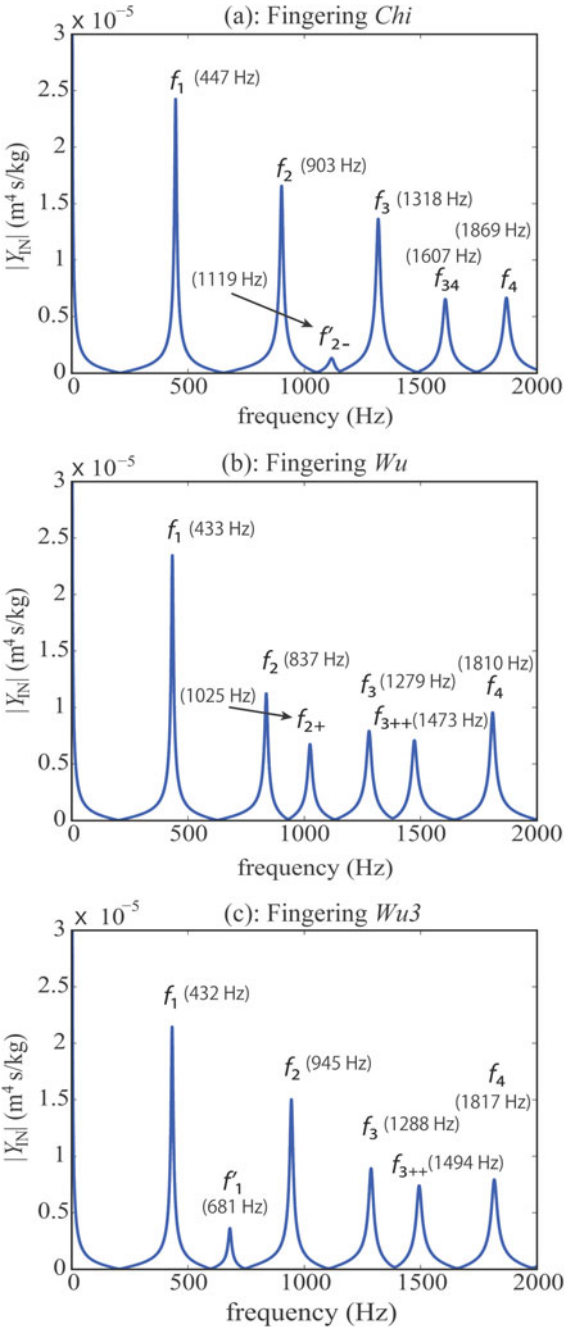

Fig. 10 The calculated absolute value of the input admittance $|Y_{IN}|$ for three fingerings [16]. **a** Normal fingering *chi*; **b** cross fingering *wu*; **c** cross fingering *wu3*

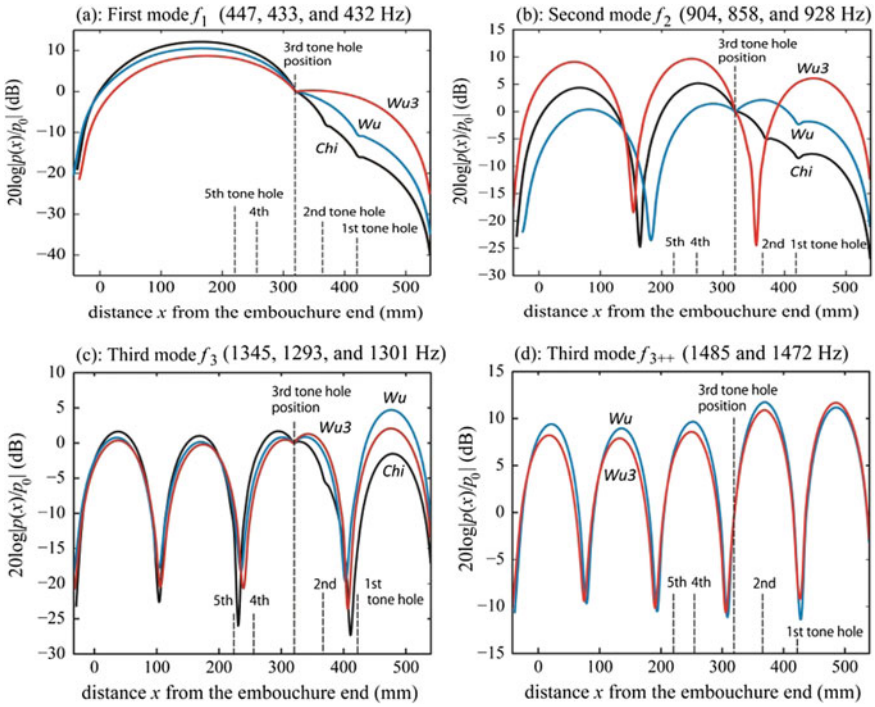

Fig. 11 Standing-wave patterns for the respective mode given by the three fingerings [16, 34]. The mode frequencies noted in each frame are in order of fingering *chi*, *wu*, and *wu3*

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